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

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Executive Summary

The team of Alabama Agricultural and Mechanical University (AAMU), Denbury Resources, Inc., Geological Survey of Alabama (GSA), Southern Company Services, Inc., University of Alabama (UA), University of Alabama at Birmingham (UAB), and University of North Carolina at Charlotte (UNCC) 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 present report describes work and accomplishments during the first quarter of the second year of work, from January 1 to March 31, 2008.

The work being 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 (UA and UAB), 2. Geology and Petrology (GSA and Southern Company), 3. Reservoir Fluid Properties and Phase Behavior (UA), 4. Petroleum Reservoir Simulation (UA), 5. CO$_2$ Liquefaction, Transportation, and Storage (Southern Company and Denbury Resources), 6. Well Preparation and CO$_2$ Injection (Denbury Resources), 7. Surface Monitoring (AAMU), 8. Seismic Monitoring (UNCC), 9. Saline Formation Simulation (UAB), 10. Visualization of Geologic Structure and Flows (all partners), and 11. Reservoir Management Plan and Economic Analysis (all partners).

Citronelle Unit B-19-10 #2 well (Permit No. 3232) will serve as the CO$_2$ injector for the first field test. CO$_2$ will be injected into the Upper Donovan 14-1 and 16-2 sands. The sands will be water flooded for six months prior to CO$_2$ injection, to restore the formation to conditions similar to those that will exist at other wells when they are converted from water injection to CO$_2$, and establish a baseline for production from the test pattern under water flood conditions. Workover of the injector (B-19-10 #2) and two producers (B-19-7 and B-19-9) is complete, in addition to one producer (B-19-8) that required no workover. One plugged and abandoned producer (B-19-10 #1) remains to be evaluated. Water injection was begun in February 2008 and reached a rate of 150 bbl/day, but unset the retrievable packer in the injector. A permanent packer is being installed. Water injection is expected to resume on April 28 or 29, 2008, and continue until CO$_2$ injection begins in October 2008. A pressure test in the injector in March established bottom hole conditions of 4000 psia and 245 °F.

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 over the area surrounding the well. Well logs in the cross sections are being correlated, with emphasis on characterization of the 14-1 and 16-2 sands. Correlation of the sands reveals that, 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 heterogeneity. The petrology and stratigraphy have led to significant revision of the conventional geologic model for the field derived...
from early studies of the formation in the 1950's and 1960's, and will have significant bearing on the approach to the test injection and interpretation of its results.

A rolling ball viscometer, with which to measure minimum miscibility pressure, viscosity, and density of oil-CO\textsubscript{2} mixtures at reservoir temperature and pressure, is being assembled and tested. This instrument will provide the means for rapid and cost-effective measurement of oil-CO\textsubscript{2} mixture properties and is an excellent tool with which to examine the extension of oil-CO\textsubscript{2} miscibility through addition of other gas constituents to CO\textsubscript{2}, a component of the advanced CO\textsubscript{2}-EOR technology proposed by Kuuskraa and Koperna (2006).

Static estimates of the storage capacity of Citronelle Dome, including saline formations in the Lower and Upper Tuscaloosa Groups and Eutaw Formation, and the Donovan Sands of the Rodessa Formation, are a total of 0.5 to 2 billion short tons of CO\textsubscript{2}. Preliminary estimates, based upon the analysis by Berg (1975), indicate that leakage of CO\textsubscript{2} through cap rock is not expected from any of the formations considered as storage reservoirs, but a refined assessment using more accurate values for the rock and fluid properties is recommended.

A scheme was devised and the apparatus constructed for measurement of CO\textsubscript{2} fluxes from soil at four locations surrounding each of the five wells in the test pattern. A test plot for monitoring of plant species was established at each well.

The dependence of species richness and species density in Alabama on location and environmental factors, such as latitude, elevation, annual average temperature, precipitation and roadless area has been analyzed by Chen and Wang (2007) and Chen and Roberts (2008). Their state-wide view of species distributions will help to discriminate whether any changes observed at Citronelle might be associated with carbon storage, or with changes due to other phenomena occurring on a larger spatial scale.

The Refraction Microtremor (ReMi) technique was proposed for observation of shear wave anomalies cause by fracturing in the shallow subsurface in the vicinity of the injection well. A longer array of wireless accelerometers was proposed to detect CO\textsubscript{2} migration in the reservoir. Both methods make use of signals from naturally-occurring seismic events, so would be least disruptive to the Citronelle community, least likely to upset oil production, and of greatest interest to researchers in seismic imaging.

Extrapolating from the analysis by Kuuskraa and Koperna (2006), indications based upon present economic conditions and estimates of EOR performance are that a CO\textsubscript{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 correlation of sands in stratigraphic cross sections, reservoir simulations, establishment of the ecological background and baseline, completion of the rolling-ball viscometer, analysis of options for seismic monitoring of CO\textsubscript{2} migration, continuation of the water flood, and planning for the CO\textsubscript{2} injection in October. Richard Esposito will present a paper describing the planning and preparation for the first pilot CO\textsubscript{2} injection under the project at the Seventh Annual Conference on Carbon Capture and Sequestration in Pittsburgh, May 5-8, 2008.
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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 CO₂ 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 CO₂ 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 (CO₂-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 CO₂ 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 CO₂ storage. However, the geology of the heterogeneous siliciclastic rocks in this field is very different from those where CO₂-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 CO₂-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 CO₂-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 CO₂, 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 CO₂-EOR at other sites having geologic structure similar to that of the Rodessa Formation, which is very different from the Permian Basin structure where CO₂-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 CO₂ 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 CO₂ in the reservoir.

Phase II. Studies will include the effect of nitrogen on oil-CO₂ interaction, a stability analysis of the anhydrite dome overlying the reservoir, and refined reservoir simulations and visualizations. A second CO₂ 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 CO₂ in the formation, and comparison of simulation versus field test results.

Phase III. Migration of CO₂ 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 CO₂ 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 Appendix A 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 collaborative 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 CO2 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-CO2 interaction.** Determination of minimum miscibility pressure. Evaluation of propensity for oil components to precipitate in the presence of CO2. Measurement of viscosity of the oil as functions of temperature and CO2 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 CO2 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. **CO2 Liquefaction, Transportation, and Storage**
Richard Esposito, Southern Company
Jack Harper, Denbury Resources

The logistics of procuring, transporting, and storing CO2 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ for the project. This includes provision for onsite storage of CO₂, installation of CO₂-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 CO₂ for future EOR projects, including identification of sites for CO₂ 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 CO₂.

**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 CO₂ fluxes and ecology.** Establish baseline CO₂ 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 CO₂ 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 CO₂ and fluorocarbon tracer in shallow boreholes and concentration profiles in soil near the surface to determine whether CO₂ 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 CO₂.** Determine if seismic measurements are able to detect changes in the formation and the presence and migration of CO₂.

2.9. **Saline Formation Simulation**  
Konstantinos Theodorou, University of Alabama at Birmingham

Simulation of CO₂ injection and analysis of the fate of CO₂ injected into saline formations were not explicitly called for in the original statement of work, though the possibility of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ injection strategy to ensure efficient oil sweep.

**Task 12. Economic and market analysis.** Verify that production using CO₂ 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

Eric S. Carlson, University of Alabama
Shen-En Chen, University of North Carolina at Charlotte
Xiongwen Chen, Alabama A&M University
Peter E. Clark, University of Alabama
Gary N. Dittmar, Denbury Resources
Richard A. Esposito, Southern Company Services
Jack Harper, Denbury Resources
Denise J. Hills, Geological Survey of Alabama
Ermson Nyakatawa, Alabama A&M University
Jack C. Pashin, Geological Survey of Alabama
Kathleen A. Roberts, Alabama A&M University
Peter M. Walsh, University of Alabama at Birmingham

3.1.1. Communication among the Partners

Eric Carlson has set up a high-performance server and registered a new collaboratory website for the project under the name <citronelleoil.us>. He and his students subjected it to weeks of testing and determined that it is performing properly. During the second quarter of this year, Eric will set up workspaces for all of the researchers and create wikis for each of the groups. He and his group members will collect all of the documents produced under the project and upload them to the site. They will also locate the available Citronelle data and have that uploaded as well. Eric has found that wikis are an efficient collaboratory framework and feels that they will be an effective means for communication and reporting by the group. A trial run using wikis will be conducted during the third quarter to explore their possibilities and introduce this medium to members of the team not familiar with it.

3.1.2. Publication

Xiongwen Chen and Kathleen Roberts of AAMU prepared a paper, accepted for publication in the journal *Biodiversity and Conservation*, entitled: "Roadless Areas and Biodiversity: A Case Study in Alabama, USA," in which they examine the relationships between roadless area and local species richness. The paper documents a positive correlation between species richness and the metric "roadless volume" (RV), introduced by Watts and coworkers (2007), which is the integral, over the area of interest, of the product of land area and distance to the nearest road. The paper continues the study by Xiongwen Chen and his coworkers, of state-wide patterns of species richness and species diversity, upon which those in Mobile County and the region of Citronelle, AL, are
superimposed. This will permit determination of whether or not changes observed at Citronelle are associated with carbon storage, or are due to other phenomena occurring on larger spatial scales.

3.1.3. **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 publications are found and as new studies of the Field and region are published, including those resulting from work under the present project.

3.1.4. **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.

3.1.4.2. Citronelle, Alabama, January 31 and February 1, 2008.

Xiongwen Chen and Ermsn Nyakatawa of Alabama A&M University, and Graduate Research Assistant, Kathleen Roberts, met with Peter Walsh of UAB and Alec Bailey of Denbury Resources at Citronelle on January 31 and February 1. During this visit, Xiongwen Chen and Kathleen Roberts marked off 10 m x 10 m test plots in undisturbed areas near each of the five wells in the test pattern, in which they will monitor the growth of plants and distribution of plant species. Ermsn Nyakatawa examined each of the well sites in preparation for measurements of CO₂ concentration and flux from soil surrounding the wells. Following the visit, Ermsn and Peter Walsh prepared a proposed plan for installation of the equipment and a program of measurements to document any changes in CO₂ concentrations and fluxes. The proposed arrangement of the equipment and schedule for the measurements are described in Section 3.7.1 of this report.


The entire research group met at Denbury Resources' offices in Citronelle on February 21, to review the well work that has been done, the plan for surface facilities, arrangements for CO₂ transportation and storage, seismic imaging, environmental measurements, the timing of fluid sampling, and data requirements. The day began at 8:30 a.m. with a visit to the test wells in the field until 10:30, followed by discussion and presentations, including a working lunch, from 10:30 to 2:30.
The first stop on the tour of the test site was the B-19-8 Tank Battery, where Mike Sullivan and Gary Dittmar of Denbury Resources explained the current waterflood operation, the layout of the facilities and equipment to be installed for the CO₂ test injection, and operations during CO₂ injection. CO₂ storage will be located at the B-19-8 Tank Battery and piped to the injector. Equipment to separate gas from oil and water will be located at both the B-19-8 and B-19-11 Tank Batteries. The second stop was at the CO₂ injector, well B-19-10 #2, shown in Figure 3.1.1, where Gary Dittmar described the work that had been done on the well to convert it from producer to injector, the materials chosen, pressure testing, the plan for water injection, and the piping changes needed to prepare for CO₂ injection. The third stop was at well B-19-9, a temporarily abandoned producer in the test pattern, scheduled for workover in preparation for the water flood and CO₂ injection. The last stop was to view workover in progress at well B-19-7, where the crew was preparing to dump concrete below the 16-2 and 14-1 sands. The production tubing was already bundled in preparation for its installation. Production was expected to begin in about 5 weeks.

Figure 3.1.1. Jack Pashin of the Geological Survey of Alabama at the injection well, B-19-10 #2. The CO₂ injection head and water line are already in place.
Back in Denbury Resources' offices, Gary Dittmar of Denbury reviewed what has already been done to prepare for water and CO₂ injection and what remains to be done, including the pump and other equipment to be procured. He described the gas-liquid separator and the handling of produced gas, water, and oil, presented the results of the initial pressure test, and provided a survey map specifying the exact relative locations of the injector and four producers. A step injection test is planned. Mark Rainer of Denbury discussed the geology of the 16-2 and 14-1 sands, referring to a large cross section showing the correlation of the sands between the injector and producers. There were numerous questions from the members of the group regarding oil properties and production data, such as API gravity, additives, pressures, and production rates. The frequency of collection and analysis of fluid samples was also discussed.

Jack Harper, of Denbury Resources, noted that a likely range of CO₂ injection rates, for planning purposes, is 800,000 to 1 million cubic feet per day. Richard Esposito, of Southern Company, reviewed the effort to identify a supplier who will receive CO₂ at Denbury’s facilities at Jackson Dome, liquefy it, and deliver it to Citronelle at acceptable cost. Richard also reviewed the logistics of CO₂ delivery at the rate of 45 to 55 short tons per day, equivalent to 2 to 3 truckloads per day, and the desirability of sharing storage tanks with other CO₂ injection projects. The pros and cons of portable and fixed storage tanks were discussed. Portable tanks are preferable, but more costly and more difficult to obtain. Richard estimates that approximately 2 months will be needed to reach decisions regarding the delivery and storage options. Tommy Henderson, of Denbury Resources, noted that some truckers refuse to make deliveries over dirt roads, such as that into the B-19-8 Tank Battery.

Eric Carlson of the University of Alabama observed that it may be worthwhile to have pressure transducers in the producers at the beginning of water injection, to provide for observation of any pressure response occurring at the producers. Following the meeting, Eric performed some rough calculations to determine whether or not this would be feasible. Eric estimates, using a porosity of 15%, viscosity of 1 cP, permeability of 10 mD, sand thickness of 20 ft, distance of 1000 ft from injector to producers, and water injection rate of 100 bbl/day, that a change of 20 psi (enough to detect above the noise) would be observed at the producers in 15 days. Based on that estimate, his conclusion is that placing pressure bombs in the producers (as many as possible) and recording the pressures for 30 days would provide a valuable set of data.

Ermson Nyakatawa of Alabama A&M University presented his proposal for measurement of CO₂ concentrations and fluxes from soil in the vicinity of the injector and producers (please see Section 3.7.1). He plans to place gas sampling probes, soil thermometers, soil moisture probes, and soil gas flux canisters at four points surrounding each well, 5 to 10 feet beyond the tree line, out of the way of people and vehicles, where the wooded area is undisturbed. Ermson and his students will need two days to put the probes in place and collect a representative set of soil samples for analysis. He would then like to return once a month for one day each time to record the data. Ermson proposed installation of a weather station at B-19-8 Tank Battery, to monitor temperature, humidity, precipitation, and wind speed and direction. This was seen not to be a
sufficiently secure location, in spite of the significant amount of equipment already located there. It was decided that placing it behind the office building would be best, though that is somewhat distant from the test site.

Shen-En Chen, of the University of North Carolina at Charlotte, then described the refraction microtremor (ReMi) seismic measurements that he proposes for observation of CO₂ migration, described in Section 3.8. The sources of the waves refracted by the CO₂ plume can be simply the motion of people and vehicles on the surface. Excitations by thumper truck or dynamite, that are more intrusive to the community and production operations, are not required. Shen-En proposes installing, temporarily, for each set of measurements, an array of sensors in an "X" pattern (Figure 3.8.1), along the line from well B-19-7, past the injector, to well B-19-9, and along the line from well B-19-10, again past the injector, to well B-19-8. If the sensors that he plans to employ initially turn out not to be sufficiently sensitive, he has an alternative detector design that is buried a foot or so underground. One survey is planned during the water flood, prior to CO₂ injection. A second survey would be performed 2 to 3 weeks after the start of CO₂ injection, and another survey 3 to 5 months later. Two suggestions were made: (1) to consult with Alec Bailey of Denbury Resources, to ensure that Denbury has right-of-way along the proposed paths of the sensor array, and (2) to consult with Bob Schellhorn of Denbury Resources in Plano, regarding the feasibility of the method, considering the depth and thickness of the sands.

Kathleen Roberts of Alabama A&M University concluded the day's discussion with a description of the 10 x 10 meter plots that she and Xiongwen Chen have marked off at each of the five wells in the test pattern, to monitor the distribution of plant species and their rates of growth. Kathleen and Xiongwen also plan to measure the flux of CO₂ from soil at each site, but using temporarily installed probes, rather than the more permanent installation proposed by Ermson Nyakatawa. Their measurements will be a bit more distant from the wells than Ermson's. During the visit to the test site on January 31 and February 1, Xiongwen and Kathleen measured the circumferences of the trunks of representative plants in each of the five test plots. The original idea had been to monitor the average growth rate of each species. However, Kathleen returned to the field on February 22, the day after the group meeting, to tag individual plants, so the growth rate of each plant and dependence of growth rate on size of plant can be monitored, adding a new level of detail to the measurements.

Because of the number of days of work in the field anticipated by team members from Alabama A&M University and the University of North Carolina at Charlotte, it was suggested that the work be coordinated so as many as possible of the visitors to the test site will be present at once. Following the meeting, a summary of the field work to be done and a proposed schedule, presented in the following section, were prepared and submitted to Denbury Resources for review.

The next meeting of the full team will be held in Birmingham, in approximately 3 months.
3.1.5. Future Visits to Citronelle Oil Field

Good coordination of visits to the test site by project team members with Denbury Resources' personnel in Citronelle, is essential to the successful execution of the work. The proposed frequency of visits to the test site to set up equipment and collect data, the number of hours to be spent in the field during each visit, and the specific work to be done are described below.

Four types of work are planned:

- **Set-up and monitoring of the test plots chosen to observe the growth of vegetation near the injector, producers, and tank batteries by Xiongwen Chen and Kathleen Roberts of Alabama A&M University (AAMU).**

- **Measurement of soil properties and CO$_2$ concentration and flux from soil near the injector and producers by Ermson Nyakatawa and his students at Alabama A&M University (AAMU).**

- **Seismic imaging using sensors laid out in an "X" (Figure 3.8.1) across the test well pattern by Shen-En Chen and Wenya Qi of the University of North Carolina at Charlotte (UNCC).**

- **Collection of reservoir fluid samples (oil, water, and gas) by Peter Clark of the University of Alabama (UA) and Peter Walsh of the University of Alabama at Birmingham (UAB).**

The timing, duration, and specific activity connected with each of these components of the project are described below. A proposed schedule for the visits to the field is shown in Table 3.1.1.

3.1.5.1. Set-up and Monitoring of Test Plots.

Xiongwen Chen and Kathleen Roberts, AAMU

- **Complete set-up of the test plots.** Two 8-hour days are requested in May 2008 to complete the set-up and tagging of plants in test plots at the injector, four producers, and two tank batteries and complete the first set of measurements of the circumferences of the trunks of the tagged plants in each of the seven test plots.

- **Periodic measurements of tagged plants and ambient air in the seven test plots.** Visits of 6 hours each, once a month, beginning in April 2008, are requested to monitor the rate of growth (circumference of trunks) of the tagged plants in the test plots, the composition of ambient air in the vicinity of the five wells and two tank batteries, and the CO$_2$ flux to the soil surface. Forty minutes would be spent at each of the wells and plots making the measurements, with 10 minutes allowed per site for the trip from Denbury's office to the field, from well to well, and back to the office. If it were possible, we would like to increase the frequency of visits for ambient air, soil, and growth measurements to two per month, during and for several months following CO$_2$ injection. Two 8-hour days, back-to-back, are requested once a year, in October or November, following the growing season, for a complete survey of plant growth in the
test plots. This work is listed under the month of November 2008 in Table 3.1.1. All of the visits would be coordinated with those described below, to minimize the total time that Denbury employees would be needed to oversee the work in the field.

3.1.5.2. Soil Properties and CO₂ Fluxes from Soil.
Ermson Nyakatawa and students to be identified, AAMU

a. **Set-up of soil monitoring equipment.** Two 8-hour days in May 2008 are requested to set up soil gas probes, gas sampling chambers, soil thermometers, and soil moisture probes just past the tree line at each of the five wells in the test pattern. These days would be chosen to coincide with the two days requested for set-up of test plots, described under Part 3.1.5.1a, above.

b. **Periodic measurement of soil conditions at the five wells.** Visits of 6 hours each, once a month, beginning in June 2008, are requested to record the data from the probes described in Part 3.1.5.2a, above, to monitor soil conditions and CO₂ flux to the soil surface at the five wells over time. Soil samples would be collected during one of these visits each year.

3.1.5.3. Seismic Imaging using the Refraction Microtremor (ReMi) Technique.
Shen-En Chen and Wenya Qi, UNCC

a. **Pre-injection baseline survey.** Assuming that the indemnification agreement between Denbury and UNCC can be concluded, two 8-hour days are requested 1 to 2 weeks prior to CO₂ injection (approximately September 2008), to perform a baseline survey during water injection. This visit would be scheduled to overlap with the visits described in Parts 3.1.5.1b and 3.1.5.2b, above.

b. **Post-injection monitoring surveys.** Two visits of two 8-hour days each are requested to monitor the migration of the CO₂ plume 2 to 3 weeks after the start of CO₂ injection (November 2008), then again 3 to 5 months after the start of CO₂ injection (approximately February 2009). These visits would also be timed to coincide with visits described in Parts 3.1.5.1b and 3.1.5.2b.

3.1.5.4. Reservoir Fluid Sampling.
Peter Clark, UA, and Peter Walsh, UAB

Monthly visits of 4 hours or less are requested to collect samples of produced oil, water, and gas. These visits would be scheduled to coincide with those described in Parts 3.1.5.1b and 3.1.5.2b, above.

A proposed schedule for the visits during the 11-month period from April 2008 to February 2009 is shown in Table 3.3.1. Alec Bailey in Denbury Resources' office in Citronelle would be consulted each month to determine the most convenient day or days for the visits in the following month.
Table 3.1.1. Proposed schedule of visits by the DOE project team to Citronelle Oil Field.*

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Organization</th>
<th>Investigators</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Apr</td>
<td>May</td>
</tr>
<tr>
<td>Plant species, growth rate, ambient air, CO₂ flux</td>
<td>AAMU</td>
<td>X. Chen K. Roberts</td>
<td>1x6h</td>
<td>2x8h</td>
</tr>
<tr>
<td>Soil properties, CO₂ flux, soil samples</td>
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<td>E. Nyakatawa</td>
<td>2x8h</td>
<td>1x6h</td>
</tr>
<tr>
<td>Seismic imaging</td>
<td>UNCC</td>
<td>S. Chen W. Qi</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2x8h</td>
</tr>
<tr>
<td>Reservoir fluid sampling</td>
<td>UA UAB</td>
<td>P. Clark P. Walsh</td>
<td>1x4h</td>
<td>1x4h</td>
</tr>
</tbody>
</table>

*The notation "a×b h" is meant to indicate a visits to the field during that month, lasting b hours. Where two or three investigators are requesting visits in a given month, the visits will be scheduled to overlap.
3.2. Geology and Petrology
David C. Kopaska-Merkel, Denise J. Hills, and Jack C. Pashin
Geological Survey of Alabama
Richard A. Esposito, Southern Company Services

During the quarter under review, petrographic work has focused on: (1) continued study of thin sections already prepared, and (2) selecting additional thin sections to prepare from the target well, B-19-10 #2 (Permit No. 3232), and from well C-1-6 (Permit No. 713). New thin sections from the target well will be used to better characterize the target sandstone's porosity and permeability characteristics and its mode of deposition. Well C-1-6 is represented by a very long and well-preserved core. This core includes muddy zones (shale, silty shale, muddy siltstone) that are not well represented in other cores. The muddy zones are important, because they contain clues about depositional environments that are not preserved in sandstone units. Further, muddy zones may be source rocks for hydrocarbons.

Figure 3.2.1 shows a portion of the target well. Note that sandstone above the target interval contains root casts and abundant calcite cement. These rocks are red, which indicates oxidation. A brief period of subaerial exposure and soil formation took place shortly after this unit was deposited. Red paleosols are common in the Rodessa at Citronelle Field, indicating repeated episodes of exposure and weathering. By contrast, photomicrographs of sandstone in the injection interval indicate no characteristic soil microfabrics and retain significant porosity. Even though some of these samples contain considerable calcite cement, they are porous and permeable enough to host hydrocarbons.

Early diagenesis (soil formation), which in turn was controlled by topography and short-term sea level change, may have strongly influenced sandstone porosity and permeability in the Rodessa at Citronelle Field. If this inference is borne out, mapping of sand units could help improve prediction of reservoir quality. Also, a strong correlation between paleosols and petrophysics would imply that a major component of reservoir quality was determined before deposition of the unit ended.

Beyond that, work continued on stratigraphic correlation. We have been correlating all well logs in the 4 square miles around the injector. The 14-1 and 16-2 sandstone units are heterogeneous but can be correlated across significant distances. The intervening 15 sandstone consists of multiple sandstone bodies representing channel fills that merge southward into a composite sandstone unit. Along the southern margin of the area of interest, moreover, the 15 sandstone merges with the 16-2 sandstone.

All spontaneous potential (SP) and resistivity logs in the area of interest have been digitized, and correlations are being finalized. Next the tops and bottoms of each sand will be recorded to facilitate the development of 3-D models of sandstone architecture. In addition, the quantity and location of net pay in each sandstone will be recorded.
Figure 3.2.1. Graphic representation of part of the core from the target well (Permit No. 3232). Tick marks correspond to 10-foot depth intervals. Width and color of core log indicate rock type: brown = mudstone, yellow = siltstone or sandstone, orange = conglomerate. Thin-section photomicrographs illustrate typical rock texture, microfabric, and porosity.
Standard 1-inch plugs were made of the 14-1 and 16-2 sands in the B-19-10 #2 well (Permit No. 3232) at 1-foot intervals for determination of porosity and permeability. These were sent to Core Laboratories (Houston, TX) for analysis. Plots of porosity and permeability versus depth are shown in Figures 3.2.2 and 3.2.3, respectively. Porosity of the 14-1 and 16-2 sands varies from 5 to 20%, with an average of 12%. Permeability varies from 0.02 to 13 mD, with an average of 2 mD.

![Figure 3.2.2. Measurements of porosity by Core Laboratories on plugs prepared by David Kopaska-Merkel of GSA from the drill core from the injector.](image)
Figure 3.2.3. Measurements of air permeability by Core Laboratories on plugs prepared by David Kopaska-Merkel of GSA from the drill core from the injector.
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, has been constructed. The 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. Using these data, maps of oil-CO$_2$ mixture properties can be constructed, should there be significant variation from sand to sand.

![Figure 3.3.1. Rolling ball viscometer (Peter E. Clark, University of Alabama).](image)

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.

During the quarter under review, the circuits necessary to drive the Hall-effect transducers, shown in Figure 3.3.2, were completed and a test for reproducibility of the
measurements was performed. At a given angle, the travel time for the rolling ball could be measured to an accuracy better than 0.5%. Figure 3.3.3 shows four runs at different angles, where the large (blue) points are the results of the first run at a given angle and the small (red) points are the results from repetition of the measurements at the same angle. We expect the reproducibility to improve as the precision with which the angle of incline is controlled improves. The transducer mounting bracket was also redesigned to eliminate crosstalk between the transducers.

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

The system is being assembled and pressure tested one step at a time. Modifications to the Ruska pump were necessary to make it work properly in this application. Peter Clark's group is in the process of testing the floating piston accumulators. Next, the pressure transducers will be plumbed into the system. A design for measuring the angle of the tube and holding the angle at a fixed point is under development.
Figure 3.3.3. Four runs of the rolling ball viscometer at different angles of incline, where the large (blue) points represent measurements during the first run at a given angle and the small (red) points are the results from repetition of the measurements at the same angle (Peter E. Clark, University of Alabama).
3.4. Petroleum Reservoir Simulation
Konstantinos Theodorou and Peter M. Walsh
University of Alabama at Birmingham

Simulations were run by using the MASTER (Miscible Applied Simulation Techniques for Energy Recovery) Version 3.0 reservoir simulator from DOE (Ammer and Brummert, 1991; Ammer, Brummert, and Sams, 1991; Zeng, Grigg, and Chang, 2005). Calculations were done for two sets of conditions and two lengths of the time for CO₂ injection, described below.

The first simulations were run using a value for the permeability of the sands obtained by taking the average of the measurements shown in Figure 3.2.2: 2 mD. The injection pressure was set at 4000 psia and the pressure at the producers at 2600 psia. Oil and water saturations were assumed to be 65 and 35%, respectively. At the low value chosen for the permeability, the CO₂ injection rate was only between approximately 10,000 and 100,000 scf/day.

The simulations were begun with water injection to establish a condition typical of current water flood performance in the field, roughly 10 bbl of oil per well per day. The decline in calculated water flood recovery during this period, to a value in the vicinity of 40 bbl/day for the four producers, is shown in Figure 3.4.1. CO₂ injection was started on day 118. In the first simulation under these conditions CO₂ was injected for 85 days, with the results shown in Figure 3.4.1 as the curve identified by open circles. It takes approximately 50 days for CO₂ injection to turn production around. On stopping CO₂ injection and returning to water flood, oil production continues to increase for a few days, peaking at a level similar to that at the onset of CO₂ injection.

In the second simulation at low permeability and low CO₂ injection rate, CO₂ injection was continued for an additional 43 days, for a total of 128 days, with the results shown by the curve identified by open triangles in Figure 3.4.1. Injection of CO₂ for the longer period results in a substantial increase in the peak oil production rate.

Because the CO₂ injection rates were excessively low, when using the average value for the permeability of the samples from the injection well drill core, a second set of simulations was run with the permeability adjusted to 26 mD, to provide CO₂ injection rates in the anticipated range. Oil saturation was set at a lower value of 40% (balance water). The pressures at the injector and producers were the same as before, 4000 and 2600 psia, respectively.

Results for the second set of calculations are shown in Figure 3.4.2. Initial production, under water flood, declines to the baseline value near 40 bbl/day for all four producers. Response to CO₂ injection appears shortly after the onset of CO₂ injection at 118 days. CO₂ injection rates are in the range from approximately 100,000 to 700,000 scf/day. The two periods of CO₂ injection shown in Figure 3.4.2 were chosen to give cumulative amounts of CO₂ injected of 5000 tons (129 days, 85 million std. ft³ CO₂, curve identified by open circles) and 7500 tons (184 days, 128 million std. ft³ CO₂, curve
identified by open triangles). Though the oil production rates are unexpectedly high, the contrast between the responses to CO$_2$ under the shorter and longer injection times is interesting. Injection for the longer period approximately doubles the increment in peak oil production rate associated with CO$_2$ injection, just as in the low permeability case shown in Figure 3.4.1.

Figure 3.4.1. Simulation of oil production from the four producers in the test pattern using the low value for permeability (2 mD) and high value for oil saturation (65%), starting with water injection for 118 days, followed by CO$_2$ injection for 85 days (open circles) and 128 days (open triangles), and returning to water injection.
Figure 3.4.2. Simulation of oil production from the four producers in the test pattern using the high value for permeability (26 mD) and low value for oil saturation (40%), starting with water injection for 118 days, followed by CO₂ injection for 129 days (open circles) and 184 days (open triangles), and returning to water injection.

3.5. CO₂ Liquefaction, Transportation, and Storage
Richard A. Esposito, Southern Company Services

Richard Esposito is negotiating with gas service providers to obtain pricing for various combinations of CO₂ liquefaction, transportation, storage, and injection services, both for the present project and for other projects on which Southern Company is a partner.
3.6. **Well Preparation and CO₂ Injection**
Gary Dittmar, Jack Harper, and Alec Bailey, Denbury Resources

Workover of the injector (B-19-10 #2) and two producers (B-19-7 and B-19-9) was completed. One producer (B-19-8) required no workover and its gathering lines are in place. The plugged and abandoned producer (B-19-10 #1) remains to be evaluated. Water injection was begun and reached a rate of 150 bbl/day, but the retrievable packer in the injection well came unset, so is now being replaced with a permanent packer. Water injection is expected to resume on April 28 or 29. Thirty-day pressure recording "bombs" were placed in producers B-19-7 and B-19-9 and will be pulled on May 16. The pressure records will therefore overlap with approximately 16 days of water injection, providing an opportunity to observe interaction between the injector and two producers.

3.7. **Surface Monitoring**
Xiongwen Chen, Ermson Z. Nyakatawa, and Kathleen A. Roberts
Alabama A&M University

3.7.1. **Soil Flux Measurements (Ermson Nyakatawa)**

Ermson Nyakatawa visited the test site in Citronelle on January 31 and February 1, 2008 with Peter Walsh, Xiongwen Chen, Kathleen Roberts, and Denbury Resources' host Alec Bailey, for a visual tour and inspection of the area. The objective was to understand the nature of the terrain and equipment, for planning of the number and location of sampling points. Following that visit, Ermson and Peter Walsh prepared the following proposal for the placement of instrumentation for measurement of soil conditions and CO₂ flux. The proposal was approved by the Denbury Resources representatives and other project team members at the meeting in Citronelle on February 21.

3.7.1.1. Proposal for Measurements of Soil Conditions and CO₂ Flux at Citronelle

Alabama A&M University (AAMU) was tasked, in the proposal to DOE, with measurement and documentation of CO₂ fluxes from soil in the vicinity of the injection test. The purpose of the measurements is to verify that CO₂ not recovered from produced oil and gas, and recycled for EOR, remains in the target formation and does not seep back to the surface. The work has a second objective, which is to evaluate procedures for documenting CO₂ storage, should regulations requiring verification of material balances for CO₂ be implemented in the future.

The measurements that Ermson proposes have three components: (1) monthly measurements of CO₂ flux from soil and monitoring of CO₂ in the top 36 in. of soil near the injection and production wells, (2) monthly measurement of soil conditions (temperature and moisture content), because CO₂ is naturally produced in soil by respiration of microorganisms and decay of plant matter, so normal changes in CO₂ production due to changes in biological activity with season and climate can be
explained, and (3) collection of soil samples once a year for elemental analysis, especially carbon.

A schematic diagram of the proposed sampling system is shown in Figure 3.7.1. It consists of the following components: (1) four 0.25 in. o.d. sampling probes inserted at four depths up to 36 in., through which gas samples are periodically extracted from the soil, collected in sample containers, and taken to the laboratory for analysis, (2) a 1.5 in. o.d. soil moisture probe, also inserted at up to 36-in. depth, (3) a soil thermometer, at a depth of 18 in., and (4) a chamber driven into the soil surface to 4-in. depth, in which gas evolved from the surface accumulates and is collected for analysis. The probes and sample chamber protrude 2 to 3 inches from the ground surface.

The proposed sites for the probes and sampling equipment are indicated in Figure 3.7.2. Four sampling points would be chosen, equally spaced around each of the five wells in the test pattern. Because the probes need to be out of the way of vehicles and located in a region of naturally-occurring vegetation, the optimum locations would be 5 to 10 ft beyond the tree lines, in the wooded areas adjacent to the clearings in which the wells are located. The probes would be barely visible among the foliage and litter on the forest floor. We would have to take our chances on the sampling chambers' being chosen by the occasional hunter for target practice.

Figure 3.7.1. Proposed soil gas sampling system (Ermson Z. Nyakatawa, AAMU).
The initial set-up of the probes and sampling chambers is expected to take two days. After that, monthly visits to collect gas samples and soil data are expected to take one day. This proposal can certainly be modified, if it would place an excessive burden on the Denbury personnel who would accompany Ermson Nyakatawa and his students in the field.

3.7.1.2. Progress during the Quarter under Review

The bases for the soil flux sampling chambers have been fabricated from 8 in. PVC pipe caps, as well as the sampling chambers themselves. The bases will be left in place in the field, at the locations indicated in Figure 3.7.2, so are painted brown to make them blend in with the litter on the ground. The sampling chambers, which are mounted on the bases only during sampling, have been left white, to reflect solar radiation and minimize its effect on the gas temperature in the chambers. The bases are ready for installation at the test site.
3.7.2. **Atmospheric Measurements and Citronelle Flora**  
* (Xiongwen Chen and Kathleen Roberts)  

During the quarter under review, Kathleen Roberts and Xiongwen Chen were engaged in the following work:

i. Air quality was monitored monthly across the area of Citronelle, except for the test site itself, pending approval of the measurement plan in Table 3.1.1.

ii. Four 10 m x 10 m observation plots were established in forest areas adjacent to the injection and production wells. Field surveys were conducted on January 31, February 1, and February 22. All of the relevant information on flora in the plots was measured and recorded. Some replacement of temporary tree tags by more permanent ones remains to be done. Establishment of two additional observation plots at the tank batteries also remains to be done, pending approval of the plan outlined in Section 3.1.5.2 and Table 3.1.1.

iii. Kathleen Roberts attended the meeting on February 21 in Citronelle, and presented the plan for her component of the research work.

iv. A procedure was devised for routine calibration of the multicomponent gas analyzer, for determination of minor components in ambient air.

v. Xiongwen Chen communicated frequently with the principal investigator to request additional monitoring plots in the forest near the tank batteries and a flexible schedule of visits to the test site, including one message by e-mail to justify the requests.

vi. Having, at present, only limited access to the test site, the group is considering using remote sensing to estimate the background concentrations of atmospheric gas components and aerosols.

vii. A paper, entitled, "Roadless Areas and Biodiversity: A Case Study in Alabama, USA," by Xiongwen Chen and Kathleen Roberts, presenting work supported in part by the present project, was accepted for publication in the journal, *Biodiversity and Conservation*.

Not having free access to the test site places this group in a mode of operation with which they are not familiar. Discussion of arrangements that will permit sampling with frequency sufficient to produce a high quality data set continues.
3.8. Seismic Monitoring
Shen-En Chen and Wenya Qi, University of North Carolina at Charlotte

During the group meeting and site visit in Citronelle on February 21, Shen-En Chen presented the plan for seismic imaging. The Refraction Microtremor (ReMi) method was proposed as the principal seismic technique, to be conduct on a time-lapse basis. ReMi has the ability to profile subsurface shear wave velocities using conventional seismic refraction equipment. The passive technique utilizes the refraction of naturally occurring waves by the density gradient at the boundary of the CO₂ plume. The sources of the waves can be simply the motion of people and vehicles on the surface or microfractures occurring underground. Excitations by thumper truck or dynamite, that are more intrusive to the community and production operations, are not required.

Three tests will be conducted during the pilot injection project. A baseline survey will be conducted 1 to 2 weeks prior to CO₂ injection during the water flood. Two other surveys will be scheduled 2 to 3 weeks after the start of CO₂ injection and 3 to 5 months afterward, to monitor the progress of the CO₂ plume. By analyzing the time-lapse shear wave velocity anomalies, CO₂ migration in the reservoir and potential fracturing and leakage may be detected.

As shown in Figure 3.8.1, measurements will be made using linear arrays of sensors between the injection well and the neighboring producing wells. At short distances from the CO₂ source at the injection well, monitoring will utilize a 24-channel 4.5 Hz geophone set to identify shear wave velocity anomalies in the shallow subsurface medium immediately surrounding the injection well, that might be induced by potential fracturing in the well. A longer sensor array, covering the distances between the injection well and four surrounding producing wells, will use a group of wireless accelerometers to detect CO₂ migration in the reservoir. By comparing the seismic testing results to production data, this information may aid in optimizing the injection rate, identifying the CO₂ path, and optimizing the locations for future CO₂ injection. The geomodeling software SeisOpt ReMi Version 4.0 from Optim Inc. (Reno, NV, see publications at http://www.optimsoftware.com/white_papers/) will be used for seismic data processing. Since different sensors will be used in this research, the UNCC group have been working on data conversion and data input in the required seismic data formats.
3.9. **Saline Formation Simulation**  
Konstantinos Theodorou and Peter Walsh, University of Alabama at Birmingham

A preliminary analysis was made of the possibility of leakage though the cap rock serving as the seal for CO$_2$ stored in saline formations in Citronelle Dome. The effectiveness of cap rock as a seal is a function of the difference in pressure required to drive a column of carbon dioxide from the pores of the formation in which it is stored, through pore throats in the cap rock. Under hydrostatic conditions, the forces acting are capillary pressures in the formation and cap rock, and the buoyant force on the column of carbon dioxide, due to the difference between its density and that of surrounding water. The problem was analyzed by Berg (1975), who derived the following equation for the critical height of a fluid column capable of upward migration from a reservoir into barrier facies under hydrostatic conditions:

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

(3.9.1)
In the case that the reservoir fluid is CO$_2$, and the surrounding fluid is brine, $\gamma$ is the surface tension of brine against CO$_2$, $r_{t,cap}$ is the radius of pore throats in the cap rock, $r_{p,res}$ is the radius of pores in reservoir rock, $g$ is the acceleration due to gravity, and $\rho_w$ and $\rho_{CO_2}$ are the formation water and carbon dioxide densities, respectively, under reservoir conditions.

Pore throat radii in the seal and pore radii in the reservoir rock are given by the following relationships for rhombohedral packing of uniform-size spherical grains (Graton and Fraser, 1935, cited by Berg, 1975):

$$r_{t,cap} = 0.5(0.154 D_{cap})$$

$$r_{p,res} = 0.5(0.414 D_{res})$$

where $D_{cap}$ and $D_{res}$ are the grain diameters in cap and reservoir rock, respectively. In the absence of grain or pore size measurements, the effective grain size can be estimated using the following correlation (Berg, 1975):

$$D_e = 3.476 (k \phi^{-0.1})^{1/2}$$

in which $k$ is the permeability ($m^2$) and $\phi$ is the porosity (dimensionless).

The following values of the parameters in Eqs. (3.9.1), (3.9.2), and (3.9.3) were assumed to be characteristic of reservoirs in the Citronelle Dome:

- $k = 1.283 \times 10^{-14}$ m$^2$ (13 millidarcy, estimate for CO$_2$ storage reservoir)
- $\phi = 0.13$ and 0.20 (CO$_2$ storage reservoir)
- $D_{res} = D_e = 24$ and 72 $\mu$m (CO$_2$ storage reservoir, Eq. (3.9.3))
- $\rho_w = 1000$ kg/m$^3$ (estimate of the density of brine at 5000 psig, 245 °F)
- $\rho_{CO_2} = 647$, 702, and 715 kg/m$^3$ (various depths)

For the purpose of illustrating the application of the analysis by Berg (1975), we take the following values for two parameters whose evaluation remains as a subject for investigation in future work:

- $D_{cap} = 2$ $\mu$m (cap rock, fine siltstone or shale)
- $\gamma = 0.035$ N/m (surface tension of brine against CO$_2$)

Site-specific porosities and permeabilities, grain sizes, or pore throat diameters in the barrier facies under consideration can be estimated from published work on similar rocks. The surface tension of brine in contact with CO$_2$, especially for supercritical CO$_2$, may be more difficult to find, though a search of the literature may provide data on which reasonable estimates may be based. The value chosen above ($\gamma = 0.035$ N/m) is that recommended by Berg (1975) for water in contact with natural gas.
Substitution of these values into the equations gives estimates of critical CO$_2$ column heights from 130 to 160 m (420 to 530 ft). Only the upper Donovan Sand in the Rodessa Formation has a thickness approaching this range, and the Ferry Lake Anhydrite, that serves as its seal, is thought to be even less permeable than a siltstone or shale having 2 μm grain size, the cap rock chosen as the example here. On the basis of these preliminary estimates, leakage of CO$_2$ through cap rock is not expected from any of the formations considered as storage reservoirs in our October 27, 2007 Quarterly Progress Report and listed in Table 3.9.1 of that report (Walsh et al., 2007, p. 26). The reservoirs examined there are the Eutaw and Upper Tuscaloosa Sands, the Pilot and Massive Sands, and the Donovan Sands of the Rodessa Formation. However, a more accurate assessment of the brine-CO$_2$ surface tension and pore radii in reservoir rock and seals is recommended.

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 processes 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 is complete. Simulation of the saline formations will begin when the ECO2N module is successfully implemented with the TOUGH2 code.

Eric Carlson attended a Python programming language convention in Chicago to meet with representatives from Enthought, Inc. (Austin, TX). Eric and others have convinced Enthought to begin posting distributions of Python along with Python packages, standardized for different operating systems, which will save him and his group significant time. Visualization templates for the project will be set up during the third quarter of this year using these standards. Eric is also studying Python-based web frameworks, to decide how to set up the data framework for the project, for access through the project portal.

Peter M. Walsh, University of Alabama at Birmingham

This section has been carried over, with minor revisions, from our January 30, 2008, Quarterly Progress Report.

In our October 27, 2007 Quarterly Progress Report, we presented a summary of a study by Advanced Resources International (Kuuskraa and Koperna, 2006) of the costs and benefits 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%.

The analysis by Kuuskraa and Koperna (2006) showed that, with high oil prices and adequate CO$_2$ supply (with CO$_2$ price tied to oil price), 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, were 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 a CO$_2$ flood in 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 are expected to be adopted at Citronelle (e.g. drilling horizontal wells), at least in the near term, and the behavior of Citronelle sands under CO$_2$ flood is known only from the pilot CO$_2$ injection 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). Ten tasks were scheduled for completion at the end of the quarter under review: Tasks 1, 2, 3, 4, 8, 9, 10, 11, 12, and 14. The status of work under these tasks is described below.

Task 1. Establish collaboratory environment. Eric Carlson has set up a high-performance server and registered a new website for the project under the name <cironelleoil.us>. Workspaces have been established for all of the researchers. A trial run using wikis for collaboratory work will be conducted during the third quarter of this year, to explore their possibilities and introduce the medium to members of the team not familiar with it. All of the documents produced under the project will be uploaded to the site. 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 site described above, for exchange of information among the members of the research group, so that site, <cironelleoil.us>, 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 (B-19-10 #2, Permit No. 3232) was originally permitted as an injector, so it only required repermitting. The supporting documents specified under UIC regulations were submitted to the State Oil and Gas Board of Alabama in January 2008.

Task 4. Analysis of rock samples. A comprehensive examination of drill cores from Citronelle Field is being performed by Jack Pashin, Denise Hills, and David Kopaska-Merkel at GSA. The most recent results are described in Section 3.2 of the present report. This work has led to significant revision of the conventional geologic model for the field, received from early studies of the formation in the 1950's and 1960's, and will have significant bearing on the approach to the test injection and interpretation of its results. 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. The group at 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, the targets of the
first CO\textsubscript{2} injection.  Study of other cores from Citronelle continues, having become 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) were analyzed for porosity and permeability.

**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, 2007. Analysis of well logs and cores has shown that the reservoir heterogeneity characteristic of Citronelle Field is well represented in this 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 will be more difficult to implement than was anticipated. UNCC is examining the seismic techniques described in Section 3.8 of this report. There is still time to establish an acceptable approach and conduct background measurements during the water flood to be conducted from May to October 2008.

**Task 10. Baseline soil CO\textsubscript{2} fluxes and ecology.**  Ermsom Nyakatawa of AAMU has visited Citronelle and specified the placement of instruments for measurements of CO\textsubscript{2} volume fractions and CO\textsubscript{2} fluxes from soil in the vicinity of the injector and producers. Twenty sets of the sampling chamber base, to be permanently installed at the site, and the removable sample chamber itself have been fabricated. Xiongwen Chen and Kathleen Roberts of AAMU have established test plots near the injector and producers, in which to monitor plant growth and species distribution. Two more plots remain to be established at the tank batteries. CO\textsubscript{2} in ambient air is being monitored across Citronelle to establish the background and its seasonal fluctuations.

**Task 11. Reservoir management plan.** Features of a reservoir management plan that would qualify the present project as "next generation CO\textsubscript{2}-EOR," according to Kuuskraa and Koperna (2006), are: increasing the amount of CO\textsubscript{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\textsubscript{2}, implementation of flood performance diagnostics, and employment of a professional technical team. The technical group focused on Citronelle at Denbury Resources, augmented by the group engaged in the present project, more than meets the latter requirement. The costs and benefits of the other components of next generation CO\textsubscript{2}-EOR will be examined in turn.

**Task 12. Economic and market analysis.** CO\textsubscript{2}-EOR in Citronelle is expected to add approximately 30 million barrels of oil to economically recoverable U.S. oil reserves. Under the oil and CO\textsubscript{2} prices expected to prevail, on average, for the foreseeable future, and incorporating some of the features of "next generation CO\textsubscript{2}-EOR" (though not, for example, the drilling of horizontal wells) specified by Kuuskraa and Koperna (2006), the analysis by Advanced Resources International (2006) indicates that a CO\textsubscript{2}-EOR project in Citronelle would be profitable.
Task 14. Preparation of wells for Field Test No. 1. Workover of the injector (B-19-10 #2) and two producers (B-19-7 and B-19-9) was completed. One producer (B-19-8) required no workover and its gathering lines are in place. A plugged and abandoned producer (B-19-10 #1) remains to be evaluated. Water injection was begun and reached a rate of 150 bbl/day, but the retrievable packer in the injection well came unset, and is being replaced by a permanent packer. Water injection is expected to resume on April 28 or 29, 2008.

4.2. Findings and Accomplishments

Work during the first 14 months of the project (February 2007 through March 2008) was focused on the following components: geology and petrology of the formation, reservoir fluid properties, preparation of the wells and planning for the first CO₂ injection, and estimates of CO₂ 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 CO₂ that is representative of the field, in a remote location away from private homes, and including a well already permitted as a gas injector.

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

Construction of a rolling ball viscometer for determination of oil-CO₂ minimum miscibility pressure, density, and viscosity at reservoir conditions, and effects of solvent composition.

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 CO₂-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 (reptiles and amphibians) in Alabama by Xiongwen Chen and Yong Wang of AAMU accepted for publication in Acta Herpetologica.

Refereed paper on the relationships between roadless area and local species richness in Alabama by Xiongwen Chen and Kathleen Roberts of AAMU accepted for publication in Biodiversity and Conservation.

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

Identification of critical path items and actions needed to prepare for CO₂ liquefaction, transport from Jackson or Eucutta, MS, to Citronelle, storage at the test site, and injection.

The total CO₂ storage capacity of the Eutaw Formation, Upper and Lower Tuscaloosa Groups, and Rodessa Formation in the Citronelle Dome estimated to be between approximately 500 million and 2 billion short tons of CO₂.

Evaluation of seismic methods for monitoring CO₂ migration at the large depths of Citronelle oil reservoirs (11,500 ft).

Preliminary measurements of background levels of CO₂ in ambient air at the site, showing large variability induced by automobile and truck exhausts and plant respiration.

Establishment of 10 m x 10 m test plots at the injector and four producers, in which to monitor plant growth and species distribution.

Construction of twenty sampling chambers for measurement of CO₂ fluxes from soil at four locations surrounding each of the five wells in the test pattern.

Application to the State Oil and Gas Board of Alabama for repermitting of Citronelle Unit B-19-10 #2 well for water and CO₂ injection.

Workover was completed on the injector (B-19-10 #2) and two producers (B-19-7 and B-19-9). Only the plugged and abandoned producer (B-19-10 #1) remains to be evaluated. Water injection was begun and reached a rate of 150 bbl/day.

### 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 CO₂-EOR and storage, including estimates of storage capacity, was prepared by Jack Pashin, Richard Esposito, and Peter Walsh, and accepted for publication in *Environmental Geosciences*, the archival journal of the Division of Environmental Geosciences of the American Association of Petroleum Geologists. Jack 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 2007, then at the DOE/NETL Sixth Annual Conference on Carbon Capture and Sequestration, in Pittsburgh, in May 2007, 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 2007.

Shen-En Chen and Wen-Ya Qi of the University of North Carolina at Charlotte presented options for seismic monitoring of CO2 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 2007.

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*.

Xiongwen Chen and Kathleen Roberts of AAMU prepared a paper on the relationships between roadless area and local species richness in Alabama, accepted for publication in *Biodiversity and Conservation*.

Richard Esposito will present a paper describing the planning and preparation for the first pilot CO2 injection under the present project, entitled: "Pilot Design for CO2-EOR and Sequestration Potential in the Citronelle Oil Field in the Mississippi Interior Salt Basin of Alabama," at the Seventh Annual Conference on Carbon Capture and Sequestration, Pittsburgh, PA, May 5-8, 2008.

These publications, presentations, and the workshop keep the reservoir engineering and carbon storage communities informed about the progress of the work and its implications for successful CO2-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 has been engaged since the beginning of the project (February 6, 2007 through March 31, 2008) 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 No. 3232) have been digitized, providing a dense grid of well-log cross sections over the area surrounding the well. Well logs in the cross sections are being correlated, with emphasis on characterization of the 14-1 and 16-2 sands, the targets of the first CO₂ injection. Correlation of the sands is revealing that, 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 heterogeneity.

Early diagenesis (soil formation), controlled by topography and short-term sea level change, may have strongly influenced sandstone porosity and permeability in the Rodessa Formation at Citronelle Field. If this inference is borne out, mapping of sand units could help to improve the prediction of reservoir quality.

This work on petrology and stratigraphy has led to significant revision of the conventional geologic model for the field, received from early studies of the formation in the 1950's and 1960's, and will have significant bearing on the approach to the test injection and interpretation of its results.

**Reservoir Fluid Properties.** Peter Clark and his research group at the University of Alabama are completing the assembly and testing of a rolling ball viscometer with which to measure minimum miscibility pressure, viscosity, and density of oil-CO₂ mixtures at reservoir temperature and pressure. This instrument will provide the means to determine oil-CO₂ 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. The rolling ball viscometer is also an excellent tool with which to evaluate the extension of oil-CO₂ miscibility through addition of other gas constituents to CO₂, a component of the advanced CO₂-EOR technology proposed by Kuuskraa and Koperna (2006).

**Pilot Injection.** Workover of the injector (B-19-10 #2) and two producers (B-19-7 and B-19-9) was completed. One producer (B-19-8) required no workover. Only the plugged and abandoned producer (B-19-10 #1) remains to be evaluated. Water injection was begun in February 2008 and reached a rate of 150 bbl/day, but the retrievable packer in the injection well came unset. A permanent packer is being installed. Water injection
is expected to resume on April 28 or 29, 2008, and continue until CO₂ injection is begun in October 2008. A pressure test in the injector in March established bottom hole conditions of 4000 psia and 245 °F.

CO₂ 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 Donovan Sands of the Rodessa Formation are a total of 500 million to 2 billion short tons of CO₂. 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 CO₂ 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 CO₂, including mineralization.

Preliminary estimates of the potential for leakage of CO₂ through cap rock, based upon the analysis by Berg (1975), indicate that leakage is not expected from any of the formations considered above as storage reservoirs. However, a refined assessment using more accurate values for the input parameters (brine-CO₂ surface tension and pore radii in reservoir rock and seals) is recommended.

Surface Monitoring and Ecology. Ermsen Nyakatawa at AAMU has devised a scheme and built the sampling chambers for measurement of CO₂ fluxes at four locations surrounding each of the five wells in the test pattern.

Xiongwen Chen and his coworkers at AAMU have documented the dependence of species richness and species density in Alabama on location and environmental factors, such as latitude, elevation, annual average temperature, precipitation (Chen and Wang, 2007), and roadless area (Chen and Roberts, 2008). Their state-wide view of species distributions will help to discriminate whether any 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. Shen-En Chen at UNCC proposes to use the Refraction Microtremor (ReMi) technique to observe shear wave anomalies cause by fracturing in the shallow subsurface in the immediate vicinity of the injection well. A longer array of wireless accelerometers would be used to detect CO₂ migration in the reservoir. Both methods make use of signals from naturally-occurring seismic events, so 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 imaging technology.

Reservoir Management and Economics. Kuuskraa and Koperna (2006) proposed the following improvements in CO₂-EOR technology: (1) Increased volume of CO₂ 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-CO₂ miscibility by addition of gas
constituents to CO₂, and (5) Implementation of flood performance diagnostics and improved flood control. Though not all of the features of next generation CO₂-EOR discussed by Kuuskraa and Koperna may be adopted at Citronelle (e.g. drilling horizontal wells or reduction of mobility ratio, because WAG is not currently planned for field-wide EOR), and the behavior of Citronelle sands under CO₂ injection is so far known only from the few data available from the pilot CO₂ 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 CO₂-EOR project in Citronelle would be profitable and would add approximately 30 million barrels of oil to economically recoverable U.S. oil reserves.
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AAMU</td>
<td>Alabama Agricultural and Mechanical University, Normal, AL</td>
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<tr>
<td>AAPG</td>
<td>American Association of Petroleum Geologists</td>
</tr>
<tr>
<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA</td>
</tr>
<tr>
<td>DRI</td>
<td>Denbury Resources Inc., Plano, TX, and Citronelle, AL</td>
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<tr>
<td>EOR</td>
<td>enhanced oil recovery</td>
</tr>
<tr>
<td>GSA</td>
<td>Geological Survey of Alabama, Tuscaloosa, AL</td>
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<tr>
<td>HCPV</td>
<td>hydrocarbon pore volume, dimensionless</td>
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<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory, Berkeley, CA</td>
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<tr>
<td>MMP</td>
<td>minimum miscibility pressure</td>
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<tr>
<td>RTD</td>
<td>resistance temperature detector</td>
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<tr>
<td>SENSOR</td>
<td>System for Efficient Numerical Simulation of Oil Recovery, Coats Engineering</td>
</tr>
<tr>
<td>SO</td>
<td>Southern Company, Birmingham, AL</td>
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<tr>
<td>SP</td>
<td>spontaneous potential</td>
</tr>
<tr>
<td>UA</td>
<td>University of Alabama, Tuscaloosa, AL</td>
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<tr>
<td>UAB</td>
<td>University of Alabama at Birmingham, Birmingham, AL</td>
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<tr>
<td>UIC</td>
<td>Underground Injection Control</td>
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<tr>
<td>UNCC</td>
<td>University of North Carolina at Charlotte, Charlotte, NC</td>
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<tr>
<td>WAG</td>
<td>water-alternating-gas method of enhanced oil recovery</td>
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Symbols

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<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$D_{cap}$</td>
<td>grain diameter in cap rock, m</td>
</tr>
<tr>
<td>$D_e$</td>
<td>effective grain diameter, Eq. (3.9.3), m</td>
</tr>
<tr>
<td>$D_{res}$</td>
<td>grain diameter in reservoir rock, m</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration due to gravity, $= 9.8 \text{ m/s}^2$</td>
</tr>
<tr>
<td>$k$</td>
<td>permeability, $\text{m}^2$</td>
</tr>
<tr>
<td>$r_{p,\text{res}}$</td>
<td>radius of pores in reservoir rock, m</td>
</tr>
<tr>
<td>$r_{t,\text{cap}}$</td>
<td>radius of pore throats in cap rock, m</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>surface tension, $\text{N/m}$</td>
</tr>
<tr>
<td>$\rho_{\text{CO}_2}$</td>
<td>density of carbon dioxide, $\text{kg/m}^3$</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>density of water, $\text{kg/m}^3$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>porosity, dimensionless</td>
</tr>
</tbody>
</table>

Subscripts

- $cap$ | cap rock |
- $e$ | effective grain diameter |
- $p$ | pore |
- $res$ | reservoir (grain diameter, pore radius) |
- $t$ | pore throat |
- $w$ | water |
References


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.


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 CO₂ 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 CO₂ 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 CO2 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-CO2 interaction.
Determination of minimum miscibility pressure. Evaluation of propensity for oil components to precipitate in the presence of CO2. Measurement of viscosity of the oil as functions of temperature and CO2 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 CO2 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

Establish baseline CO2 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 CO₂ injection strategy to ensure efficient oil sweep. UA, GSA, SO, UAB

Task 12. Economic and market analysis.
Verify that production using CO₂ 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 CO₂ 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 CO₂ 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 CO₂ for the project. This includes provision for onsite storage of CO₂, installation of CO₂-compatible flow lines, the skid for the compressor, retting the well head, and possible workover of the well. Since Southern Company's objectives are to supply CO₂ for future EOR projects, including identification of sites for CO₂ 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 CO₂. 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 CO₂ flooding, and re-evaluate the long term viability of the project.
Phase II (September 1, 2008 – April 30, 2010):

Determine if seismic measurements are able to detect changes in the formation and the presence and migration of CO2. 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 CO2 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 CO2 and fluorocarbon tracer in shallow boreholes and concentration profiles in soil near the surface to determine whether CO2 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 CO2 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-CO2 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 CO2 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 CO2 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 CO2 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. CO₂ fluxes and ecology.**  
Continue to monitor for CO₂ 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 CO₂ injection, including provision for onsite storage of CO₂, installation of CO₂-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 CO₂. All

**Task 32. Geophysical testing for influence of CO₂.**  
Seismic measurements to observe the migration of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emission. However, the absence of CO₂ emission does not necessarily imply no impact to the environment. CO₂ 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 CO₂, oil, and water as functions of reservoir properties and time, the oil yield by CO₂ EOR, and the capacity of the formation for CO₂ 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 CO₂ 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 CO₂ EOR simulation. Monitor adjacent wells for produced oil, water, and gas, including CO₂. All

**Task 46. Geophysical monitoring of the flood.**
Seismic measurements to monitor the progress of the CO₂ 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 CO₂ 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 CO₂ from sources in the region. This will include a topical report on the capability of the Rodessa Formation for storage of CO₂. 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 CO₂ 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

<table>
<thead>
<tr>
<th>Phase and Critical Path Milestone Description</th>
<th>Task</th>
<th>Planned Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil and CO₂ miscibility testing completed</td>
<td>5</td>
<td>Mar. 31, 2007</td>
</tr>
<tr>
<td>Economic and market analysis completed</td>
<td>12</td>
<td>Sep. 30, 2007</td>
</tr>
<tr>
<td>Permit to conduct Field Test No. 1 issued</td>
<td>3</td>
<td>Sep. 30, 2007</td>
</tr>
<tr>
<td>Justification for proceeding to Phase II submitted</td>
<td>20</td>
<td>Aug. 31, 2008</td>
</tr>
<tr>
<td><strong>Phase II</strong></td>
<td></td>
<td>Sep. 1, 2008 - Apr. 30, 2010</td>
</tr>
<tr>
<td>Geomechanical stability analysis completed</td>
<td>23</td>
<td>Nov. 30, 2008</td>
</tr>
<tr>
<td>Field Test No. 1 completed</td>
<td>15</td>
<td>Dec. 31, 2008</td>
</tr>
<tr>
<td>Permit to conduct Field Test No. 2 issued</td>
<td>21</td>
<td>Apr. 30, 2009</td>
</tr>
<tr>
<td>Field Test No. 2 completed</td>
<td>31</td>
<td>Oct. 31, 2009</td>
</tr>
<tr>
<td>Justification for proceeding to Phase III submitted</td>
<td>36</td>
<td>Apr. 30, 2010</td>
</tr>
<tr>
<td><strong>Phase III</strong></td>
<td></td>
<td>May 1, 2010 - Dec. 31, 2011</td>
</tr>
<tr>
<td>Refinement of the reservoir management plan completed</td>
<td>41</td>
<td>Oct. 31, 2010</td>
</tr>
<tr>
<td>Permit to conduct Demonstration issued</td>
<td>37</td>
<td>Feb. 28, 2011</td>
</tr>
<tr>
<td>Demonstration completed</td>
<td>45</td>
<td>Jun. 30, 2011</td>
</tr>
</tbody>
</table>
Appendix B: Presentations, Publications, and Reports

B.1. Presentations and Workshops


B.2. Publications


X. Chen and K. A. Roberts, "Roadless Areas and Biodiversity: A Case Study in Alabama, USA," Accepted for publication in *Biodiversity and Conservation*, January 25, 2008.


B.3. Reports


P. Walsh, "Summary of Meeting of CO\textsubscript{2}-EOR Group in Citronelle, February 21, 2008," Report to partners and participants in the meeting, February 26, 2008.

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


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.


