the ENERGY lab

PROJECT FACTS

Carbon Storage - RCSP

Southeast Regional Carbon Sequestration Partnership—Development Phase

Cranfield Site and Citronelle Site Projects

Background

The U.S. Department of Energy Regional Carbon Sequestration Partnership (RCSP) Initiative consists of seven partnerships. The purpose of these partnerships is to determine the best regional approaches for permanently storing carbon dioxide (CO_2) in geologic formations. Each RCSP includes stakeholders comprised of state and local agencies, private companies, electric utilities, universities, and nonprofit organizations. These partnerships are the core of a nationwide network helping to establish the most suitable technologies, regulations, and infrastructure needs for carbon storage. The partnerships include more than 400 distinct organizations, spanning 44 states and four Canadian provinces, and are developing the framework needed to validate geologic carbon storage technologies. The RCSPs are unique in that each one is determining which of the numerous geologic carbon storage approaches are best suited for their specific regions of the country and are also identifying regulatory and infrastructure requirements needed for future commercial deployment. The RCSP Initiative is being implemented in three phases, the Characterization Phase, Validation Phase, and Development Phase. In September 2003, the Characterization Phase (2003–2005) began with the seven partnerships characterizing geologic and terrestrial opportunities for carbon storage and identifying CO_2 stationary sources within the territories of the individual RCSPs. The Validation Phase (2005–2013) focused on evaluating promising CO_2 storage opportunities through a series of small-scale field projects. Finally, the Development Phase (2008-2018+) activities are proceeding and will continue evaluating how CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically at large scales. These field projects are providing tremendous insight regarding injectivity, capacity, and containment of CO_2 in the various geologic formations identified by the partnerships. Results and assessments from these efforts will assist commercialization efforts for future carbon storage projects in North America.

The Southeast Regional Carbon Sequestration Partnership (SECARB), led by the Southern States Energy Board (SSEB), represents the 11 southeastern states of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia, and counties in Kentucky and West Virginia. SECARB is comprised of more than 100 partners and stakeholders. The partnership estimates that 33 percent of CO_2 stationary source emissions across the RCSP regions come from the SECARB states.

CONTACTS

Traci Rodosta
Carbon Storage Technology Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1345
traci.rodosta@netl.doe.gov

Bruce Brown
Project Manager
National EnergyTechnology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-5534
bruce.brown@netl.doe.gov

Kenneth Nemeth
Executive Director
Southern States Energy Board
6325 Amherst Court
Norcross, GA 30092
770-242-7712
nemeth@sseb.org

PARTNERS

Advanced Resources International
AGL Resources
Alabama Oil & Gas Board
Alawest
Alpha Natural Resources
American Coalition for Clean Coal Energy
American Electric Power
Amvest Gas Resources
Applied Geo Technologies
ARCADIS
Arch Coal
Arkansas Oil & Gas Commission
Association of American Railroads
Augusta Systems, Incorporated

U.S. DEPARTMENT OF ENERGY

PARTNERS (CONT.)

Baker Hughes Incoporated
Big Rivers Electric Corporation
Blue Source
BP America
Buchanan Energy Company of Virginia, LLC
Buckhorn Coal Company
CDX Gas, Llc
Cemex
Chevrontexaco Corporation
Clean Coal Technology Foundation of Texas
Clean Energy Systems, Inc.
Clemson University
CO_2 Capture Project
Composite Technology Corporation
CONSOL Energy, Inc.
Core Laboratories
CSX Gas
Dart Oil & Gas Corporation
Denbury Resources, Inc.
Dominion
Duke Energy
Eastern Coal Council
Edison Electric Institute
Electric Power Research Institute (Epri)
Entergy Services, Inc.
Equitable Resources
Exxon Mobile
Florida Municipal Electric Association
Florida Power & Light Company
Geological Survey Of Alabama
Geomet, Inc.
Georgia Environmental Facilities Authority
Georgia Forestry Commission
Georgia Power Company
Halliburton
Integrated Utility Services, Inc.
International Coal Group
Interstate Oil & Gas Compact Commission
Kentucky Geological Survey
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Louisiana Department of Environmental Quality
Louisiana Geological Survey
Marshall Miller & Associates
Massachusetts Institute of Technology
McJunkin Appalachian Oil Field Supply Company
Mississippi Power Company
Mississippi State University
National Coal Council
National Mining Association
Natural Resource Partners

SECARB's deep saline formations offer significant safe and permanent storage capacity for these emissions. Moreover, SECARB, along with the other RCSPs, continues to develop best practices to support the wide-scale transfer and advancement of information and technology derived from its projects.

Project Description

Project Summary

SECARB is conducting two large-volume injection field projects; one in the lower Tuscaloosa Formation (Cranfield Site, also known as the Early Test) and one in the Paluxy Formation (Citronelle Site, also known as the Anhtropogenic Test) (Figure 1). These formations are key components of a larger, regional group of similar formations, called the Gulf Coast Wedge.

Cranfield Site

The "Early Test," which was the first Development Phase field project to begin CO_2 injection operations, injected CO_2 into the lower Tuscaloosa Formation. The Early Test began injection in April 2009 at the Cranfield oilfield located east of Natchez, Mississippi after a successful Validation Phase field project that injected 627,744 metric tons of CO_2 into the Tuscaloosa at the same site. For the Development Phase, the Early Test injected a total of 4,743,898 metric tons through January 2015, at which time SECARB ended its monitoring activities of the injection. However, Denbury Resources, Inc. continues CO_2 injection operations at the site as part of their ongoing oil recovery operations.

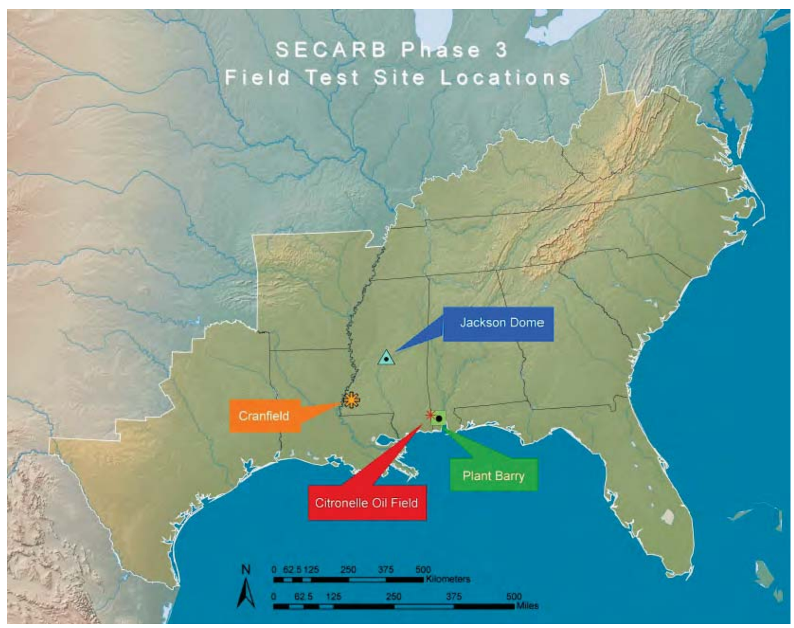

Figure 1 - Location of Early Test and Anthropogenic Test

Citronelle Site

The "Anthropogenic Test," is the second field project and it injected a total of 114,104 metric tons of CO_2 into the Paluxy Formation. Injection operations ceased on September 1, 2014 and post injection monitoring operations are ongoing. The CO_2 was supplied by a pilot unit capturing CO_2 from flue gas produced from a Southern Company's coal fired facility, Plant Berry in Bucks, Alabama and transported 12 miles by pipeline to the Citronelle Field injection site.

Description of Geology

Cranfield Site

The lower Tuscaloosa Formation is one of the named stacked sandstone formations of the Gulf Coast Wedge. It is a Cretaceous-age, sandstone saline formation that occurs in the subsurface along the Gulf of Mexico Coastal Plain from western Florida to Texas (where it is defined as the Woodbine Formation). The Tuscaloosa Formation contains an upper section of alternating shales and sands and a basal section, the Massive Sand Unit, which contains a thick layer of clean, coarse-grained sand. The formation was deposited during a major period of global sea level rise, and its deposition has been interpreted as an upward gradation from fluvial and deltaic sedimentation (the Massive Sand) to shelf deposition (alternating sands and shales). The reservoir is in the lower Tuscaloosa, above a regional unconformity, in valley-fill-fluvial conglomerates and sandstones separated by alluvial and overbank within-unit seals. The reservoir is composed of stacked and incised channel fills and is highly heterogeneous, with flow unit average porosities of 25 percent and permeability averaging 50 millidarcy (mD), ranging to a Darcy (D). Chlorite is the major cement in these relatively immature sediments. The well-sorted, clean, coarse-grained nature of the Massive Sand, a result of this environment, makes it an ideal candidate for CO_2 injection due to its high permeability and porosity. As the sea level continued to rise, the valley-fill depositional environment gave way to a deep marine environment, during which the overlying middle (Marine) Tuscaloosa Formation was deposited. This formation consists of about 500 feet of low-permeability shale, providing an excellent confining zone for CO_2 injection into the lower Tuscaloosa Formation (Figure 2).

Shale is also found in the lower portion of the Tuscaloosa Formation acting as a barrier to the vertical migration of sandy substrates. Deposition that occurred during the early Cretaceous Period was based on a cycle of marine and delta sedimentation and deposition. The high porosity and permeability of the sandstones in the region are due to the cycles of deposition throughout time.

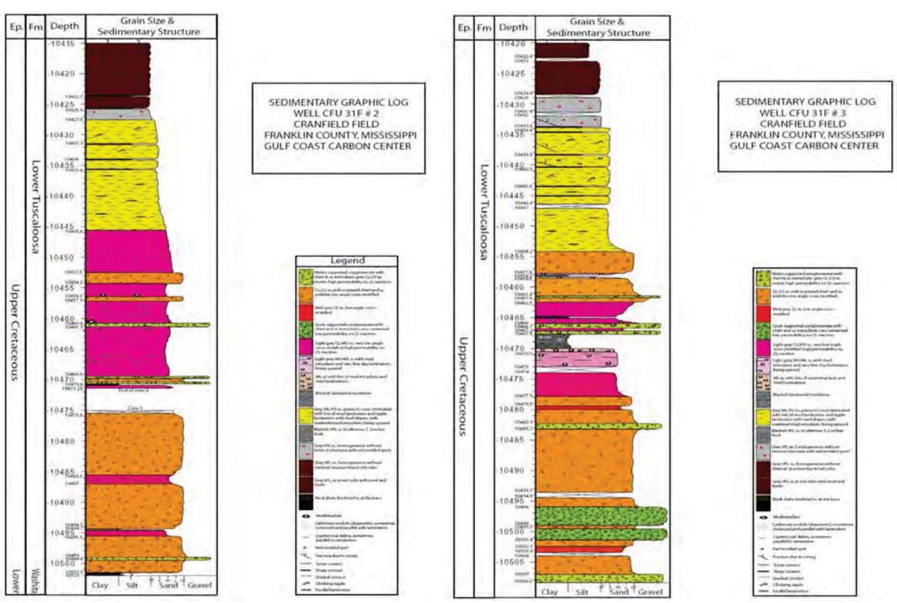

Figure 2 - Stratigraphy present at the Cranfield (Early Test) site. Image provides a comparison of the graphic core logs of the observation wells, CFU 31F-2 and CFU 31F-3, provides a visual representation of the heterogeneous reservoir. Courtesy of the Gulf Coast Carbon Center.

PARTNERS (CONT.)

Norfolk Southern
North American Coal Corporation
North Carolina State Energy Office
Nuclear Energy Institute
Oak Ridge National Laboratory
Old Dominion Electric Cooperative
Peabody Energy
Penn Virginia Corporation
Phillips Group, The
Pine Mountain Oil & Gas, Inc.
Pocahontas Land Corporation
Powell River Project
Praxair
Progress Energy
QEA, LLC
Rentech, Inc.
RMB Earth Science Consultants
RMS Strategies
SCANA Energy
Schlumberger
Shell Oil Company
Smith Energy
South Carolina Department of Agriculture
South Carolina Electric & Gas Company
South Carolina Public Service Authority/Santee Cooper
Southern Company
Southern Natural Gas/El Paso
Southern States Energy Board
Susan Rice and Associates, Inc.
Tampa Electric Company
Tennessee Valley Authority
Texas Bureau of Economic Geology
TXU Corporation (Luminant Energy)
United Company, The
University of Alabama
University of British Columbia
Virginia Center for Coal and Energy Research
Virginia Department of Mines, Minerals, and Energy
Walden Consulting
Winrock International

PROJECT DURATION

Start Date	**End Date**
09/22/2007	09/30/2017

COST

Total Project Value
$93,689,241

DOE/Non-DOE Share
$64,949,078 / $28,740,163

AWARD NUMBER

FC26-05NT-42590

Citronelle Site

The injection horizon is the Lower Cretaceous-age Paluxy Formation. The Paluxy is a 1,150 feet thick package of sand, silt and shale strata, which occurs at a depth of about 9,800 feet at the project site. The porous and permeable sands of the Paluxy Formation represent a typical fluvial deposition reservoir in terms of their areal extent and petrophysical characteristics. There are approximately 475 feet of net sand in the Paluxy Formation, which occurs in over 20 sand units that range in thickness from 9 to 80 feet. The Paluxy appears to contain a mix of continental, fluvial and marginal marine deposits. Relationships between sand units within the formation are complex. A detailed mapping and petrophysical assessment of the Paluxy Formation suggests that average sand porosity is 19% and average permeability ranges from 30 to 90 millidarcies. Several of the Paluxy sand units appear to be laterally extensive, and are targeted as the injection zones for the Anthropogenic Test.

Following this deposition was another marine transgression, which deposited the shales, limestones, and sandstones that are known as the Washita-Fredericksburg Shale. This shale would be the primary confining zone for carbon dioxide stored in the Paluxy Formation. The shale appears to possess the appropriate criteria (lateral continuity, low permeability) to act as an effective CO_2 seal. In addition to the basal Washita-Fredericksburg shale, there are secondary overlying confining units including the Middle (Marine) Tuscaloosa Formation, the Selma Group, and the Midway Shale, which occur stratigraphically between the injection zone and the base of the lowermost underground source of drinking water (USDW). As such, a vertical interval of over 8,000 feet with numerous low permeability barriers occurs between the proposed CO_2 injection zone and the base of the lowermost USDW.

Injection Operations

Injections were designed to occur at a scale sufficient to successfully address issues of injection rate and cumulative injection impacts that may be factors in the design of future large-scale, commercial carbon storage deployments.

Cranfield Site

This project was focused on the down dip "water leg" of the Cranfield Unit, operated by Denbury Resources, Inc. The area selected for the Early Test is immediately north of SECARB's Validation Phase "Stacked Storage" study in the Cranfield oil field near Natchez. The stacked storage injection field project had its operations carried over to the Development Phase Early Test. During injection operations, CO_2 from Jackson Dome was supplied to the Cranfield Site via pipeline and delivered to the center of Cranfield where the CO_2 is accurately measured at the purchase pump.

Injection initiation was phased across the field. Injection began in the "High Volume Injection Test" (HiVIT) in a few wells in 2008 as part of the Validation Phase field project. The 1 million metric tons per year rate was obtained in December 2009 when the Detailed Area of Study (DAS) well injection rate was stepped up (Figure 3). The 1.5 million metric tons stored goal was reached in early 2011. By the completion of project injection activities in January 2015, a total of 4,743,898 metric tons had been injected and stored.

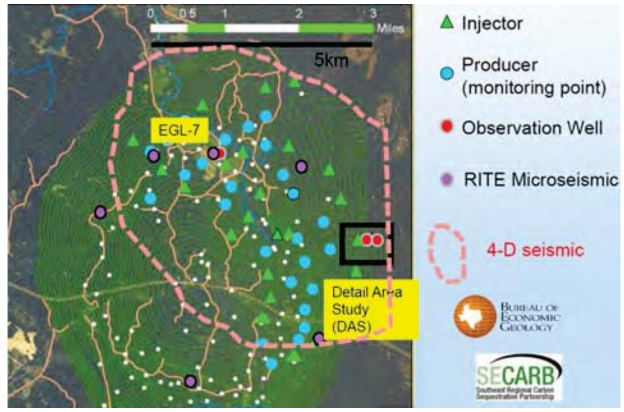

Figure 3 - Map showing the DAS at Cranfield

Citronelle Site

This project was conducted approximately 12 miles northwest of Southern Company's Plant Barry in a saline formation within the Citronelle Oil Field in Mobile County, Alabama. The CO_2 was captured, dehydrated, and compressed to approximately 2,000 pounds per square inch gauge (psig). It was transported over a short distance (~12 miles) via 4-inch carbon steel pipe to the injection site at Citronelle, Alabama (Figure 4). Three wells were drilled for the project—a reservoir characterization well, a characterization/observation/ backup injection well, and a dedicated CO_2 injection well. Drilling operations on the characterization well began in December 2010, with the remaining wells drilled in late 2011 and early 2012. In addition to these wells, the project utilized several existing oilfield wells surrounding the CO_2 injection site to monitor injection operations and to ensure public safety. By completion of the injection portion of the project in January 2015, a total of 114,104 metric tons were injected and safely stored at the site.

Figure 4 - Construction of the CO_2 pipeline for the Plant Barry Site.

Source of CO_2

Cranfield Site

The naturally occurring CO_2 for the Early Test will be provided by Denbury Resources' CO_2 pipeline from the Jackson Dome near Jackson, Mississippi. The source is commercially available, high purity, highly reliable, and low cost.

Citronelle Site

The CO_2 for the Anthropogenic Test was supplied from a pilot unit capturing CO_2 from flue gas using amine capture technology from a 25 megawatt (MW) slipstream of Southern Company's Plant Barry power plant. The pilot unit had a CO_2 removal efficiency of 90 percent and was capable of producing 100,000 to 150,000 metric tons of CO_2 per year. At the time of operation, the project was recognized as the largest integrated CO_2 capture and injection project on a coal-fired power plant in the United States.

Simulation and Monitoring of CO_2

SECARB adhered to a vigorous monitoring, verification, accounting (MVA) and assessment program during the Development Phase project. Each site was instrumented with multiple sensor arrays.

For the Early Test, the project team employed numerous monitoring techniques, including a first deployment of pressure surveillance in the above-zone monitoring interval to collect data on the performance of the lower part of the confining system. Soil gas and groundwater were monitored field wide and a detailed assessment of soil gas was conducted at the P-site (a near-surface laboratory to study a plugged and abandoned [P&A] well, well pad, historic fluid disposal pit, and natural plant activity). The project team is assessing the effectiveness of groundwater monitoring as a field-wide detection tool. Additional field-wide monitoring includes time-lapse 3-D seismic survey, a six-well microseismic array fielded by the Research Institute of Innovative Technology for the Earth (RITE) of Japan, and commercial production data provides important calibration points for the modeling. The 3-D seismic survey was interpreted to show CO_2 accumulation and has been used to add confidence in the fluid flow model. No indication of release to shallower zones was found on the time-lapse, 3-D seismic survey. No microseismicity related to CO_2 injection was detected at the site as part of the RITE study. The Early Test employed an integrated simulation and modeling program to develop interpretable and significant research results from monitoring the CO_2 flood. The integrated program began with characterization and extends through several types of predictive modeling, including monitoring planning, monitoring modification in response to improved data, and monitoring long-term injection. This iterative process requires integration of expertise from various disciplines. It is important to use modeling to assess uncertainties that result from each data collection effort, including the syn- and post-injection monitoring, and focus data collection on reducing uncertainties.

For the Anthropogenic Test, ten existing MVA tools are deployed. These include CO_2 composition, CO_2 volume, tracers introduced in the CO_2 stream, bottom-hole pressure, pulsed neutron logs (CO_2 saturation), time-lapse crosswell seismic imaging and vertical seismic profiling (wellbore deployed), injection temperature and spinner logs, above-zone pressure and fluid monitoring, soil gas flux, and drinking water aquifer monitoring. To help predict plume movement and assess the ultimate fate of the injected CO_2, the project team utilized GEM-GHG simulation software. The GEM-GHG reservoir flow simulator, for instance, was employed to model subsurface CO_2 injection into the injection zone. GEM-GHG is a robust, equation-of-state, fully compositional reservoir simulator for modeling the flow of three-phase, multi-component fluids. The simulator includes the capability of modeling CO_2 (and other gases) injection in parallel with comprehensive CO_2 trapping, including residual gas trapping via relative permeability hysteresis, CO_2 dissolution in the aqueous phase and intra-aqueous reactions, mineral dissolution, and precipitation.

Goals and Objectives

The primary objective of the DOE's Storage Program is to develop technologies to safely and permanently store CO_2 and reduce emissions without adversely affecting energy use or hindering economic growth. The Programmatic goals of Carbon Storage research are: (1) develop and validate technologies to ensure for 99 percent storage permanence; (2) develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness; (3) support industry's ability to predict CO_2 storage capacity in geologic formations to within 30 percent; and (4) developing Best Practices Manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation. SECARB's overall goal is to validate the efforts of the public outreach, research, and field activities implemented under the Characterization and Validation Phases. Specific objectives include:

- Conducting a large-volume, high-pressure injection field project that benefits from existing CO_2 infrastructure and reasonable CO_2 costs.
- Assessing the viability and logistics of injecting over 1 million metric tons of CO_2 per year into a regionally significant saline formation in the Gulf Coast.
- Achieving a more thorough understanding of the science, technology, regulatory framework, risk factors, and public opinion issues associated with large-scale injection operations.
- Executing a geologic storage field project that covers all aspects of capture, separation, and storage, while fulfilling technical, regulatory, social, and economic considerations.
- Refining capacity estimates of the formation using results of the field project.

Accomplishments to Date

Cranfield Site

The active injection portion of the Early Test were completed on January 31, 2015, though post injection monitoring operations continue In addition to public outreach and knowledge sharing, ongoing efforts include data compilation, interpretation, intensive modeling, compilation of lessons learned, and application to next projects as well as long term pressure and soil gas, groundwater, and reservoir geochemistry.

- SECARB injection into brine leg below and east of oil-water contact started in November 2009 and concluded field work on January 31, 2015. During that time, they successfully injected, stored, tracked, and monitored 4,743,898 metric tons of CO_2.
- High frequency real-time CO_2 mass, bottom-hole injection well pressure, and temperature were continuously monitored.
- High frequency real-time observation well parameters were on-going for the duration of the project. Observations included bottom-hole pressure and temperature at the injection zone (before instrument failure), tubing pressure, and temperature at surface, casing pressure and temperatures, casing deployed bottom-hole pressure and temperature at the above-zone monitoring interval (AZMI).
- On-going casing-deployed cross-well Electrical Resistance Tomography detects strong changes in conductivity believed to be attributed to replacement of brine by CO_2.
- Natural and introduced geochemical program with U-tube sampler was implemented to observe evolving flow field as plume matured and injection rate increased. Methane exsolved as CO_2 dissolved, which is an important indicator of CO_2-brine contact and dissolution. CO_2 developed preferred non-radial flow paths following sinuous channels.
- Performed repeat cross-well seismic tomography in a three-well array to image lateral variability in the plume.
- Performed repeat offset and walk-away VSP surveys, as well as 3D VSP surveys.
- Plugged and abandoned injection and monitoring wells used during the project.
- Performed extensive simulations of the injection and history matched results with actual field data to produce best match simulations for oil production, water production, and gas production. Additionally, 4D seismic results were comparable to fluid flow simulation results.
- Performed a regional scale reactive transport model of the injection to assess impacts of CO_2 leakage on groundwater chemistry and to monitor network efficiency. The findings are summarized as follows:
  - No obvious degradation in groundwater quality (except degradation in pH) if only CO_2 is leaked. Salinization would be problematic if brine+CO_2 are leaked.
  - Dissolved CO_2 appears to be a better indicator than dissolved organic content, pH, and alkalinity for CO_2 leakage detection at the CO_2-EOR site, however, this is dependent on regional hydraulic gradient, leakage rate.
  - Monitoring network efficiency depends on regional hydraulic gradient, leakage rate, flow direction, and also aquifer heterogeneity. Impact of dispersion coefficient could be neglected.
  - The existing groundwater wells can monitor CO_2 leakage from up to 60 P&A wells and MN8, the ideal monitoring network which consists of 35 water wells can detect CO_2 leakage from almost all P&A wells.
  - Site characterization, lab experiments, single-well particle plugging tests (PPTs), and reverse time migration (RTM) imaging could provide enough information for a risk assessment.

Citronelle Site

- The project, in collaboration with Southern Company, successfully installed and operated a post-combustion CO_2 capture facility at Plant Barry. Capture operations commenced on June 3, 2011 and a total of 240,000 tons of CO_2 were successfully captured.
- Successfully designed, constructed, and maintained the 12 mile pipeline used to transport the CO_2 from Plant Barry to the injection well.
- Characterized the Citronelle Field prior to the injection operations. A major geologic characterization effort was conducted on the injection reservoir (9,400 ft. deep saline Paluxy formation) and associated confining units using existing well data. Detailed maps of the Paluxy Reservoir sand units and multiple overlying confining units were created.
- Performed a crosswell seismic survey in June 2014 that successfully captured a time-lapse image of the CO_2 plume.
- Ongoing monitoring of the CO_2 plume using soil CO_2 flux, tracer monitoring, vertical seismic profiling, crosswell seismic, pressure monitoring, and pulsed neutron capture logging indicate that the CO_2 is contained.
- Entered the 3 year post injection phase monitoring effort that will be completed in September 2017. There has been no evidence of release or endangerment of USDWs.

Bene its

The Lower Tuscaloosa Formation, which is representative of the Gulf Coast geology, has been identified as one of the largest known potential carbon storage reservoirs. , could be used to store 50 percent of the CO_2 produced in the SECARB region during the next 100 years - an estimated 50 billion metric tons. The Gulf Coast Wedge includes the largest saline storage reservoir (in terms of extent and capacity) for the SECARB region, as well as the United States. Annual stationary point source emissions of CO_2 have been estimated to be 1 billion metric tons. Using the ranges of reported capacity, the Gulf Coast Wedge can accommodate these emissions for approximately 300 to nearly 1,200 years, using capture and storage technologies. These volumes are sufficient to support commercialization of this CO_2 storage reservoir and demonstrate that CO_2 capture and storage is a viable option.