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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, Denbury Resources, Inc., Geological Survey of Alabama, Southern Company Services, Inc., University of Alabama, University of Alabama at Birmingham, and University of North Carolina at Charlotte are engaged in a Cooperative Agreement with the U.S. Department of Energy, National Energy Technology Laboratory, to evaluate the potential for carbon-dioxide-enhanced oil recovery and carbon dioxide sequestration in the Citronelle Oil Field in Mobile County, Alabama. The present report describes work and accomplishments during the third quarter of the project, from July 1 to September 30, 2007.

The work to be done is viewed as having the following components, with the organizations having the relevant expertise and resources, and best suited to lead the planning and execution of the work, identified in parentheses following each topic: 1. Communication and Technology Transfer (University of Alabama and University of Alabama at Birmingham), 2. Geology and Petrology (Geological Survey of Alabama and Southern Company), 3. Reservoir Fluid Properties and Phase Behavior (University of Alabama), 4. Petroleum Reservoir Simulation (University of Alabama), 5. CO_2 Liquefaction, Transportation, and Storage (Southern Company and Denbury Resources), 6. Well Preparation and CO_2 Injection (Denbury Resources), 7. Surface Monitoring (Alabama A&M University), 8. Seismic Monitoring (University of North Carolina at Charlotte), 9. Saline Formation Simulation (University of Alabama at Birmingham), 10. Visualization of Geologic Structure and Flows (all partners), and 11. Reservoir Management Plan and Economic Analysis (all partners). Subcontracts with the Geological Survey of Alabama and all of the university partners, except the University of North Caroline at Charlotte, are in place.

Technology transfer during the quarter under review was accomplished by responding to reviewers' comments and finalizing a manuscript accepted for publication in *Environmental Geosciences*, describing the geology and petrology of Citronelle. The paper is entitled, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," by Richard Esposito, Jack Pashin, and Peter Walsh. The paper includes estimates of the CO_2 storage capacity of selected saline formations. The most recent work on sedimentology will be presented by Jack Pashin at the 2007 Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology, in Corpus Christi, October 21-23. Reporting on a second component of the work, Wen-Ya Qi, Shen-En Chen, Peter Walsh, Richard Esposito, and Jack Pashin presented a paper, entitled, "Geosensing for CO_2 Sequestration Monitoring in an Oil Field: Possible Global Warming Solution," at the 3rd National Conference on Environmental Science and Technology, held at North Carolina A&T State University in Greensboro, September 12-14.

Work with cores at the Geological Survey of Alabama continued throughout the quarter. Four cores have now been slabbed, and two of those cores have been described and logged graphically. Considerable effort was placed on characterization of the 16-2 sand and adjacent strata in the B-19-10 #2 well, which will be used for injection in the first field test. The 16-2 sandstone interval in the well is nearly 19 feet thick and fines upward from intraclastic conglomerate to medium- and very fine-grained sandstone. Analysis of the well log indicates that pay is restricted to the upper part of the sandstone, although examination of the core indicates that additional pay that has not been perforated exists between the two conglomerate layers. The core log indicates that the 16-2 sandstone is highly heterogeneous, yet few porosity and permeability data are available for this interval. It is recommended that one core plug per foot be taken from the core and sent to a qualified laboratory for analysis. Wells in a 4-square-mile area round the injector have been incorporated into a Petra project, and the available SP, resistivity, gamma-ray, density, and neutron logs have been digitized. A network of cross sections is being constructed for this area, and the 16-2 sandstone interval has been identified in all the wells. Depositional features observed in the major Rodessa reservoir sandstone intervals are consistent with mesotidal sand-mudflat successions. Basal ravinements apparently represent the floors of coalescing channel-shoal complexes, whereas the variegated mudstone intervals represent a combination of mixed sand-mud flats and reddened soil profiles. All indications, so far, are that the B-19-10 #2 injector and adjacent producers are a good choice for the first CO_2 injection test, and that the reservoir heterogeneity characteristic of the Citronelle Field is well represented in this five spot pattern.

Produced water from the Citronelle Oil Field is disposed of primarily in saline sandstone units within the Tuscaloosa Group at depths of 1830 to 2200 m (6000 to 7200 ft). Accordingly, the Tuscaloosa-Eutaw section is an attractive saline formation for storage of CO_2, in addition to the Rodessa Formation. Static estimates of the CO_2 storage capacity of the Eutaw Formation, Upper and Lower Tuscaloosa Groups, and the Rodessa Formation were made, based upon the receiving formation area, thickness, average porosity, density, temperature, and pressure. An efficiency factor having upper and lower limits of 0.4 and 0.1, respectively, was incorporated to account for residual water saturation. In addition, a permeable fraction efficiency factor of 0.9 for the Tuscaloosa-Eutaw sands and 0.6 for the Rodessa Formation was assigned to account for shale dispersion, based on visual observations of drill core samples from the rock matrix. Porosity of the Tuscaloosa-Eutaw sands was estimated at 20% while an average porosity of 13% was used for the Rodessa sands. The total static estimate of the storage capacity of these formations is between approximately 500 million and 2 billion short tons of CO_2 (480 million to 1.9 billion metric tonnes of CO_2).

Work during the coming quarter is focused on development of the flexible framework for computation, visualization, and communication, continuing analyses of the cores and well logs, completion of the rolling-ball viscometer for determination of oil-CO_2 mixture viscosity and density under reservoir conditions, dynamic simulations of CO_2 storage, baseline characterization of the test site, analysis of options for seismic monitoring of CO_2 migration, and planning for the first test.

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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 CO_2 emissions (Pashin et al., 2005). Separation of carbon dioxide from combustion products followed by storage in geologic formations is among the most promising approaches to reducing the rate at which CO_2 accumulates in the atmosphere as a result of both human activity and natural processes (Stevens et al., 2001; Friedmann and Homer-Dixon, 2004).

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

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

1.2. Objectives

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

1.3. Scope of Work

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

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

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

1.4. Deliverables

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

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

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

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

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

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

2. Research Plan - Phase I

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

2.1. Communication and Technology Transfer

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

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

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

2.2. Geology and Petrology

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

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

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

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

2.3. Reservoir Fluid Properties and Phase Behavior

Peter Clark, University of Alabama

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

2.4. Petroleum Reservoir Simulation

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

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

2.5. CO_2 Liquefaction, Transportation, and Storage

Richard Esposito, Southern Company
Jack Harper, Denbury Resources

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

2.6. Well Preparation and CO_2 Injection

Jack Harper, Denbury Resources
Richard Esposito, Southern Company
Peter Walsh, University of Alabama at Birmingham

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

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

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

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

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

2.7. Surface Monitoring

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

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

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

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

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

2.8. Seismic Monitoring

Shen-En Chen, University of North Carolina at Charlotte

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

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

2.9. Saline Formation Simulation

Konstantinos Theodorou, University of Alabama at Birmingham

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

2.10. Visualization of Geologic Structure and Flows

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

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

2.11. Reservoir Management Plan and Economic Analysis

Peter Walsh, University of Alabama at Birmingham.

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

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

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

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

3. Progress of the Work

3.1. Communication and Technology Transfer

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

3.1.1. Collaboratory Environment and Education

During the past quarter, we have evaluated many graphics systems, scripting languages, and graphical user interface systems. Based on these assessments, we have designed a very flexible framework for computations, visualization, productivity, and communications. For now, within this framework, we will use components that have been reliable and reasonably bug-free for over at least a year. However, the modular design of the system will allow for upgrading innovative, high-performance components that are just too unstable to use for now.

Development of the system will be brisk over the next quarter. We will begin testing it in engineering classes and for Citronelle Field reservoir engineering studies during the first quarter of 2008.

In order to distribute this new framework, we will probably also need to create and distribute a very functional, easy-to-install version of the general Python language (a version that is appropriate for our project team and technology transfer targets). For over three years, Enthought Scientific Computing (www.enthought.com) has distributed such a package. Unfortunately, their distribution is now outdated, and they have no current plans to keep it updated. Instead, they have decided to use a distribution system that is great for software developers but too cumbersome for novices. We are pleading with Enthought to reconsider this decision, but are prepared to do this if necessary. So far, we have tested distributions for Windows XP and Vista, but have not done so yet for OS X or Linux. The new framework is platform-independent, so being able to distribute to all major operating systems is a high priority.

Although creation of various Python distributions might be cumbersome, this effort has one very big potential benefit. By providing this general tool to the public, the project exposure for our work could be much broader than to just the oil and gas community, and the benefits of the project will extend far beyond the petroleum industry.

3.1.2. Presentations and Publications

A paper entitled, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama,"

by Richard Esposito, Jack Pashin, and Peter Walsh, has been accepted for publication in *Environmental Geosciences*, the archival journal of the Division of Environmental Geosciences of the American Association of Petroleum Geologists. The paper documents the analysis of the Citronelle Oil Field and associated saline formations that make them, respectively, ideal sites for CO_2-EOR and CO_2 storage, and includes estimates of the CO_2 storage capacities of the individual zones and the total capacity of the formations analyzed.

Wen-Ya Qi and Shen-En Chen, of the University of North Carolina at Charlotte, presented a paper with coauthors Peter Walsh, Richard Esposito, and Jack Pashin, entitled, "Geosensing for CO_2 Sequestration Monitoring in an Oil Field: Possible Global Warming Solution," at the 3rd National Conference on Environmental Science and Technology, held at North Carolina A&T State University, Greensboro, NC, September 12-14, 2007. The presentation reviewed seismic techniques for monitoring CO_2 migration: surface wave, seismic reflection, seismic refraction, downhole seismic, crosshole seismic, and microseismic methods, enumerating the advantages and disadvantages of each.

Richard Esposito has included summaries of the Citronelle CO_2-EOR project in his recent presentations of carbon capture and storage technology and options. The first was entitled "Carbon Capture and Geologic Storage," presented at the Florida Electric Power Coordinating Group Environmental Committee's Annual Conference, June 18-19, 2007. The second was entitled, "Carbon Capture and Storage as a Clean Coal Initiative," presented to the Alabama Mining Institute, Tuscaloosa, AL, September 25-26, 2007.

Jack Pashin will also present the paper, "Citronelle Dome: A Giant Opportunity for Multi-Zone Carbon Storage and Enhanced Oil Recovery in the Mississippi Interior Salt Basin of Alabama," coauthored with Richard Esposito and Peter Walsh, at the 2007 Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology, in Corpus Christi, TX, October 21-23, 2007.

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 D to this report. The bibliography is revised as additional past papers and reports are found and as new studies of the Field and region are published, including those resulting from work under the present project.

3.1.4. Meetings of the Research Group

Jack Harper, Gary Dittmar, and Mark Rainer of DRI met at GSA with Jack Pashin, Denise Hills, Richard Esposito, and Peter Walsh on July 2, to make the final selection of five-spot for the first CO_2 injection test.

Peter Clark, Richard Esposito, and Peter Walsh met with Jack Pashin and Denise Hills at GSA on August 31, to discuss Jack Pashin, Denise Hills, and Richard Esposito's recent findings from examination of the drill core from the well chosen for the first injection test. Also discussed was DRI's recommendation to conduct the first test in October and November 2008, rather than in February and March of 2008. The conclusion from the latter discussion was that the later date was preferable, for the reasons outlined in Section 4.3 of this report.

Richard Esposito has made numerous visits to GSA during the quarter under review, to participate with Jack Pashin and Denise Hills in the petrographic analysis of the drill cores from Citronelle provided by DRI.

The next meeting of the research group will take place in November at the Citronelle Field, to inspect the injection and monitoring wells chosen for the first CO_2 test injection, gather information from the records stored at the site, and further develop the plan for the first test.

3.2. Geology and Petrology

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

Work with cores at the Geological Survey of Alabama continued throughout the quarter. Four cores have now been slabbed, and two of these cores have been described and logged graphically. The whole cores only include sandstone intervals; shale intervals were apparently disposed by the unit manager during the 1980s. Fortunately, one core chip per foot is in the sample collection of the Geological Survey of Alabama, and these samples are invaluable for characterizing the Rodessa Formation.

Considerable effort was placed on characterization of the 16-2 sand and adjacent strata in the B-19-10 #2 well, which will be used for injection in the field test. Billets for thin sections have been cut and have been sent to National Petrographic for thin sectioning. The 16-2 sandstone interval in the well is nearly 19 feet thick and fines upward from intraclastic conglomerate to medium- and very fine-grained sandstone, as shown in Figure 3.2.1. The conglomeratic intervals are cemented with calcite, whereas the sandstone intervals are oil-stained. Perforations are in the upper part of the sandstone, which is cross-bedded in the lower part and is intensely bioturbated in the upper part. Analysis of the well log indicates that pay is restricted to the upper part of the sandstone, although examination of the core indicates that additional pay that has not been perforated exists between the two conglomerate layers.

The core log indicates that the 16-2 sandstone is highly heterogeneous, yet few porosity and permeability data are available for this interval. For this reason, we recommend that one core plug per foot be taken from the core and sent to a qualified laboratory for analysis.

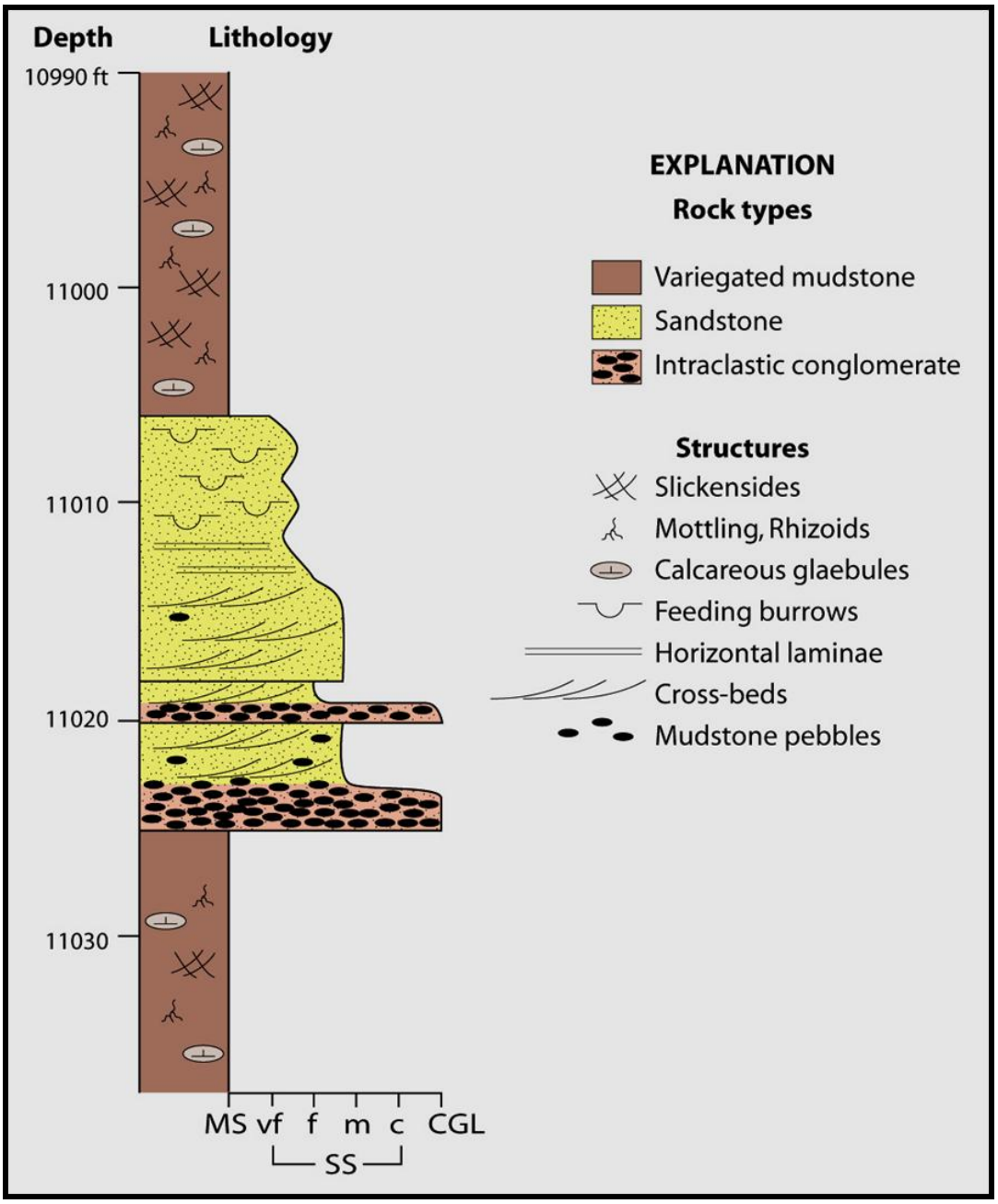

Figure 3.2.1. Core log of the 16-2 sand and adjacent strata at well no. B-19-10 #2 in the Citronelle Oil Field (Geological Survey of Alabama), the well chosen for injection of water followed by CO_2 in the first field test.

Grain size scale at bottom:

MS	mudstone
vf	very fine-grained sandstone
f	fine-grained sandstone
m	medium-grained sandstone
c	coarse-grained sandstone
CGL	conglomerate

Wells in a 4-square-mile area round the injector, shown in Figure 3.2.2, have been incorporated by the Geological Survey of Alabama into a Petra project, and the available SP, resistivity, gamma-ray, density, and neutron logs have been digitized. A network of cross sections is being constructed for this area, and the 16-2 sandstone interval has been identified in all wells. In a parallel effort, Denbury Resources constructed a map, shown in Figure 3.2.3, comparing the thickness of the 16-2 sand indicated by SP logs with the thickness contours for the sand over a region similar to that shown in Figure 3.2.2.

A stratigraphic cross section constructed by the Geological Survey of Alabama along line A-A' of Figure 3.2.2 is shown in Figure 3.2.4. Localized sandstone units up to 35 ft below the 16-2 sandstone appear to constitute multi-story incised valley fills, whereas the 16-2 sandstone appears to overlie a widespread, low-relief ravinement surface. An array of sand- and mud-plugged channel fills are apparent in the upper part of the 16-2 interval. Importantly, a mud-plugged channel fill apparently truncates the upper part of the sandstone in the B-19-10 #2 injector, thus CO_2 will be injected into the lower part of the sandstone body. Thinner sandstone units are developed above the 16-2 sandstone and also appear to be developed above ravinement surfaces of variable lateral extent.

Depositional features observed in the major Rodessa reservoir sandstone intervals are consistent with mesotidal sand-mudflat successions. Basal ravinements apparently represent the floors of coalescing channel-shoal complexes, whereas the variegated mudstone intervals represent a combination of mixed sand-mud flats and reddened soil profiles. A modern analog for this system exists in western India and southwestern Pakistan, where sandy channel-shoal complexes and red mud flats are forming. The semidiurnal tide range in this area is about 2 meters, and the mudflats tend to be exposed during the dry season and submerged by a combination of prevailing onshore winds and high rainfall during the annual monsoon.

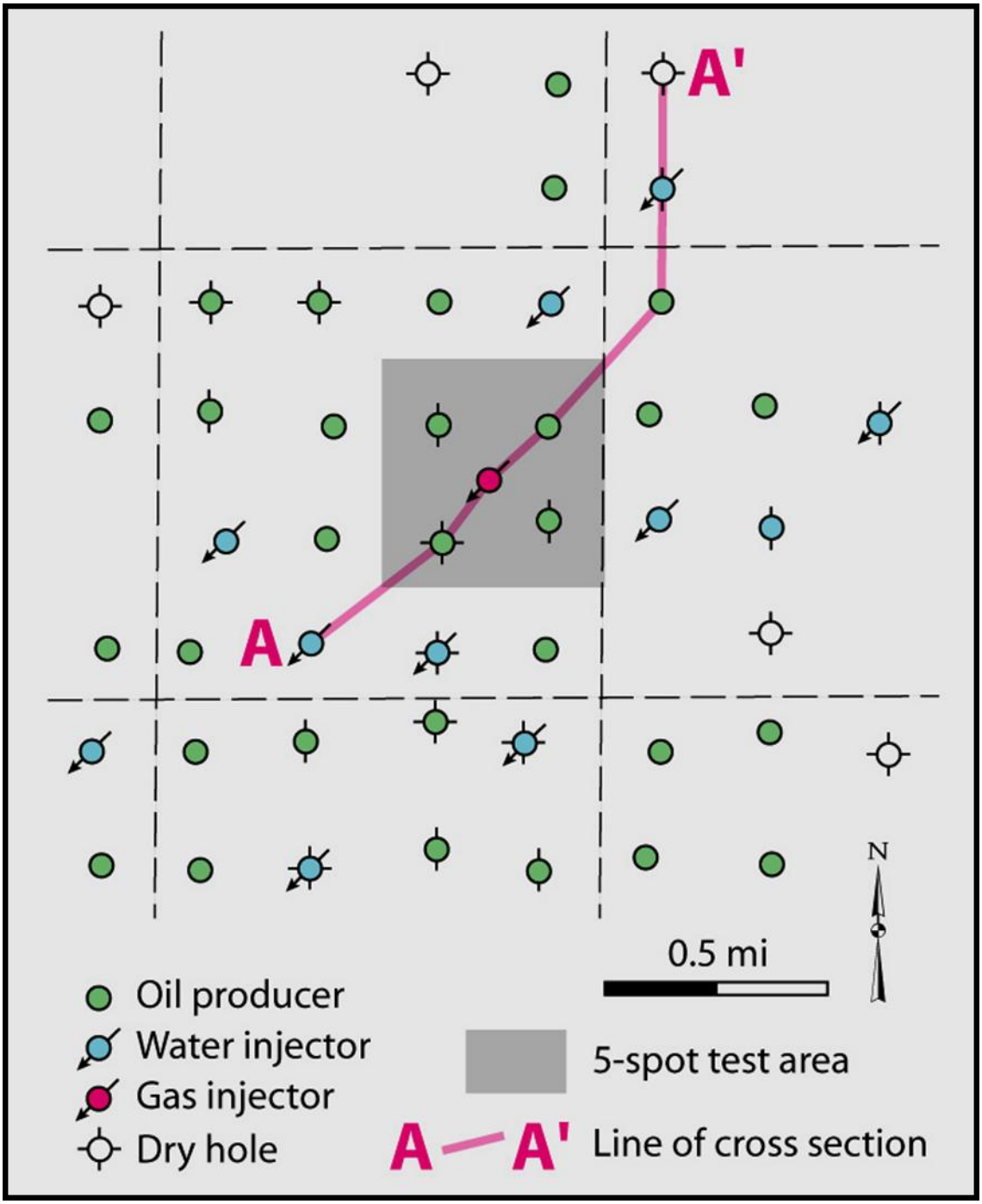

Figure 3.2.2. Candidate enhanced oil recovery test area, Citronelle Oil Field (Geological Survey of Alabama). The five-spot pattern selected for the first test injection is indicated by the dark grey area and the gas injector is the circle filled in red. The stratigraphic cross section along line A-A' is shown in Figure 3.2.4.

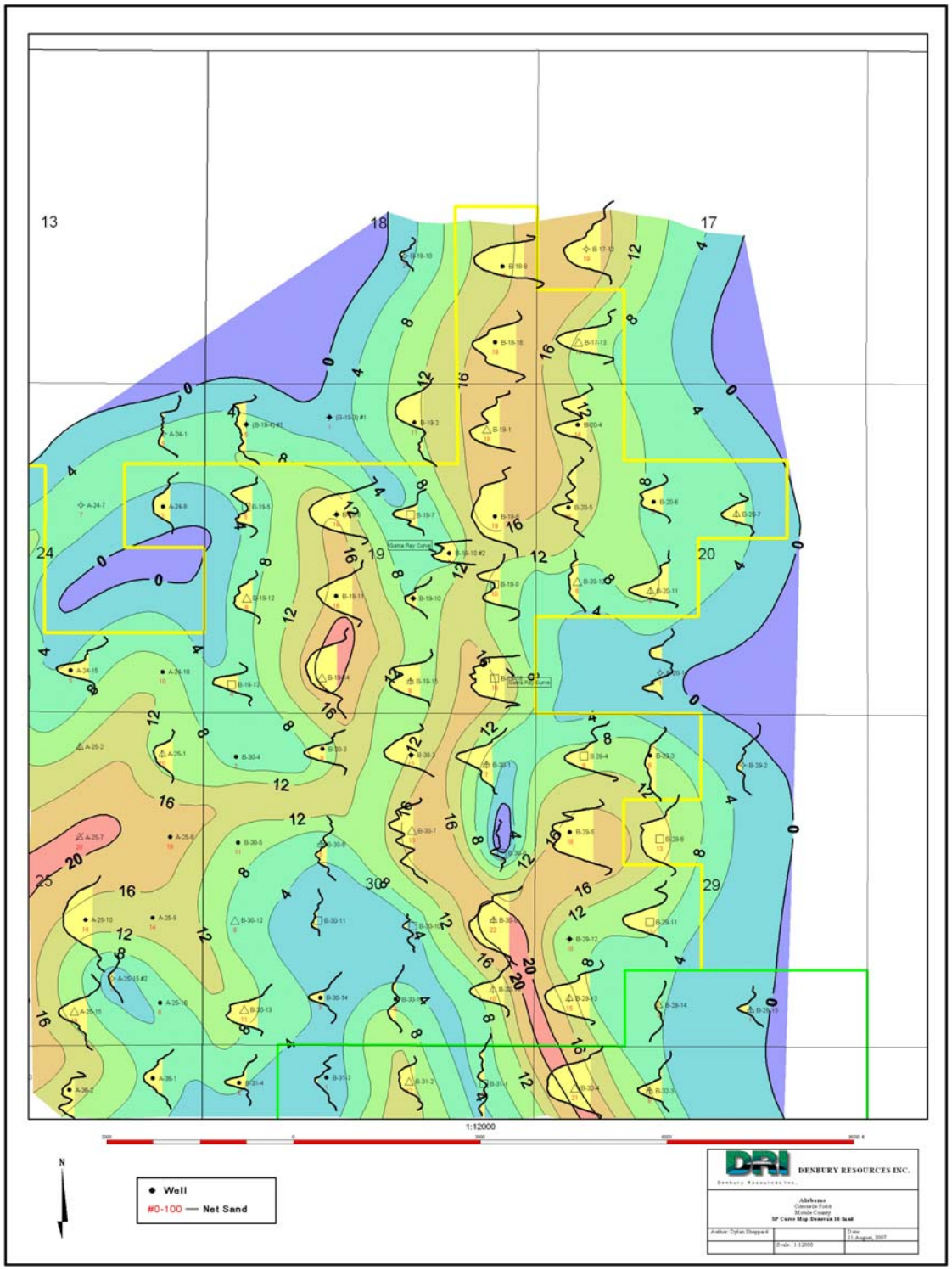

Figure 3.2.3. Thicknesses of the 16-2 sand, determined from spontaneous potential (SP) logs, superimposed on the map of thickness contours in the vicinity of the test injection well (Dylan Sheppard, Denbury Resources, Inc.). Wells are indicated by small filled circles, open squares, and open triangles, with their identification numbers. Sand thicknesses from the SP logs are shown in red below the well symbol, in feet.

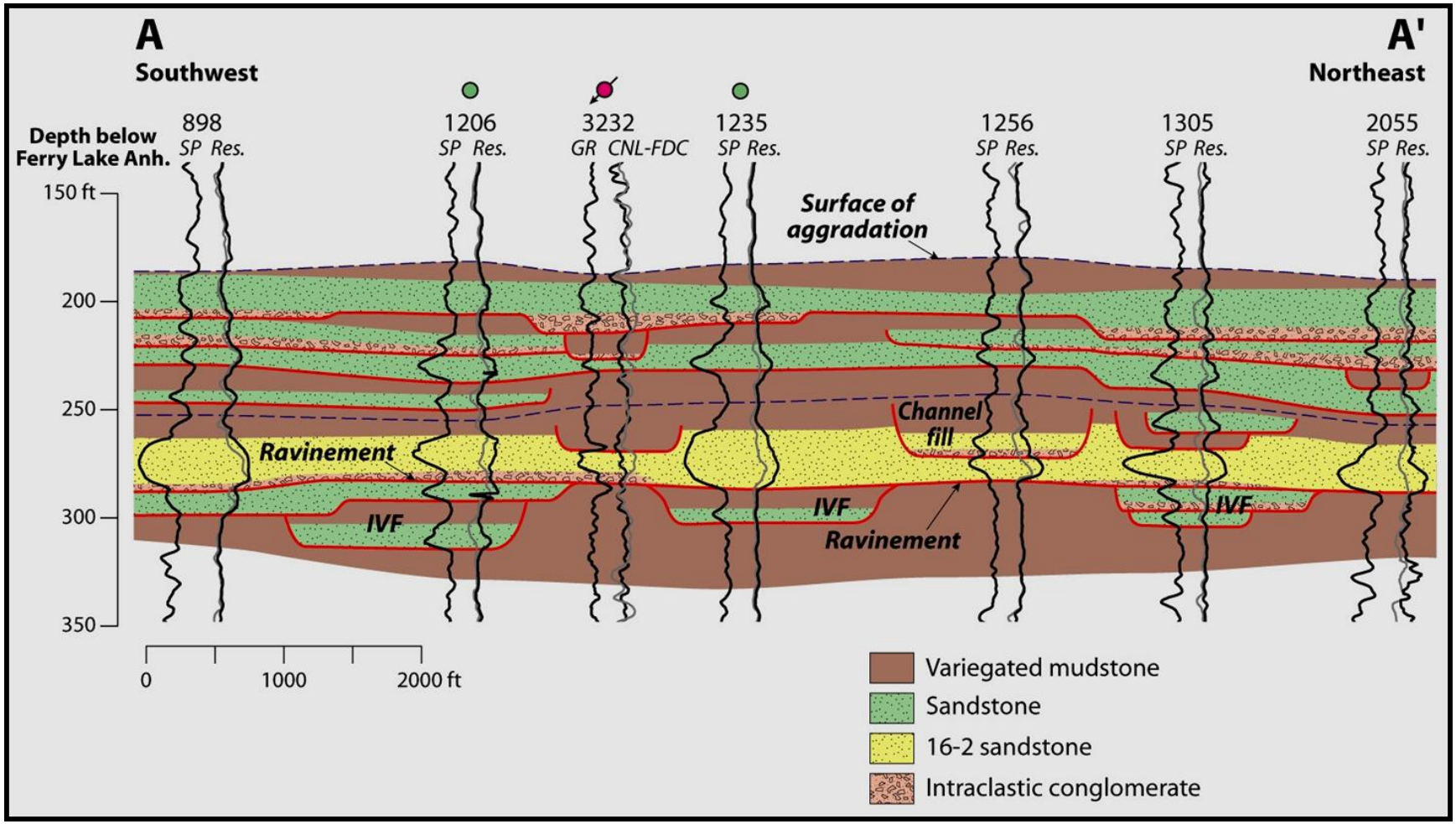

Figure 3.2.4. Stratigraphic cross section along line A-A' in Figure 3.2.2, including well no. B-19-10 #2 (Permit No. 3232, to the left of center, above), chosen as the injection well for the first field test. "IVF" (three places along the lower part of the figure) is "incised valley fill."

3.3. Reservoir Fluid Properties and Phase Behavior

Peter E. Clark, University of Alabama

3.3.1. Minimum Miscibility Measurement Overview

The measurement of the minimum miscibility pressure has traditionally been accomplished using a slim-tube apparatus. This method is somewhat qualitative in that it relies on the observation of bubbles in the flowing stream. In order to obtain a more quantitative measurement, a high-pressure rolling ball viscometer is being constructed. At a minimum this instrument will allow a more quantitative determination of the minimum miscibility pressure. It also offers the promise of determining the viscosity and density as a function of carbon dioxide partial pressure.

3.3.2. Progress during the Quarter under Review

The rolling ball viscometer consists of several subsystems that have to work together in order to make a measurement. Both the temperature control and measurement system and the angular position control system require programming. A control program was written for the temperature controller that allows us to set and hold the test temperature to an accuracy of 0.01°C for a period of several hours. The oven consists of a 1-inch copper tube wrapped with heating tape and insulated with flexible foam insulation. This subsystem is finished. We are still working on temperature measurement methods for inside the viscometer tube. Measurements will be made with RTD probes. A driver circuit for the RTD probes is currently under development.

Angular position is controlled with a stepper motor controller. The controller allows us to write a series of short programs to control the angular position of the viscometer. A program has been written to rock the tube slowly to insure complete mixing of the carbon dioxide and oil before measurement. Other programs have been developed to set a specific angle for the tube so that a measurement can be made. Work to insure that the angle that is inputted into the motor controller is the one that results is continuing. Angular measurements will be made with a precision rotational sensor.

A rolling ball viscometer relies on timing the movement of a ball that rolls down the measurement tube. To accomplish this, we are using four Hall-effect transducers spaced approximately one inch apart. The exact spacing will be optimized based on the length of the measurement tube. The driver circuits have been built and tested. Part of the last quarter was spent on developing the software to acquire the position data. Late in the quarter, a new driver program for the data acquisition subsystem was purchased and we are working to incorporate this software into the control system.

3.3.3. Plan for the Next Quarter

We have acquired new laboratory space with a walk-in hood. This space is being modified to hold the instrument. A new way of connecting the carbon dioxide line has been developed. The flexible tubing that we had planned to use was just too stiff. A high

pressure-rotating elbow has been located and ordered. This will be installed and the instrument will undergo initial testing in the fourth quarter.

3.4. Petroleum Reservoir Simulation

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

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

3.5. CO_2 Liquefaction, Transportation, and Storage

Richard A. Esposito, Southern Company Services, Inc.

[This section is reproduced verbatim from our Quarterly Progress Report of April 30, 2007, because no revision has yet been necessary, and because it is central to the planning of the first test injection.]

The Phase I injection of 5000 tons of CO_2 will require 250 truck-loads at the 20 ton per truck limit. Use of food-grade CO_2 is recommended because of complications in handling gas containing H_2S. A flash plant is recommended for liquefaction, because it is simple and low cost, but is only 60% efficient, so 8400 tons of CO_2 gas would be required to produce 5000 tons of liquid. The cost to rent a flash plant has not been established, but it is almost certain to be less costly than compression.

Transportation of CO_2 liquid by truck from the Denbury Resources site at Eucutta, MS, to Citronelle (80 miles each way) is estimated to cost $2.00 per mile for a total of 80 x 2 x $2 x 250 = $80,000 for the Phase I injection.

Provision should be made for storage of at least one day's supply at the injection site. Purchase of a storage tank has higher initial costs, but is likely to result in lower long-term costs compared to leasing. Storage of 110 tons of CO_2 liquid would require a 30,000 gallon tank, whose purchase price is expected to be $120,000. Leasing is expected to cost $50,000 to $60,000 per month.

A pump skid will be required for an injection rate of up to 2.2 million scf per day and surface conditions ranging from CO_2 liquid to vapor. Lease and operation of an injection skid is expected to cost $70,000 to $100,000 per month. A skid may be difficult to purchase because of limited availability in the present market. A process heater will also be needed. Purchase or lease of the heater is expected to cost $15,000 to $25,000.

A process analysis should be conducted for the anticipated range of CO_2 injection rates, including the effects of well bore diameter, depth, reservoir temperature, and pressure, to determine pump horsepower and process heater duty requirements. We need to identify suppliers and options for pump services, such as a custom-built pump skid, the process heater, and the storage tank. Also need to formulate process flow diagrams and the plan for integration of the equipment, from delivery, to on-site storage, through the pumping equipment and process heater, to the wellhead connection. A system hazard review needs to be conducted, with development of a site-specific health and safety plan.

3.6. Well Preparation and CO_2 Injection

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

The details of preparation of the B-19-10 #2 well to be used as the injector, and the four surrounding wells serving as producers, will depend upon what is learned about sand thickness, porosity, permeability, and continuity from study of the cores and well logs, described in Section 3.2.

3.7. Surface Monitoring

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

Xiongwen Chen and student Kathleen Roberts visited Citronelle at the end of September to see how to implement their research work. The goals of the visit were to determine background information including: (1) where are the oil wells located and how are they distributed, (2) what kind of landscape and ecosystems are present, and (3) what are the potential disturbances to measurements? During the trip, they acquired an up-dated map of the area. They found that (1) the majority of the oil wells are located in the residential area of Citronelle and the distribution of wells has a high spatial autocorrelation, (2) the landscape in the research area is mainly composed of residential property, woodlands (mainly pines and hardwood trees), and grasslands. There are invasive plant species in the grassland. There are very limited public lands but some still possibly available for monitoring sites, such as schools, hospitals, commercial areas and some abandoned churches. It will be very helpful if they can obtain geological structure maps. The visit brought to their attention the fact that human activities (e.g. traffic, construction, and land use) and seasonal biologic change from the ecosystem may contribute the main fluctuations in gas emission (CO_2 and CH_4). This is helpful for the design of field monitoring. Also the trip caused them to think about how they can implement their work smoothly, without intruding in the daily activities of residents, and made them aware of the need for a system hazard review and development of a site-specific health and safety plan.

3.8. Seismic Monitoring

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

During this quarter, Shen-En Chen and Wenya Qi continued their investigation of the best geophysical testing techniques for Citronelle and presented the general concept of this research at the Third National Conference on Environmental Science and Technology (September 12-14, 2007, Greensboro, North Carolina). Current research efforts are focused on reviewing the literature on geophysical sensing techniques for reservoir production and injection monitoring and conducting limited tests at an offsite location to identify the best approach for well monitoring.

3.8.1. Surface Testing Methods

Recently, reports were located describing blind test comparisons of different seismic methods at closely spaced sites in San Jose, California, conducted by the U.S. Department of the Interior and U.S. Geological Survey. The Open-File reports can be found on the official USGS website. Fourteen noninvasive seismic methods, including six active surface wave methods, six passive surface wave methods, and two hybrid active-passive combination tests were conducted. The results of shear-wave velocity models were compared to those of three invasive methods, including OYO suspension logging, the downhole seismic method, and seismic cone penetration, in a borehole having 300 m penetration (Asten and Boore, 2005). It is evident that most active surface-wave methods applied at this site including SASW, multi-channel surface wave (MASW) and frequency-wavenumber (F-K) methods are generally insufficient for obtaining shear-velocity data to depths of order 100 m with bias clearly observable at depths greater than 50 m. The high-resolution surface reflection and refraction profile provided shear and body wave velocity profiles to a depth of 85 m (Williams, R. A., 2005). Over 100 m depth of penetration was achieved by use of the passive methods. Passive microtremor array methods using 2D arrays were proven effective in gaining depth penetration to 300+ m. The SPAC (Spatial Auto-Correlation) and HVSR (Horizontal/Vertical Spectral Ratio) measurements even resolved the bedrock at a depth of 420-550 m and probably include a basement boundary at 1000 m depth (Asten, 2005).

The motivation of the research described above was to specify surface response to earthquake hazard for engineering design in California, hence establishing shear-velocity profiles only within several hundred meters of Earth's surface. High ability to resolve layering, especially low-velocity layers, is preferable. In the case of our current research, the depth of the target subsurface layer for injection is 3580 m (11,750 feet). It is important for us to determine the limitation of the penetration depth of surface seismic methods, even for passive sensing techniques. Passive sensing techniques may be useful for site characterization, to identify salt dome stability, and to provide useful geological information of the vicinity of the selected wells for model simulations. To avoid disturbance to the neighborhood, strategies on seismic source selection and impact level, as well as sensor layout, are under development. Passive sensing may be an ideal choice for Citronelle since no active source generation is necessary; however, sensor operations and measurement techniques still need to be explored.

A series of surface tests has been conducted at a site in North Carolina. We performed both active and passive tests and are comparing the results with borehole measurements. There are some questions about the interference of high frequency components in the passive sensing data, which will be resolved in the coming month.

3.8.2. Downwell Sensing Methods

Well-based surveillance methods for reservoir monitoring were also studied and compared: The time-lapse (or 4-D) seismic survey has been widely applied worldwide as the default tool for reservoir production and injection monitoring for over a decade (Dasgupta, 2005). In this technique, sources and receivers can be placed both on the surface or down wells. However, since this method was established mainly on offshore applications, the effectiveness of this technique is limited for on-land applications, due to the difference in operating environments. In offshore field areas, the near-surface-related noise is low and the repeatability of the seismic signal is high, both of which are critical to the feasibility of this technique (Dasgupta, 2005). In addition, since surveys in relatively constant marine environments can have roughly the same sources, receivers, and acquisition geometry, the statistics may be well-suited for scaling up or down surveys of different sizes and from different areas (Beckett, 1995). The efficiency and accuracy of data acquisition and processing, can therefore be improved. However, surveys on or near land are different from one area to another, and from well to well, making it difficult to apply consistent methods and interpretation using this technique. Moreover, other main barriers to time-lapse seismic methods include limited changes in acoustic properties at seismic scale caused by low production rates, poor sweep, or by a stiff carbonate matrix, dense surface infrastructure, the small areal scale of an injection pattern, the lack of suitable baseline surveys, difficult reservoirs, complex geology in the overburden, etc. For the reasons described above, time-lapse seismic has limited scope in our application.

In Vertical Seismic Profiling (VSP) methods, although receivers are positioned in a well, the sources are applied at the surface. In the case of our project, the surface source is unlikely to generate detectable seismic impact to the deep subsurface without disturbing the neighborhood at the surface. The promising Virtual Source technique (Shell patent, 2006), with processing and imaging issues addressed, is limited in its application to the use of geophones for deployment in horizontal observation wells.

Based on the study and comparison of different geophysical techniques, downhole seismic and microseismic methods are considered more suitable for reservoir monitoring both during and after injections. With the processing and interpretation of the monitoring data, detection of reservoir condition changes and fluid front movement, as well as potential fracturing, are believed to be the best that can be achieved. In downhole surveys, a string of hydrophones or a single clamped tri-axial geophone is lowered into a borehole to measure the travel time of first-arrival seismic waves at regular intervals. The P- and S-wave arrival times for each receiver location are combined to produce travel-time versus depth curves for the complete hole. Based on this information, in

conjunction with density data from geophysical logging of the borehole, total velocity profiles can be produced. In downhole tests, transient or continuous seismic energy sources can be generated, either on the ground surface at a fixed distance from the top of the borehole, or from seismic vibrators placed in the borehole along with receiving sensors. An illustration of the downhole test configuration is shown in Figure 3.8.1. A solenoid vibrator is chosen as the seismic source, which will be placed down the borehole along with the receiving sensors. The frequency range of the seismic source is under study. Sensors with high resolution are needed because very subtle seismic variations are expected from the small variations in density in the formation, estimated to be only 3%. Crosshole surveys could also be conducted, where one hole is used to deploy the source and the other hole(s) are used to detect the arrival of the seismic energy transmitted between the two or more boreholes. The feasibility of this technique is going to be studied based on the distance between the selected injection and monitoring wells and cost considerations.

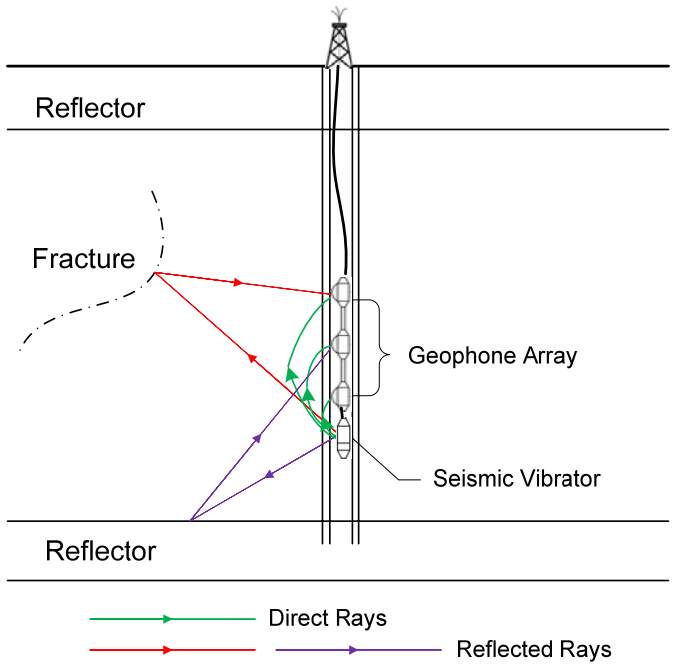

Figure 3.8.1. Downhole seismic method, schematic diagram.

Passive sensing using Acoustic Emissions and Microseismicity (or Microtremor) methods are also possible in monitoring underground injection processes (Maisons et al., 1997; Soma et al., 1997). Microseismic activity can be recorded using permanent or semi-permanent seismic sensor emplacements in single or multiple wells, as shown in Figure 3.8.2. By listening to the ambient noise in a reservoir, production fluid fronts or potential fracturing induced by injection can be detected or located, to optimize extraction and injection paths and rates (Albright et al., 1994). These methods can avoid the use of artificial input sources, but may require extensive data inversions.

In both downhole seismic and microseismic surveys, sensor selection is also very important. Different kinds of hydrophones, tri-axial geophones, wireless accelerometers,

and wired sensors have all been studied for vibration measurements. A critical issue is to have sufficient sensitivity to determine the actual reflected signals. Since a noisy environment is anticipated, sensors with high signal-to-noise (S/N) ratio should be selected. Due to the extent of data collection, strategies in data management and processing to isolate noise from real signals are also crucial to ensure good data quality. In the interpretation of recorded seismic data, finding the right attribute or combination of attributes is very important to show sensitivity to the reservoir properties of interest. Besides these, other challenges to the test operation may include sustainable power supply for long term monitoring, establishment of baseline values at the site, and extensive cabling around the site. The challenges in test planning are expected to be overcome and resolved in the near future, based on additional work in the laboratory and small-scale field tests.

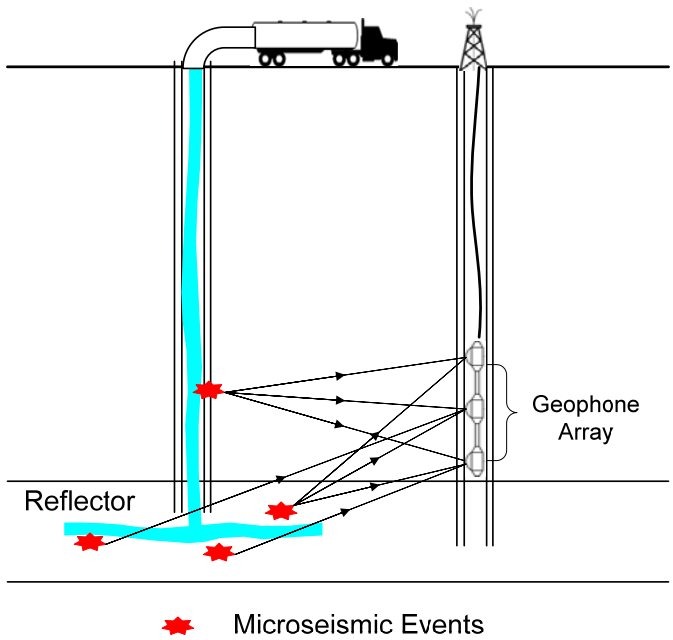

Figure 3.8.2. Microseismic method, schematic diagram.

3.9. Saline Formation Simulation

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

In our previous Quarterly Progress Report (July 30, 2007), Konstantinos Theodorou presented calculations of the CO_2 storage capacity of the Middle Donovan saline zone, that lies between the oil-bearing strata of the Upper and Lower Donovan zones. The Middle Donovan zone is attractive for storage of CO_2 because it is accessible through wells already drilled and completed for water injection and oil production from the Lower Donovan zone. Produced water from the Citronelle Oil Field is primarily disposed of in saline sandstone units within the Tuscaloosa Group at depths of 1830 to

2200 m (6000 to 7200 ft). Accordingly, the Tuscaloosa-Eutaw section, shown in Figure 3.9.1, is also an attractive saline formation for storage of CO_2.

3.9.1. Tuscaloosa Group and Eutaw Formation

The Tuscaloosa-Eutaw section is of Upper Cretaceous age and is nearly 460 m (1,500 ft) thick in the Citronelle Dome (see Figure 3.9.1). The Tuscaloosa Group disconformably overlies Lower Cretaceous deposits of the Dantzler Formation and has a distinctive internal stratigraphy. The lower Tuscaloosa Group is subdivided informally into the Massive and Pilot sands, which can be traced across southwest Alabama and into Mississippi. The lower part of the Massive sand in Citronelle Dome has a blocky well log pattern and low resistivity, whereas the upper part has a fining-upward log pattern and higher resistivity. At the top of the Lower Tuscaloosa section, the Pilot sand includes multiple sandstone layers with a serrated to blocky log pattern. The Pilot sand contains significant oil reservoirs in southwest Alabama, and overall, the lower Tuscaloosa section is interpreted as transgressive shoreline deposits (Mancini et al., 1987). Significant oil reservoirs also exist in both the Tuscaloosa Group and Eutaw Formation throughout the Mississippi Interior Salt Basin of Alabama (e.g., Bolin et al., 1989).

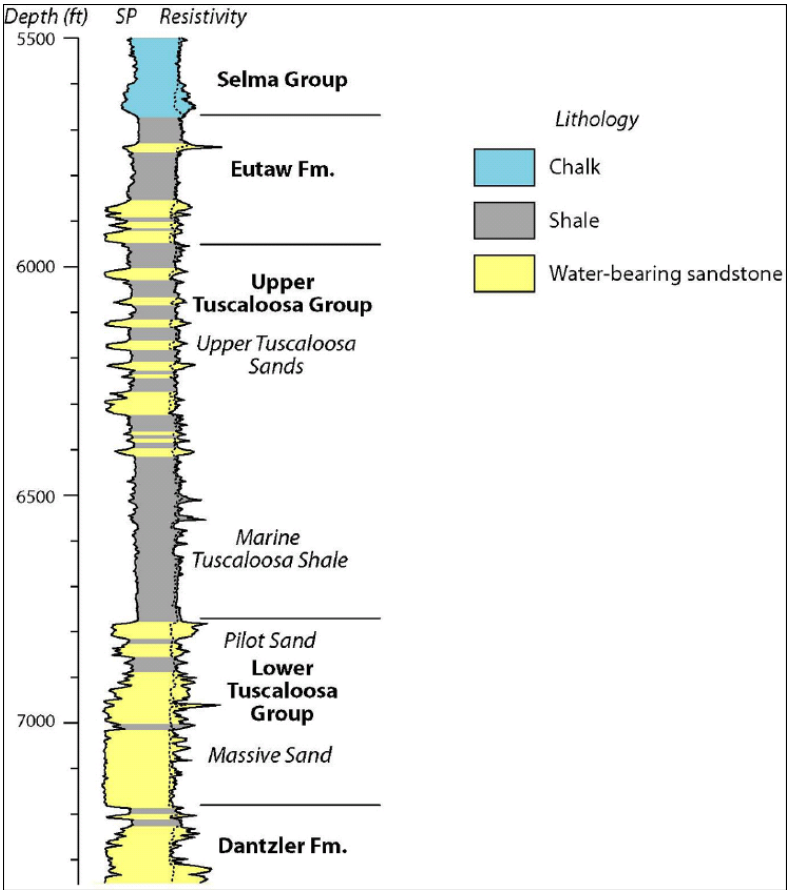

Figure 3.9.1. Geophysical well logs and stratigraphy of the Tuscaloosa-Eutaw interval and adjacent strata in the Citronelle Dome (Geological Survey of Alabama). State Oil and Gas Board of Alabama Permit 1067.

The Pilot sand is overlain by thick shale that is commonly called the Marine Tuscaloosa, and this shale unit is the top seal for the lower Tuscaloosa oil reservoirs. The shale coarsens upward into a thick succession of interbedded shale and sandstone assigned to the upper Tuscaloosa Group and is likely fluvial-deltaic in origin. Above the upper Tuscaloosa, the Eutaw Formation consists of about 84 m (275 ft) of sandstone that fines upward into shale. Although the upper Tuscaloosa is not oil productive, significant reservoirs exist in the Eutaw Formation, which is interpreted to include transgressive shoreline and shelf facies (Pashin et al., 2000). Porosity values are typically 20% or higher in Tuscaloosa-Eutaw sandstone, and permeability ranges widely from less than 50 mD to more than 3000 mD. The Eutaw Formation is overlain by more than 366 m (1,200 ft) of chalk, which composes the Selma Group. The Selma Group acts as the top seal for Eutaw reservoirs and separates the Mesozoic hydrocarbon system in the eastern Gulf of Mexico Basin from underground sources of potable drinking water in the Tertiary section.

3.9.2. Saline Formation Storage Capacity

Formation-specific capacity estimates are integral to the implementation of carbon capture and geologic storage at existing facilities. These estimates will also play an important role in the siting of new large-scale stationary emitting sources and are required for the selection of geologic sinks that are capable of providing stable, long-term storage.

Static capacity estimates do not consider transient phenomena and depend exclusively on reservoir properties and geometry. The methodology used to estimate capacity in this evaluation does not account for the site-specific partitioning of CO_2 among gas, liquid, and solid phases, as in the analysis by Pruess et al. (2001), but is a volumetric calculation based on receiving formation area, thickness, porosity, density, temperature, and pressure. An efficiency factor having upper and lower limits of 0.4 and 0.1, respectively, was incorporated to account for residual water saturation. In addition, a permeable fraction efficiency factor of 0.9 for the Tuscaloosa-Eutaw sands and 0.6 for the Rodessa Formation was assigned to account for shale dispersion, based on visual observations on drill core samples of the rock matrix.

The geometry of the Lower Tuscaloosa (Pilot and Massive sands) and the Upper Tuscaloosa-Eutaw interval is based on the areal extent of the four-way structural closure and the apparent structural spillpoint of the Citronelle Dome (72 square miles, 186×10^6 m^2). The current production area of the Citronelle Oil Field is 36 square miles (93×10^6 m^2). Reservoir thickness was determined from geophysical well logs, and porosity was determined from records in the open files of the Geological Survey of Alabama and the State Oil and Gas Board of Alabama. Porosity of the Tuscaloosa-Eutaw sands was estimated at 20% while an average porosity of 13% was used for the Rodessa sands.

The results of the capacity calculations are summarized in Table 3.9.1. At the greatest depth, in the Rodessa Formation, oil reservoirs in the lower and upper Donovan

sands are estimated to have the capacity to store between 115 and 460 million short tons of CO_2. The saline reservoirs of the middle Donovan sand could provide an additional 24 to 100 million short tons of CO_2 storage. In the lower Tuscaloosa, between 200 and 790 million short tons of CO_2 can be sequestered in the Massive sand, and between 40 and 160 million short tons is the estimated range of storage capacity for the Pilot sand. Significant capacity also exists in the upper Tuscaloosa-Eutaw section, which may hold between 150 and 600 million short tons of CO_2. The total static estimate of storage capacity of the Citronelle Dome is then between approximately 500 million and 2 billion short tons of CO_2 (480 million to 1.9 billion metric tonnes of CO_2).

Table 3.9.1. Storage Capacity of Saline Formations in Citronelle Dome.

Formation	Reservoir or Seal	Lower Limit (10%) on Capacity (million short tons)	Upper Limit (40%) on Capacity (million short tons)
Selma Chalk	Seal	~0	~0
Eutaw Formation and Upper Tuscaloosa Group			
Eutaw and Upper Tuscaloosa Sands	Reservoir	150	600
Marine Shale	Seal	~0	~0
Lower Tuscaloosa			
Pilot Sand	Reservoir	40	160
Massive Sand	Reservoir	200	790
Ferry Lake Anhydrite	Seal	~0	~0
Rodessa Formation			
Upper and Lower Donovan Sands	Reservoir	115	460
Middle Donovan Sand	Reservoir	24	100
Total		529	2110

The results of the calculations for the Middle Donovan zone presented by Konstantinos Theodorou in the Quarterly Progress Report of July 30, 2007 were 390 million short tons according to the method of Pruess et al. (2001) and 11 to 44 million short tons according to the methods adopted by the National Geological Carbon Sequestration Capacity Assessment (US DOE, 2006), compared with the range of 24 to 100 million short tons found here.

3.10. Visualization of Geologic Structure and Flows

Eric S. Carlson, University of Alabama

Please see Section 3.1.1 for Eric Carlson's observations on the implementation of the Python-based TVTK/MayaVi framework (Enthought, Inc., Austin, TX) for visual representation.

3.11. Reservoir Management Plan and Economic Analysis.

3.11.1. Reservoir Management Plan

Advanced Resources International (Kuuskraa and Koperna, 2006) evaluated the benefits and costs of possible improvements to traditional CO_2-EOR practice. The advanced CO_2-EOR technology proposed by these authors 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. The specific forms that these innovations could take in the context of the CO_2 flood being planned for the Citronelle Oil Field are as follows.

Increased volume of CO_2. The simulation results reported by Kuuskraa and Koperna (2006) indicate that significant increases in oil yield can be achieved, with proper management, by increasing CO_2 injection from the traditional average 0.4 hydrocarbon pore volume (HCPV) to, for example, 1.5 HCPV. The increase could be achieved by increasing the injection rate, decreasing the frequency and duration of water injection, and increasing the duration of the CO_2-EOR project. As Kuuskraa and Koperna point out, the optimization of these parameters depends upon the reservoir and is a subject for future research. Examination of this question is among the objectives of the test injections under the present project. The work of Kuuskraa and Koperna (2006) indicates that the plan for the commercial CO_2 flood should allow for injection of 1.5 HCPV of CO_2, including a separation and recycling plant of 3 to 4 times the traditional capacity.

Innovative flood design and well placement. It appears unlikely, based upon the information currently available, that additional wells will be drilled for the CO_2 flood at Citronelle. Existing wells will, however, be worked over and the placement of cement or bridge plugs can be optimized to target promising sands and those that may have been poorly-swept and poorly-produced during secondary recovery.

Improving mobility ratio. The simulation results of Kuuskraa and Koperna (2006) show that significant improvements in recovery are possible by addition of polymers or other viscosity enhancers, to increase injected water viscosity to 3 centipoise.

Extension of oil-CO_2 miscibility. In their simulation, Kuuskraa and Koperna reduced the minimum miscibility pressure by 500 psi, for example by addition of liquefied petroleum gas to the CO_2. Because of the great depth of the reservoir at Citronelle, enhancement of miscibility would appear not to be necessary.

Flood performance diagnostics and improved control. The features that Kuuskraa and Koperna include in this category are a supporting technical team of geologists, reservoir engineers, and economic analysts; observation wells equipped with downhole sensors; periodic 4-D seismic measurements; and pressure and residual oil saturation measurements, to monitor the progress of the CO_2 flood and take corrective action to maximize its performance.

In summary, the management plan for Citronelle would differ from traditional CO_2-EOR practice in the following ways: CO_2 injection of ~ 1.5 HCPV, well workover to optimize CO_2 sweep and oil displacement, addition of additives to increase water viscosity, implementation of observation wells with instrumentation to monitor the progress of the flood, and a team prepared to make adjustments to optimize the performance of the CO_2 flood.

3.11.2. Economic Analysis

An analysis by Advanced Resources International (2006) showed that tertiary oil recovery from Alabama oil fields with the price of oil at $30 per barrel, cost of CO_2 at $1.50 per thousand ft^3, and assuming a high risk rate of return (25% before taxes), would not be profitable using either traditional or state-of-the-art CO_2-EOR practice. However, combining state-of-the-art technology with higher oil prices ($40 per barrel) and risk mitigation incentives or lower cost CO_2, was expected to make CO_2-EOR profitable in one Alabama oil field, presumed (by us) to be the Citronelle Field.

The study of next generation CO_2-EOR technology by Advanced Resources International, described in Section 3.11.1 above (Kuuskraa and Koperna, 2006), showed that, with high oil prices and adequate CO_2 supply (CO_2 price tied to oil price), increasing oil recovery by increasing the amount of CO_2 injected to 1.5 HCPV, addition of one horizontal and one vertical well to each injection-production well pattern, use of viscosity enhancers in injected water, enhancement of miscibility by addition of other gases to CO_2, implementation of flood performance diagnostics, and employment of a professional technical team, was expected to increase the productive life and oil recovery from the majority of U.S. oil fields examined. By applying the proposed next generation CO_2-EOR technology, cumulative recovery by all methods (primary, secondary, and enhanced), is predicted to increase from the present value near 35% (primary and secondary recovery) to approximately 60%. Though not all of the features of next generation CO_2-EOR discussed by Kuuskraa and Koperna may be adopted at Citronelle (e.g. drilling horizontal wells), and the behavior of Citronelle sands under CO_2 injection is known only from the pilot CO_2 flood conducted in the early 1980's (Kennedy et al., 1983), indications based upon present economic conditions and the other information

currently available are that a CO_2-EOR project in Citronelle will be profitable and will add approximately 36 million barrels of oil to economically recoverable U.S. oil reserves.

4. Project Status

4.1. Task and Milestone Status

Five tasks were scheduled for completion by the end of the second quarter. Please see Appendix A for the original Statement of Work and Appendix B for the revisions to the Statement of Work requested in the Continuation Application submitted on October 7, 2007:

Three at the end of the first quarter, March 31, 2007:

Task 1. Establish collaboratory environment.

Task 2. Establish publicly accessible web site for two-way communication with industry.

Task 5. Analysis of oil and oil-CO_2 interaction. Completion of Task 5 is also specified as a critical path milestone (Appendix A, page A10).

Two at the end of the second quarter, June 30, 2007:

Task 4. Analysis of rock samples.

Task 8. Selection of test and monitoring wells.

And five by the end of the third quarter, September 30, 2007:

Task 3. Application for permit to conduct Field Test No. 1.

Task 9. Site characterization by geophysical testing.

Task 10. Baseline soil CO_2 fluxes and ecology.

Task 11. Reservoir management plan.

Task 12. Economic and market analysis.

The status of work under all of these tasks is described below.

Task 1. Establish collaboratory environment. A collaboratory framework for the research group was set up by Eric Carlson at <http://citronelle.eng.ua.edu>. The site is based on the open source Moodle (Modular Object-Oriented Dynamic Learning Environment) course management system (Moodle Pty. Ltd., Perth, Western Australia). It has Wiki, blogging, forums, web-page authoring, and instant-messaging tools. Preliminary tests identified some server problems that have been solved. More intensive

testing will be done over the next three months. Moodle allows optional account authentication for access, so the system will be set up to distribute materials both publicly and privately. A database of engineering, production, geologic and other data on the Citronelle Field will be established for access by the project team.

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

Task 5. Analysis of oil and oil-CO_2 interaction. The critical oil-CO_2 mixture parameter needed for simulation of test injections, the minimum miscibility pressure, was found in the report by Gilchrist (1981). Precipitate formation from the oil in the presence of CO_2 was not observed by Gilchrist. The availability of this information frees time and resources for development, by Peter Clark and his coworkers at UA, of an in-house instrument for measurement of the viscosity and density of oil-CO_2 mixtures at reservoir conditions. Determination of the minimum miscibility pressure, viscosity, and density of oil-CO_2 mixtures at an independent laboratory is much more costly than anticipated. Having the equipment available to the project will permit measurements to be made on multiple samples under a wider range of conditions, which will be a valuable component of the inputs to simulations.

Task 4. Analysis of rock samples. A comprehensive examination of a drill core from Citronelle Field was performed by Jack Pashin and his coworkers at GSA, with the results described in Section 3.3. That work has led to significant revision of the conventional geologic model for the field that has been handed down from the early studies of the formation in the 1950's and 1960's. This will have significant bearing on our approach to the test injection and the interpretation of its results. Other cores from Citronelle are being slabbed at GSA, so the examination and interpretation of their structure will continue, becoming a more ambitious undertaking, and having greater significance than anticipated in the original proposal. The determination of physical properties, such as porosity and permeability, the kind of activity originally envisioned under Task 4, has become less important, because such data are available in previous reports from the field, listed in the Bibliography (Appendix D).

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. As observed by Jack Pashin in his description of the wells in Section 3.7, the reservoir heterogeneity that is so characteristic of Citronelle Field is well represented in the five-spot test pattern chosen for the test.

Task 3. Application for permit to conduct Field Test No. 1. The well chosen for the test injection was originally permitted as an injector. It will only need to be

repermitted as an injector, requiring some supporting documents specified under UIC regulations. This is not expected to require a long lead time. It will need a mechanical integrity test to 1500 psi, to be conducted in conjunction with workover of the well to prepare it for the test.

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, on the great depth of the oil reservoirs, geophysical testing is more difficult to arrange than anticipated. UNCC is examining options, as described in Section 3.8 of this report. If permission is given to reschedule the first test injection to November 2008, then there is time to establish an acceptable technique and conduct background measurements during the water flood to be conducted approximately from March 2008 through October 2008.

Task 10. Baseline soil CO_2 fluxes and ecology. AAMU has visited Citronelle and made some preliminary measurements of the CO_2 background, as mentioned in Section 3.7 of this report. Scheduling the first test for November 2008 will permit background measurements to be made over an entire yearly plant growth cycle.

Task 11. Reservoir management plan. The features of a reservoir management plan that would qualify the present project as "next generation CO_2-EOR," in the words of Kuuskraa and Koperna (2006) are discussed in Section 3.11.1 of the present report.

Task 12. Economic and market analysis. Under the lowest likely oil and highest likely CO_2 prices expected to prevail, on average, for the foreseeable future, and incorporating some of the features of "next generation CO_2-EOR" (though not, for example, the drilling of horizontal wells) specified by Kuuskraa and Koperna (2006), an analysis by Advanced Resources International (2006) indicates that the proposed CO_2-EOR project will be profitable. Denbury Resources estimates that CO_2-EOR will add 36 million barrels of oil to economically recoverable U.S. reserves.

4.2. Findings and Accomplishments

Work during the first 8 months of the project (February through September, 2007) has been focused on the following components: geology and petrology of the formation, reservoir fluid properties, planning for the first CO_2 injection, and estimates of CO_2 storage capacity. The findings and accomplishments on each of these fronts are described below.

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

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

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

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

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

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

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

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

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

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

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

4.3. Request for Change in Schedule

Changes in the DOE-approved statement of work were requested in the Continuation Application submitted to DOE on October 7, 2007. The rationale for the changes is presented in the four paragraphs of this section, below. For ease of comparison and assessment of the proposed changes, the original DOE-approved statement of work is attached as Appendix A, containing the original list of tasks to be performed (Section A.1), the original project schedule (Section A.2), and the original milestones (Section A.3). The is followed, in Appendix B, by the requested revised list of tasks (Section B.1), the revised schedule (Section B.2), and the revised milestones (Section B.3). There is no change in the overall work to be done during the project. The milestones are all the same as in the DOE-approved statement of work, but the single milestone, entitled "Field Test No. 1 completed" has been moved from Phase I to Phase

II, with a new completion date of December 31, 2008. There is no change in the deliverables, from the DOE-approved statement of work.

Discussions with Denbury resources, the operator of the Citronelle Oil Field, and our other partners, have led us to request permission to postpone the first CO_2 injection field test at the Citronelle, AL, Oil Field from the original period of February and March 2008, to November and December 2008. The proposed changes in the schedule for the coming year are all connected with this modification.

The well to be used as the injector for the field test is currently a producer, not an injector. It will be worked over and repermitted as an injector, after which Denbury recommends that it be used as a water injector for 5 to 6 months, (1) to establish the conditions that will exist at other wells in the field when they are converted from water injection to CO_2, (2) to establish a baseline for production under waterflood conditions, with which to compare production during CO_2 injection, and (3) to repressurize the formation with water rather than CO_2, in order to have the maximum amount of CO_2 available to sweep the formation. If workover begins in October and requires one month, 5 months of water injection would not be complete until the end of March, at the earliest. This is right at the onset of the spring and summer season during which CO_2 is in short supply because it is in demand for carbonated drinks. The duration of the CO_2 injection, at the rate of 100 tons/day, is approximately 2 months.

Postponing the test from March until November would have the following additional benefits. Observation of CO_2 production from soil and vegetation in the vicinity of the test site can be made through an entire year, to establish a proper baseline. The study of the geology and petrology can be advanced to a stage at which detailed input can be provided for reservoir simulation, and the results of simulations incorporated in the design of the pilot test. Our preliminary calculations suggest that the planned 5000 tons of CO_2 is a marginal amount from which to see an effect on production. Based on the reservoir simulation, a more accurate determination can be made of the volume of CO_2 required to see a response, and the amount allocated for the test increased, if necessary. Any delay in the progress of the work is undesirable but, in this case the overall result would be increased value and benefit from the work under the project.

The end dates for Task 5, "Analysis of oil and oil-CO_2 interaction," Task 6, "Construct advanced geologic models of Rodessa reservoirs," and Task 7, "Reservoir simulation," have been extended from their original end dates in the midst of Phase I to the end of Phase I, to eliminate disruption of those activities, all of which will continue in Phase II. There is no need for cessation of work on these central tasks before the end of Phase I. Progress on all three of them is on, or ahead, of schedule and will continue throughout the project. These changes appear in the revised schedule, Table 1 in Section 3.4.

4.4. Technology Transfer

A paper presenting a detailed analysis, from the geological perspective, of the characteristics that make the Citronelle Dome an attractive candidate for CO_2-EOR and storage, including estimates of storage capacity, was prepared by Jack Pashin, Richard Esposito, and Peter Walsh. The paper has been accepted for publication in *Environmental Geosciences*, the archival journal of the Division of Environmental Geosciences of the American Association of Petroleum Geologists. Dr. Pashin and Richard Esposito will present their latest work on the geology and petrology of the Citronelle Dome at the 2007 Annual Convention of the Gulf Coast Association of Geological Societies and the Gulf Coast Section of the Society for Sedimentary Geology in Corpus Christi, October 21-23. Reporting on another component of the work, Shen-En Chen and Wen-Ya Qi of the University of North Carolina at Charlotte presented options for seismic monitoring of CO_2 migration following injection during the 3rd National Conference on Environmental Science and Technology, held at North Carolina A&T State University in Greensboro, September 12-14. The purpose of these publications and presentations is to keep the reservoir engineering and carbon storage communities fully informed about the progress of the present work and its implications for successful CO_2-EOR and storage in formations of the type found at Citronelle.

5. Conclusions

The status, findings, and conclusions from each of the principal research efforts in which the team has been engaged during the first 8 months of the project (February through September, 2007) are summarized below.

Geology and Petrology. Facies analysis of drill cores by Jack Pashin and his research group at the Geological Survey of Alabama indicates that the Rodessa Formation in Citronelle Field was deposited in the shore zone of a tide-influenced, shoal-water delta system. It is interpreted to have accumulated in a complex network of tidal shoals, channels, and mud flats. Sandy shoal and channel deposits are the dominant reservoir facies. This picture of the Rodessa depositional environment differs significantly from the fluvial meanderbelt interpretation that has guided the development and production from the Citronelle Field since 1964. The significance of this observation for enhanced oil recovery is that the oil-bearing sands have geometry and heterogeneity that are different from meandering stream deposits, and this difference is an important consideration when evaluating past reservoir performance and devising a reservoir management plan for CO_2-enhanced oil recovery.

Reservoir Fluid Properties. The minimum miscibility pressure of Citronelle oil with CO_2 is 2800 psi (Gilchrist, 1981), approximately 200 psi above present typical reservoir pressures. It will therefore be possible, without great difficulty, to conduct CO_2 flooding under the higher oil displacement, higher recovery, miscible conditions. No precipitation of heavy components from the oil in the presence of CO_2, that might decrease formation permeability during CO_2 flooding, was observed by Gilchrist (1981). Peter Clark and his research group at the University of Alabama are completing the assembly of a rolling ball viscometer with which to measure the viscosity and density of oil-CO_2 mixtures at reservoir temperature and pressure. This instrument is expected to be complete by December 2007 and will provide the means to determine oil-CO_2 mixture properties for oil samples from all locations in the Field and construction of a map of minimum miscibility pressure, should there be significant variation from sand to sand. Compositions of dissolved solids in brine from Citronelle wells were recovered from the NETL U.S. Brine Wells Database. These data are being used in the assessment of CO_2 solubility in brine and the potential for mineral sequestration, in connection with estimates of CO_2 storage capacity in saline formations in the Citronelle Dome.

Pilot Injection. The Citronelle Unit B-19-10 #2 well (State Oil and Gas Board of Alabama Permit No. 3232), in the northeastern part of the field, has been selected as the well for the first test injection of CO_2. Production will be monitored at four adjacent wells. Together these wells constitute a classic five-spot injection-production pattern. The injection well was originally drilled and permitted as a gas injector but never used

for that purpose. The production casing in this well is perforated in three zones; two are in the upper Donovan sand, and the third is in the lower Donovan. The lower Donovan perforations are now isolated below a cement plug, and since 1992, oil has been produced intermittently through the two sets of perforations in the Upper Donovan. Production data indicate that the water-oil ratio has generally been higher than 10:1. Perforations in the upper Donovan are open to two sandstone units. The upper perforations are in the 14-1 sand, which is thinner than 0.9 m (3 feet), is difficult to trace among wells, and thus is not recommended for injection during the test. The lower perforations are in the 16-2 sand, which is 3 m (10 feet) thick at this location and is easily correlated among adjacent wells. The 16-2 sand is perforated in all wells of the five-spot test pattern and appears to be a key producer in the northeastern part of Citronelle Field. Well-log cross sections indicate the thickness of the 16-2 sand ranges from 1.8 to 7.6 m (6 to 25 feet), and the log characteristics indicate that the reservoir heterogeneity so characteristic of Citronelle Field is well represented in this five-spot test pattern.

CO_2 Storage Capacity. The oil accumulation in the Citronelle Field is sealed by a thick succession of shale and anhydrite, with the oil-water contact being more than 30 m (100 ft) above the structural spill point. This structure, and those of saline formations above the oil-bearing zones, are excellent candidate sites for CO_2 storage. The range of static estimates of CO_2 storage capacity in the oil reservoirs of the Rodessa Formation, after oil recovery is complete and CO_2 injection is continued until the reservoirs are returned to a pressure of 5000 psi, is from 115 to 460 million short tons. The saline reservoirs of the middle Donovan sand could provide an additional 24 to 100 million short tons of CO_2 storage. In the lower Tuscaloosa formation, at roughly half the depth of the oil reservoir, between 200 and 790 million short tons of CO_2 can be sequestered in the Massive sand, and between 40 and 160 million short tons is the estimated range of storage capacity for the Pilot sand. Significant capacity also exists in the upper Tuscaloosa-Eutaw section, which may hold between 150 and 600 million short tons of CO_2. The total static estimate of storage capacity of the Citronelle Dome is then between approximately 500 million and 2 billion short tons of CO_2.

Economics. An analysis by Advanced Resources International (2006) showed that tertiary oil recovery from Alabama oil fields with the price of oil at $30 per barrel, cost of CO_2 at $1.50 per thousand ft^3, and assuming a high risk rate of return (25% before taxes), would not be profitable using either traditional or state-of-the-art CO_2-EOR practice. However, combining state-of-the-art technology with higher oil prices ($40 per barrel) and risk mitigation incentives or lower cost CO_2, was expected to make CO_2-EOR profitable in one Alabama oil field, presumed (by us) to be the Citronelle. A principal purpose and objective of the present project is to provide the operator with the additional expertise and resources that will ensure the application of the most advanced EOR technology at Citronelle. For example, a study of possible improvements in CO_2-EOR technology by Advanced Resources International (Kuuskraa and Koperna, 2006) showed that, with high oil prices and adequate CO_2 supply, increasing oil recovery by increasing the amount of CO_2 injection to 1 to 2 hydrocarbon pore volumes may be cost effective, depending upon the characteristics of the reservoir.

Acronyms

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

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Appendix A: Original Statement of Work, February 6, 2007

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

A.1. Tasks to be Performed

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

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

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

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

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

Field geology for CO_2 EOR and sequestration. The cores to be examined first will be those most closely linked to target areas for the field tests. The measurements will include porosities, permeabilities, and microscopic analyses. UAB, GSA, UA

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Task 45. Demonstration.
Preparation of wells and injection of as much CO_2 as possible (at least 5000 tons) into the reservoir through the test well under the optimum conditions identified in Field Test No's 1 and 2 and in parametric studies using the reservoir simulator. Collection of detailed surface and downhole data for refinement of the CO_2 EOR simulation. Monitor adjacent wells for produced oil, water, and gas, including CO_2. All

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

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

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

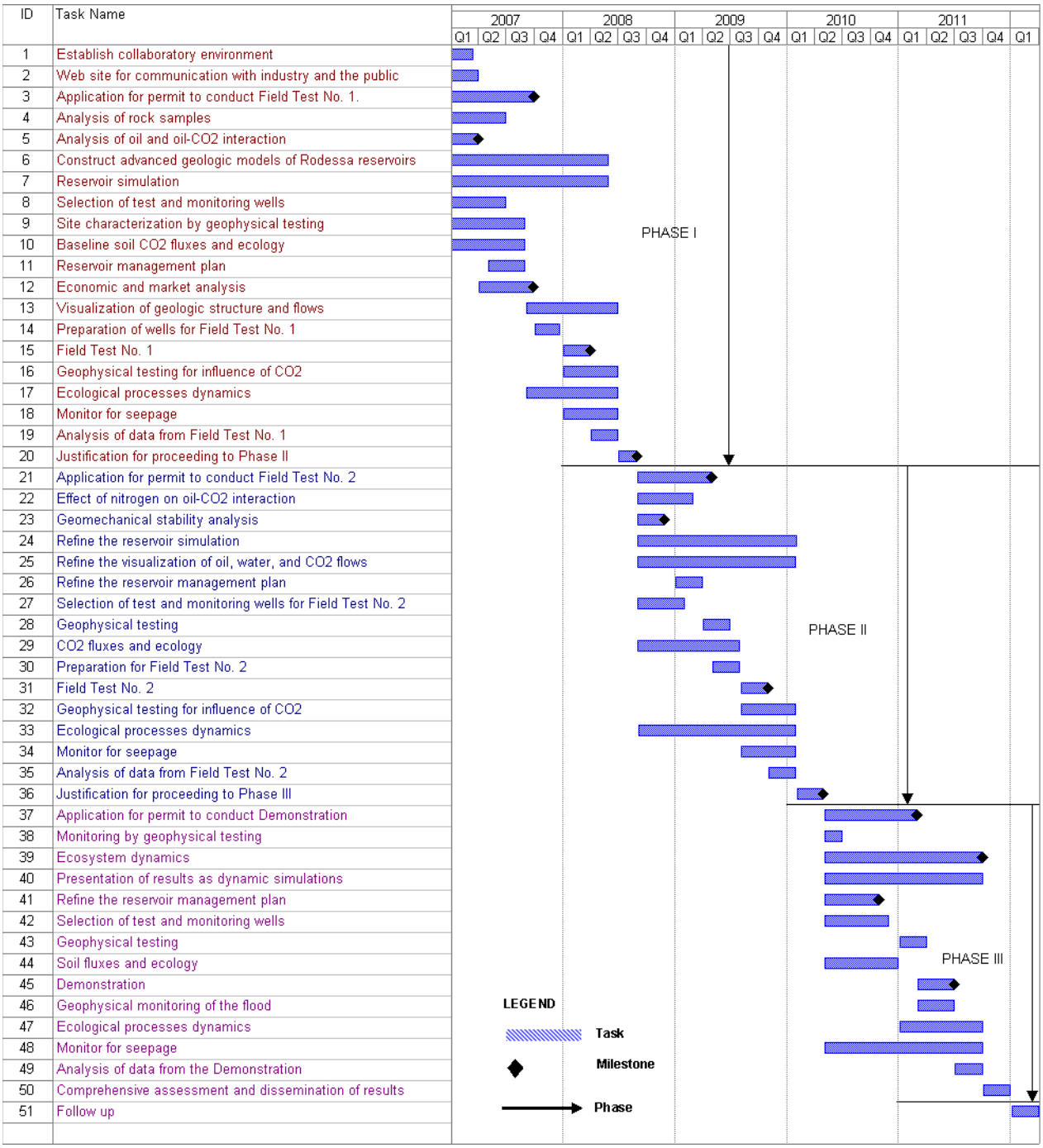
Task 49. Analysis of data from the Demonstration.
Perform complete analysis and presentation of the test data and associated environmental measurements. All

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

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

A.2. Project Schedule

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



A.3. Milestones

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

Appendix B: Proposed Revised Statement of Work, October 7, 2007

Contents:

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

B.1. Tasks to be Performed

The proposed statement of work by task, below, has been modified by adding water injection to the first field test (Task 15) and moving tasks depending directly on the field test (Tasks 16, 17, 18, and 19) from Phase I to Phase II. The field test now begins with water injection during Phase I, followed by CO_2 injection in Phase II. Task 15 is still included in Phase I. The original task numbers have been retained, for ease of comparison of the revised statement of work with the original. As a result, the tasks are no longer listed in numerical order.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

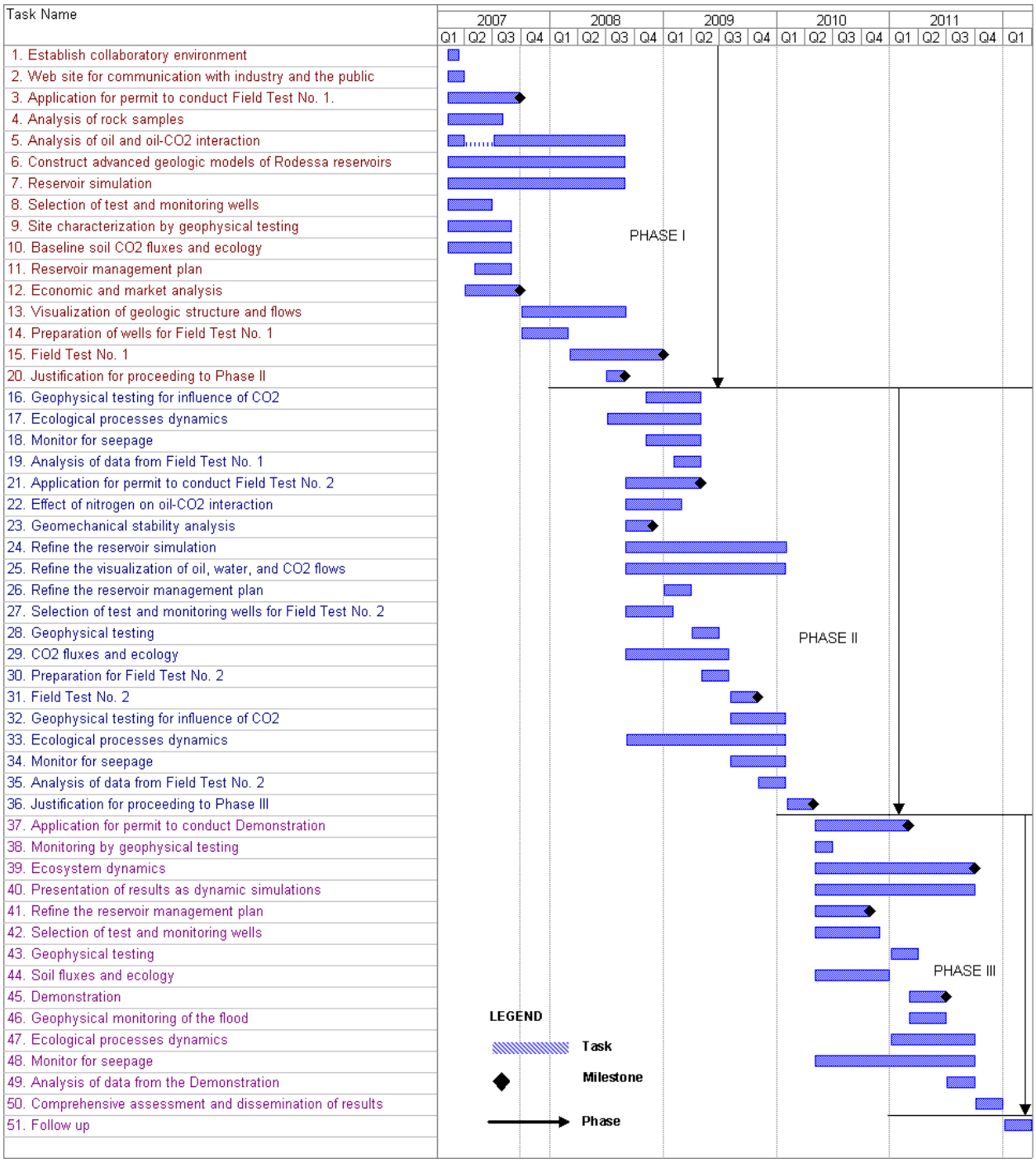
Task 49. Analysis of data from the Demonstration.
Perform complete analysis and presentation of the test data and associated environmental measurements. All

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

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

B.2. Project Schedule

The proposed revised 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.



B.3. Milestones

The milestones are all the same as in the DOE-approved statement of work, with the exception that the milestone entitled, "Field Test No. 1 completed," has been moved from Phase I to Phase II, and its completion date changed from March 31, 2008 to December 31, 2008.

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

Appendix C:
Presentations, Publications, and Reports

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

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

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

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

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

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

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

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

Appendix D:
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