

PIF: SECARB early test

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PROJECT INFORMATION FORM

1. PROJECT IDENTIFICATION	
Project Number	FC26-05NT42590
Project Title	Southeast Regional Carbon Sequestration Partnership - Phase III
Performer	Southern States Energy Board

2. PROJECT POINT OF CONTACT INFORMATION		
	DOE / NETL PROJECT MANAGER	PRINCIPLE INVESTIGATOR
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3. FIELD TEST INFORMATION	
Field Test Name	SECARB Early Test
Location	Cranfield Unit, near Natchez, Mississippi
Amount of CO₂	1.5 million tonnes over 1.5 years
Source of CO₂	Jackson Dome, near Jackson, Mississippi (Natural Source)

4. FIELD TEST RESEARCH TEAM	
1.	Test lead: Gulf Coast Carbon Center (GCCC), Bureau of Economic Geology, The University of Texas at Austin
2.	Denbury Onshore LLC.– Site Host and CO ₂ Source, 3-D seismic
3.	Sandia Technologies - Field service provider, engineering lead and HS&E at experiment site
4.	Lawrence Berkeley National Laboratory (LBNL) – Borehole Seismic, Noble Gas Tracers, U-tube field lab, modeling
5.	Lawrence Livermore National Laboratory (LLNL) – Stochastic Engine and Cross-well Electrical Resistance Tomography (ERT), modeling
6.	University of Mississippi – Groundwater monitoring and hydrogeology
7.	Mississippi State University - Groundwater geochemistry
8.	USGS Menlo Park, CA and Jackson MS, Reservoir fluid geochemistry
9.	Schlumberger Carbon Services – Logging, Cross-well seismic
10.	Oak Ridge National Laboratory National Laboratory (ORNL) Natural and introduced tracers
11.	Scottish Centre for CCS, noble gases geochemistry
12.	National Risk Assessment Partnership (NRAP) 3D VSP and 3D surface assessment, coupled ERT/seismic crosswell inversion
13.	Center for Frontiers of Subsurface Energy Security (CFSES) Advanced modeling
14.	BP – time lapse borehole gravity

5. PHASE III PROJECT COST			6. KEY PROJECT DATES	
	Dollars	Percent	Baseline Completed	9/2008 - 11/2010 (phased in five test areas)
DOE Share	\$34,186,226	59.53%	Drilling Operations Begin	4/2008 first new drill well 8/2009 DAS wells drilled (phased, 14 injection wells)

Southeast Regional Carbon Sequestration Partnership Phase III Early Test

5. PHASE III PROJECT COST			6. KEY PROJECT DATES	
Non-DOE Share	\$23,240,580	40.47%	Injection Operations Begin	10/2008 in area 12/2009 DAS injection
Total Value	\$57,426,806*		MVA Events	4/2009 - 12/2010
Expenditures as of 12/31/2010	\$37,796,045		Injection Operations End	2/2011 propose reduce DOE spend on CO ₂

*Does not include the Anthropogenic Test, continued characterization (Task 1), offshore study (Task 15), or regional activities (outreach, project assessment, project management).

7. BUDGET PERIODS			
(to add additional budget periods, press the tab key at the end of the last row)			
Period Number	Start Date	End Date	Cost
3 (FY08)	10/1/2007	12/31/2008	\$10,817,600
4 (FY09-FY14)	1/1/2009	9/30/2014	\$46,125,174
5 (FY15-FY17)	10/1/2014	9/30/2017	\$484,032

8. PRIMARY PROJECT GOAL
The two Southeast Regional Carbon Sequestration Partnership (SECARB) Phase III projects share a common goal of safely demonstrating large-scale, long-term CO ₂ injection and storage in saline reservoirs that hold significant promise for future development within the SECARB region. The program includes two field projects, the Early Test and the Anthropogenic Test; the continued characterization of regional sequestration opportunities; and a preliminary evaluation of offshore transportation and storage of CO ₂ .

9. RESEARCH OBJECTIVES
<p>The SECARB Early Test has developed a set of technology transfer objectives and a set of research-oriented objectives. The technology transfer is making available substantive experience in this region to future operators who will undertake integrated CO₂ capture and sequestration (CCS) projects in the region, U.S., and internationally. The knowledge sharing aspect of the project is significant because (1) the injection technology (CO₂ without water injection into high permeability rocks) is immediately relevant to CCS; and (2) surface monitoring opportunities in this high temperature, high rainfall area, without a dormant season, are different than those tested elsewhere and significant to other potential CCS sites worldwide. The research-oriented objectives are designed to take advantage of the opportunities of this site, augment observations made elsewhere, and move the maturity of geologic storage forward systematically. The three main areas of research focus are described below.</p> <ol style="list-style-type: none"> 1. <i>Predicting pressure response in the far-field (single brine phase) to injection rate.</i> This critical parameter is one of the novel elements of geologic storage, in that the environmental risk is related to the area of elevated pressure, as well as to the area underlain by the CO₂. Gas storage, enhanced oil recovery (EOR), and Underground Injection Control (UIC) provide little data to validate the pressure response at a relevant scale. In gas storage and EOR, injection is balanced at high frequency by withdrawal, while in UIC the injection rates are generally low relative to capacity and history-match has not been attempted. The magnitude and size of the area of elevated pressure are related to thickness, permeability, and storativity. Storativity includes rock and fluid compression and dilatancy. The relevant thickness is complicated by slow but significant flow of brine through fine-grained components of the system. In this test, the team has quantified the relationships between pressure in the single phase, two-phase flow, and injection rate under relatively well-described reservoir conditions. 2. <i>Constraining the relationship between heterogeneous flow-units and buoyant two-phase flow.</i> This complex relationship is one of the keys to assessing the “footprint” of the CO₂ plume resulting from a given injection volume. At the Frio Brine injection project, the Gulf Coast Carbon Center collected a

first assessment at relatively low injection rates, simulating the far-field condition. In the SECARB Early Test, GCCC has tested similar rocks under high injection rates with a similar tool set to collect another high quality data set. The data are being used to validate this important predictive capability.

3. *Exploring the performance of novel tool arrays.* The Early Test team collected data from acoustic and resistivity cross-well arrays to compare tool response to changing saturation and to explore both the spatial and temporal measurement precisions of these tools. The team is assessing a suite of aquifer and soil-gas techniques to determine what is useful under conditions of thick vadose zone and high natural CO₂ flux (warm, no fallow season, and wet) and in the presence of infrastructure like well pads and mud pits.

10. SUMMARY OF FIELD TEST SITE AND OPERATIONS

1. Geology, target formations, and known seals that will contain the CO₂.

The site at which the SECARB Early Test was conducted is the Cranfield Unit near Natchez, Mississippi with focus on the down-dip water leg (Figure 1). This field is an anticlinal four-way closure at a depth of 3,000 meters (m) discovered in 1943. 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) (Table 1). Chlorite is the major cement in these relatively immature sediments. The lowest element of the regional confining system is the thick marine mudstone portion of the middle Tuscaloosa (Figure 2); this is overlain by numerous confining beds. The upper-most confining unit is the thick mudrocks of the Midway Formation, below the Wilcox productive reservoir. Confining system efficacy is demonstrated by hydrocarbon accumulation (methane cap and oil rim). The field was produced to sub-economic water-cut by recycled gas drive. Then the gas was produced to economic limit, and all wells were plugged and abandoned (P&A) in 1965. A strong aquifer drive is documented by return to hydrostatic pressure prior to resumption of production in late 2008. Mineral rights were purchased by Denbury Onshore Resources LLC. New injectors with modern logs and cores and a pre-injection three-dimensional (3-D) seismic survey were completed in preparation for a new carbon dioxide-enhanced oil recovery (EOR) flood under gas drive (no water injection) with gas lift (no pumping), creating the favorable data-dense experimental setting for measuring pressure response to a large volume CO₂ injection.

Five test areas shown on **Figure 1** were matched to specific monitoring goals over optimized timeframes.

2. Consideration of potential leakage points such as faults, fractures, and existing borehole penetrations.

A detailed quantitative leakage risk assessment has been completed using the Certification Framework (Nicot and others, in review, 2011). Excerpts of this work are summarized here. Significant uncertainties that could lead to leakage risk are identified as focus areas for monitoring technique development. Leakage risk through the confining system is assessed as de minimus. The continuity and high capillary entry pressure of the base of the confining system is demonstrated by accumulation of commercial volumes of methane, and further confirmed by mapping stratigraphic continuity of thick zones of the lower part of the confining system of the middle Tuscaloosa Formation through wireline log correlation, seismic interpretation, and collection of a 20 ft core which was subjected to capillary entry pressure analysis (Lu and others, 2010).

The 3-D seismic survey shows that an elliptical fault forming an anticline crest graben displaces the injection zone on the northeast and southwest sides of the field. The northern limb bounds the western edge of the HiVIT. Separate initial gas/oil interfaces, production data, and pressure monitoring document that the fault is horizontally sealing. 3-D seismic interpretation shows that displacement dies out vertically

in the Midway Formation, the upper part of the confining system. Gas retention documents no vertical flow, and geotechnical modeling guided by well-breakout observations suggests that the current maximum horizontal stress tends to close the fault and pressure increase resulting from injection will not result in fault opening. A monitoring program was designed to test this assumption (GMT area in Figure 1), but it was unsuccessful because of instrument instability at high temperatures.

Fifteen injection wells have been constructed by Denbury in the HiVIT. Four of these are completed below the oil-water contact into the “water leg” to support the project goals. Three water leg wells were directionally drilled; the one at the DAS was vertical. There is little concern about well performance or leakage of these new wells, which were constructed to current Mississippi Oil and Gas Board standards and have cement bond logs to demonstrate cement integrity. Two new wells were drilled at the DAS to serve as observation wells for that experiment. These wells were constructed with extensive instrumentation on the casing that has potential to weaken cement bond or convey fluids up through the wirelines. Engineering solutions were designed to isolate the injection zone and a distributed temperature system installed to test the design effectiveness.

The risk assessment found that vintage wells are the only significant leakage risk. Note that management of this risk is the responsibility of the operator under State law. In the HiVIT area, there are a total of seventeen 1945-1950 vintage wells completed in the injection interval. Ten of the wells have been reentered, reworked, and used by Denbury as producers; the other wells have been left in 1965 P&A conditions. Re-entered wells throughout the field were found to be plugged and abandoned as shown on the P&A reports with multiple cement plugs and drilling mud. Pressure surveillance in the above-zone monitoring interval (AZMI) is deployed in both Phase II and the DAS (Phase III) to collect data on the lower part of the confining system. Soil gas and groundwater monitoring are being used at the P-site test to monitor a methane anomaly at a P&A well that was then reentered. Field-wide, we are assessing the effectiveness of groundwater monitoring as a well leakage-detection tool.

3. Physical information.

Supercritical CO₂ moved quickly through these high permeability sandstones so that a near-steady-state condition in CO₂ existed. Pressure and adequate data for model matching has been obtained during the observation period. Reservoir heterogeneity is a key uncertainty influence CO₂ migration, therefore effort is put into reducing this uncertainty through data collection and stochastic modeling. Physical properties are provided in **Table 1**.

4. Surface location.

The surface setting of the Early Test is deeply dissected uplands with a thick loess cover. The project activities were performed in a 10 km² area in the north-east quadrant of the Cranfield unit lease known as the HiVIT (Figure 1). The town is approximately 16 miles east of Natchez, Mississippi. The area is rural and accessible via U.S. Highway 84 to the south and U.S.

Highway 61 to the north. The nearest public lands are Natchez State Park to the northwest and Homchitto National Forest to the south. Both of these areas are isolated from the study area by the undeveloped, wooded, private lands of the Cranfield unit. The employment and labor mix in the vicinity of the project

Thickness	0-15 m “D” Sandstone CFU 29-10 well
Porosity	20-30%
Permeability	1 to 1000 mD plugs Hydrologic tests 4.1 to 159.1 mD
Salinity	155 mg/L 161,000 mS/cm Density 1.1 g/cc
Depth	3106 m
Pressure	304 bar
Temperature	126 degrees C
Dip	1.7 degrees

Table 1. Physical Information, Early Test Site

site is consistent with rural agriculture, sand and gravel production, forestry, and oilfield-based economies. Public support has been assured through professional landman activities; local property owners receive significant financial incentives for site access and share in the profit from EOR. The DAS site for example is owned by a timber company, and the project purchases timber and leases the well pad site.

5. Injection operation.

CO₂ from Jackson Dome is supplied to the Cranfield unit via pipeline and delivered to the center of Cranfield where the CO₂ is accurately measured at the purchase pump. Injection pressure is boosted to a constant 2,900 psi and the CO₂ distributed across the field via a buried pipeline system. Injection volumes and pressure is measured several times daily at each wellhead. Injection initiation was phased across the field and in the HiVIT. Volumes injected down dip which would normally be used to support to the EOR flood were boosted to obtain project metrics. Injection began in the HiVIT in a few wells in 2008, and the 1 million tonne/year rate for the HiVIT was obtained in December 2009 when the DAS well injection rate was stepped up. The 1.5 million tonnes stored goal was reached in early 2011. Recycle volumes have increased creating a quasi-steady state, although make up volumes will cause the volume stored to increase. Beyond SECARB/DOE-funded injection, the wells likely will continue to be operated by Denbury for pressure support at a reduced rate of injection.

6. Target Formation Characterization.

Extensive reservoir characterization was available at the start of the study and was greatly augmented during the study by collection of extensive log suites two reservoir cores and one mudrock core, which have undergone in-depth petrographic and petrologic analysis to provide information for modeling input. The 3-D seismic volume was assessed by stratal slicing to extract maximal information on facies continuity; work continues to improve geostatistical inputs into the model.

During early planning for injection, the risk that the lower Tuscaloosa would accept the planned volumes of CO₂ were low. Previous production history and a 3-D seismic survey documenting the extent of the target sandbody throughout the HiVIT were promising. A minimum of four wells were projected to accept the 1 million tonne/year rate. High stratigraphic complexity, at a level below resolution of available tools, is a limit on the deterministic mapping of heterogeneity. Pinch-outs of sandbodies into channel margins, as well as clay-filled channels, are mapped as possible flow-barriers, therefore, the possibility that some wells would not accept the planned rate was considered. The HiVIT and cost match plan was made large enough to accommodate eight injection wells if needed. Test results show that the injection rate is limited to ¼ million metric tonnes/well by injection tubing diameter and field pressure. Higher injection was not attempted because of limited CO₂ availability and cost vs. benefit of additional compression.

7. Figures.

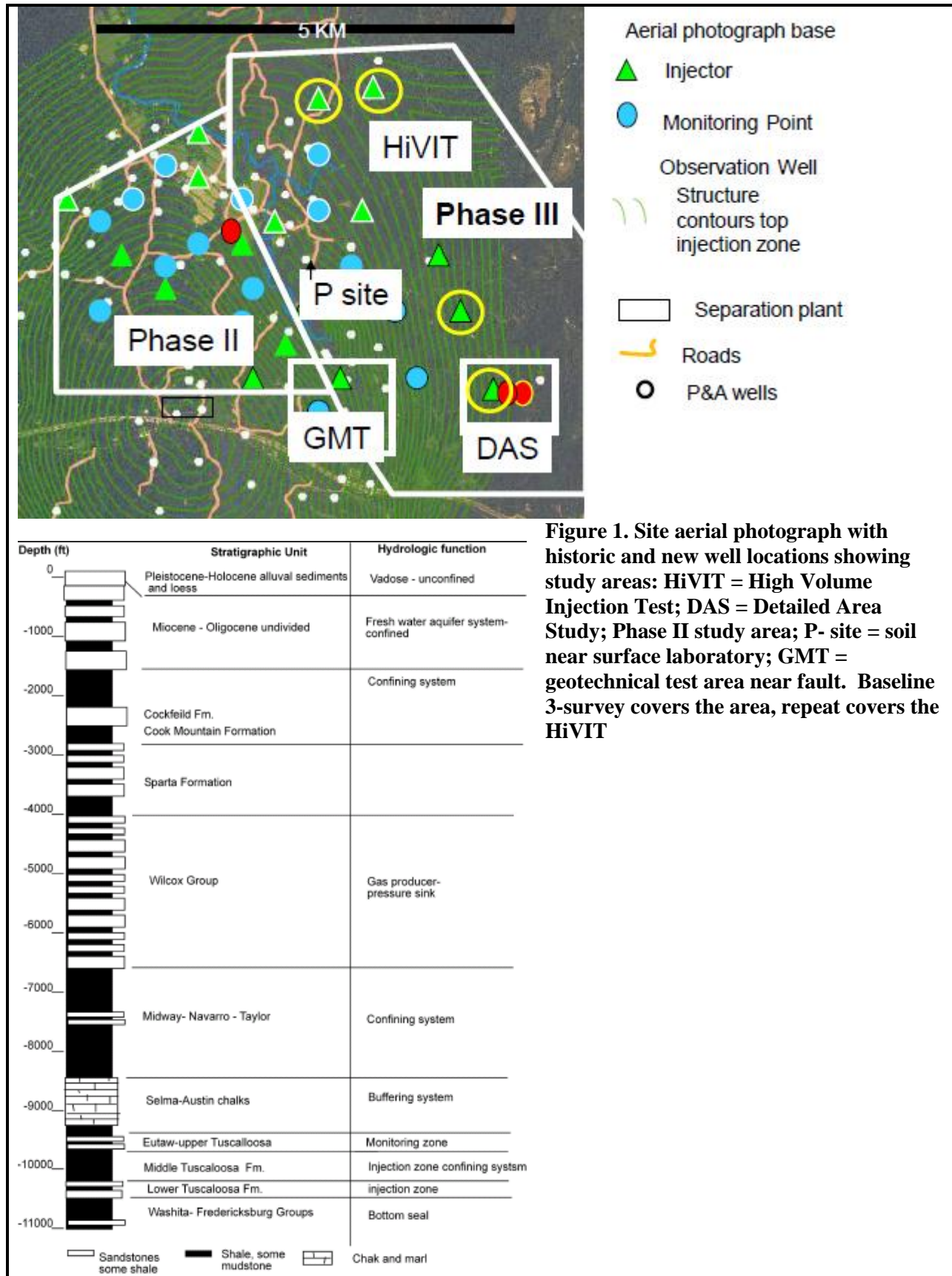


Figure 1. (left) General geologic stratigraphic column showing potential target formation, seals, and underground drinking water sources.

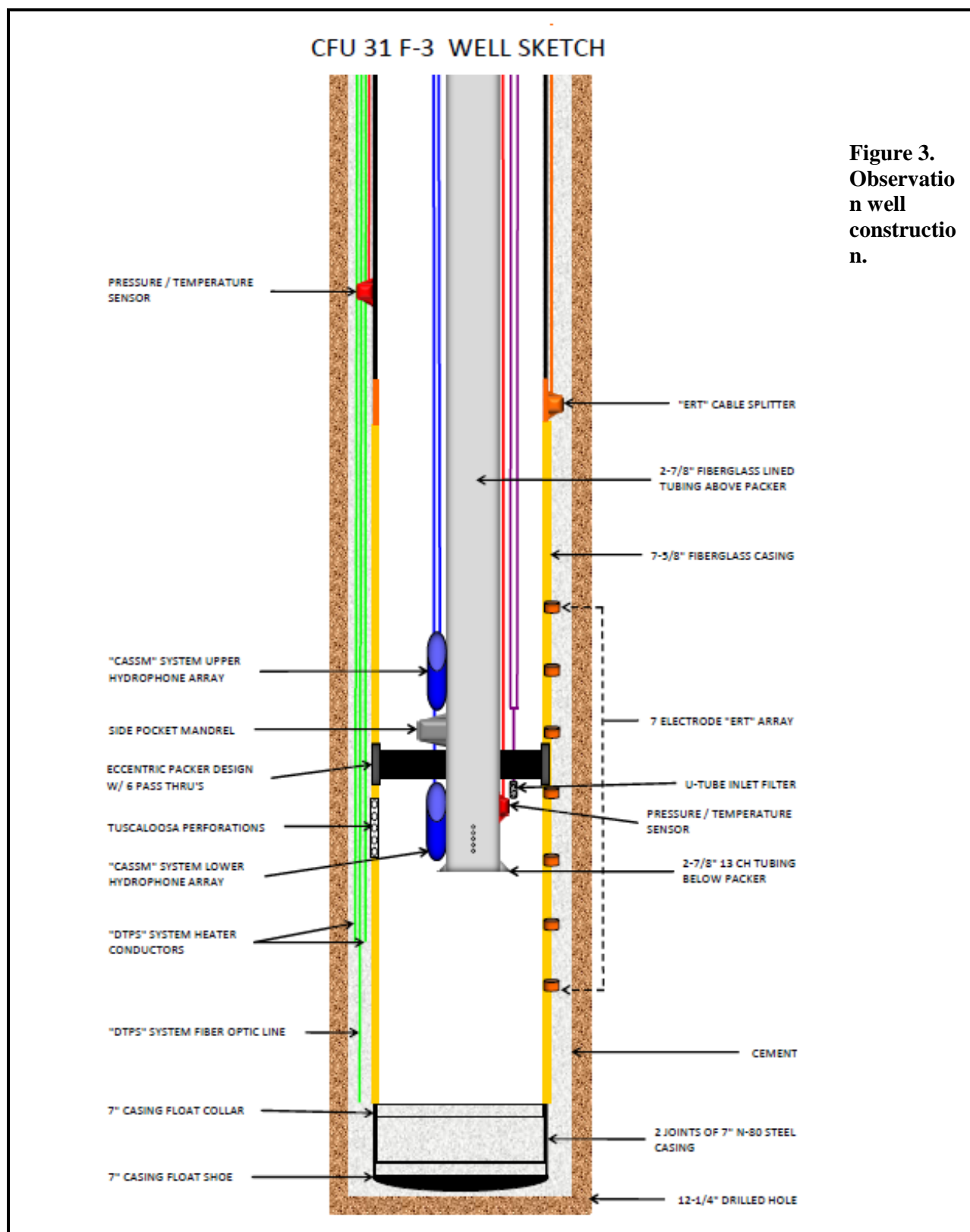


Figure 3.
Observation well construction.

11. SUMMARY OF MODELING AND MVA EFFORTS

- Characterization is recognized as the cornerstone of monitoring and modeling, and the team has invested heavily in wireline logs, core analysis of key reservoir and confining intervals, fluid sampling, hydrologic testing, and extensive and diverse laboratory follow-up. A quantitative static geocellular model has been constructed in Petrel and input into GEM-CO₂ for assessment of multiphase flow in the Phase II and the HiVIT.
- A year of design discussions guided selection of the monitoring program. The monitoring approach focused on the advancing research-oriented objectives (listed above) and balanced the opportunities and uncertainties presented by this site with cost, value, and risk of research success. The team recognized that this is one of a series of tests conducted internationally and in the US, which allowed us to focus heavily on method development and scientific objectives, because of the relatively high security offered by this site and operator. The project team selected three focus areas: the DAS to examine multiphase fluid flow and pressure at the interwell scale; the P site to experiment with effective near surface monitoring strategies at a P&A well site; and the GMT to look at sub-fracture stress near a non-trans missive fault.
- Injection rate was measured as primary signal. At the DAS, two observation wells, arrayed as a transect toward the down-dip plume edge, sampled a segment through the evolving pressure field and plume. Injection rates were stepped during the 18 month monitoring period to provide an opportunity to measure pressure response. The pressure response was linked to other metrics, especially introduced tracers. Time-lapse difference from baseline was used as a primary tool. Bottom-hole pressure on wireline is the major signal. Redundancy proved valuable, as tool durability was variable. Real-time output for the array controlled the timing of monitoring. U-tube sampling was used for high frequency tracer chromatography (PFT, SF₆, noble gasses and natural tracers) and fluid and gas phase geochemistry. Cross-well tools include repeat cross-well tomography, continuous active source seismic monitoring (CASSM) and real-time cross-well electrical resistance tomography (ERT). Offset and walk away VSP was conducted in time lapse mode and a single 3-D VSP was coordinated with repeat 3-D surface survey over the HiVIT. Fiber-optic distributed temperature sensing (DTS) was installed on the casing in one observation well and the tubing of the other. Extension of DTS to distributed temperature perturbation sensing (DTPS) using heating pulses was installed but failed due to electrical shorting of the heater cable. Surface seismometers were installed to test sensitivity to microseismic but had too much industrial noise to be useful. Time-lapse borehole gravity measurement was deployed using wireline in two wells, as well as more standard wireline sonic, resistivity and pulsed neutron (RST) tools.
- A surface monitoring experiment is using nested soil gas and groundwater sample wells to test natural flux from one near-surface CO₂ reservoir (aquifer-vadose-zone-soil-atmosphere) to another. This will determine natural variability and assess the leakage signal that could be detected above background variability at a site with the types of complexities that are expected at a commercial site.
- A suite of subsurface modeling tools are in use, including analytical assessment of pressure from gas storage literature, one-dimensional (1-D) seal flux assessment, MODFLOW for the pressure modeling in the single phase region, and GEM-CO₂ for the two phase fields are in use. For geochemical assessments PHREEQC and Geochemists workbench are the major modeling tools in use for single phase regions; CORE2D and TOUGHREACT are used to multiphase reactive volume transport and multiphase flow.

11. SUMMARY OF MODELING AND MVA EFFORTS**Measurement Technologies Employed at Field Test Site**

Measurement Technique	Measurement Parameters	Application
Introduced – noble gasses/partitioning tracers (DAS)	Dissolution of CO ₂ into brine Measured every 20 minutes Dec2-Dec31, 2009 , ever month linked to events until June 2010	Significant uncertainties in mass balance and pressure response is the amount of CO ₂ dissolved. The U-tube sampler was used to obtain high quality- high frequency fluids with intact tracers to assess dissolution and flow processes
Produced fluid composition (DAS, HiVIT)	Gasses and tracers via mass spectrometer, Selected major and minor cations, organics via GC, stable isotopes, noble gases. Same frequency as tracers	Validation of well log and cross-well CO ₂ detection, index of rock-water reaction.
Bottom-hole pressure injection (DAS)	Pressure transducers on wireline with real-time readout Every 5 seconds project duration except during failure and workover	Assess relationship between pressure field and multiphase field.
Distributed down hole temperature with heater cable (DAS)	Measure zones of behind-casing fluid replacement and fluid movement Every minute project duration	Additional data to constrain flow units, especially to determine flow-unit thicknesses under relevant conditions. Also assessment of cement integrity.
Pulsed neutron reservoirs saturation; cased hole sonic	CO ₂ saturation RST 15 days, 60days, 6 months Sonic at 1 year	Distribution of CO ₂ at measurements points, model match, validation and quantification of CASSM and cross-well ERT.
Time-lapse 3-D seismic imaging (surface deployed)	Change from baseline Repeat 1 year post injection	Extent of CO ₂ plume, lateral coalescence of plume from multiple injectors.
Time-lapse VSP (Offset and walkaway)	Seismic reflectivity change Repeat 1 year post injection	Extent of CO ₂ plume, change in reflectivity.
3D VSP	Increased vertical and lateral resolution Repeat 1 year post injection	Complements and refines 3-D surface interpretation near DAS, refine down-dip plume edge measurement.
Continuous Active Source Seismic Monitoring (CASSM); Cross-well seismic tomography	Detect timing of CO ₂ movement cross the plane of measurement Continuous except for failure	Co-inversion with ERT, investigate use for remote pressure monitoring, constraining reservoir model using petrophysical relationships.
Passive seismic monitoring	Assess value of technique in setting well below fracture pressure over 1 month period	Technique assessment
Above-zone pressure monitoring	Assess leakage signal (possible through well completions because of poor cement bond) 5 second project duration	Continuation from Phase II to obtain long record ; behind casing pressure at DAS
Cross-well electrical resistance tomography (ERT)	Improve measurement of saturation Continuous 1.2 years	Tool development will extend the range of cross-well measurement of saturation and improve the rigor of history match and seismic inversion.

11. SUMMARY OF MODELING AND MVA EFFORTS

Soil gas	Measure N ₂ / O ₂ /CO ₂ /CH ₄ ratios, introduced tracers, stable isotopes and noble gasses in vadose zone at plugged and abandoned well site Quarterly	Determine sensitivity of soil gas techniques under regional conditions. Follow-on-tracer test.
Aquifer monitoring	Quarterly fresh water sampling at 200 ft depth at injection well sites, selected cations and anions, noble gasses. Quarterly	Assessment of method in compact possibly contaminated setting, directly regulated recourse. follow-on tracer test.

12. ACCOMPLISHMENTS AND MILESTONES TO DATE

Major field tests at Cranfield have been completed by the end of January 2011. Remaining 2011-2012 technical activities 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. Public outreach and technical knowledge sharing remain focus areas also.

HiVIT (High Volume Injection Test):

- Early 2011: storage of 1.5 million tonnes of CO₂ in the HiVIT. As production increases in updip parts of the HiVIT, the volume stored will increase more slowly with time because of gas production and recycling. Current team efforts are focused on obtaining good quantification of recycle gas which is complicated by variable density because of entrained methane.
- 10/2010: Repeat 3-D seismic survey of HiVIT, including the DAS and adjacent areas including part of depleted gas cap. Image especially distribution of down-dip extent of CO₂.

DAS (Detailed Area Study)

- 11/2009- present: SECARB injection into brine leg below and east of oil-water contact, high frequency real-time mass flow meter, bottom-hole injection well pressure and temperature.
- 11/200 – present: High frequency real-time observation well parameters including 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)
- 11/2009- present: Casing deployed cross-well Electrical Resistance Tomography detects strong changes in conductivity believed to be attributed to replacement of brine by CO₂.
- 12/2009-5/2010 Natural and introduced geochemical program with U-tube sampler. Observed evolving flow field as plume matured and injection rate increased. Methane exsolved as CO₂ dissolved, important indicator of CO₂ -brine contact and dissolution. CO₂ developed preferred non-radial flow paths following sinuous channels.
- 3/2010-5/2010: Maximum injection rate at field pressure (3000 psi), rate limited by tubing diameter. Bottom-hole pressure stable and not limiting injection rate.
- 10/2010: Repeat cross-well seismic tomography in three-well array, imaged lateral variability in plume
- 11/2010: Repeat offset and walk-away VSP survey, acquire 3D VSP survey.
- 12/2010: Recovery of semi-permanent downhole instrumentations allowed the team to troubleshoot several instrument failures in receiver strings for CASSM and bottom-hole pressure gauges and reinstall bottom-hole gauges and to assess U-tube component survivability.

Near-surface laboratory to study a plugged & abandoned (P&A) well, a well pad, a history pit, and natural plant, (P-site):

- 6/2009: Methane anomaly detected by soil gas probe.
- 10/2009 Soil gas laboratory installed and monitored quarterly, observing deep-sourced methane. Isotopic signature shows that high CO₂ concentrations are derived from biogenic degradation of

methane.

- 6/2010: P&A well reentered, high methane but no pressure anomaly in wellbore fluids. Perfluorocarbon tracers introduced in the injection zone; monitoring continues.

Geomechanical test (GMT):

- 9/14/2009 -12/4/2009: Attempted near fault deployment with clamped-in geophones to assess microseismic as injection began. Locally failed because of wireline failure attributed to high temperatures and failure of biocide to control a corrosive wellbore environment.

Phase II area:

- 7/2008 – present: Dual-completed high frequency, real-time bottom-hole, well-head tubing and casing pressure and temperature at the dedicated observation well Ella G. Lees #7 continued in Phase III to create a long-term record.
- 7/2010: CO₂ breakthrough detected via tubing fluid density change. AZMI sampling planned.

10/15/2011 Finalize, distribute archive subsurface data compilation

6/16/2014 History match subsurface plume development

10/15/2014 Analyze data collected revise surface monitoring plan to maximize benefit

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13. SUMMARIZE TEST SINK STORAGE OPPORTUNITIES AND BENEFITS TO THE REGION

The Gulf Coast wedge is thick group of Mesozoic–Cenozoic units characterized by weakly indurated, mineralogically sub-mature, porous and permeable fluvial, shoreline, deltaic, and marine sandstones. Units are isolated from each other and the surface by thick, clay-rich mudrocks; those deposited in highstands are well-known as regional seals that have trapped large volumes of hydrocarbons. Units are both stratigraphically and structurally complex, with thick salt at the base favoring extensional tectonics. The Tuscaloosa Formation at Cranfield is one of the older units of the Gulf Coast wedge and provides a typical test ground relevant to the whole wedge. This wedge of sediments spans the entire region (from the Gulf of Mexico, through Texas, Louisiana, Mississippi, Alabama, Florida, Georgia, South Carolina, North Carolina, and Virginia) and includes the largest saline sinks (in terms of areal extent and capacity) for the SECARB region as well as the United States.

Table 2. CO₂ Storage Capacity of the SECARB Region's Gulf Coast Wedge Deep Saline Formations

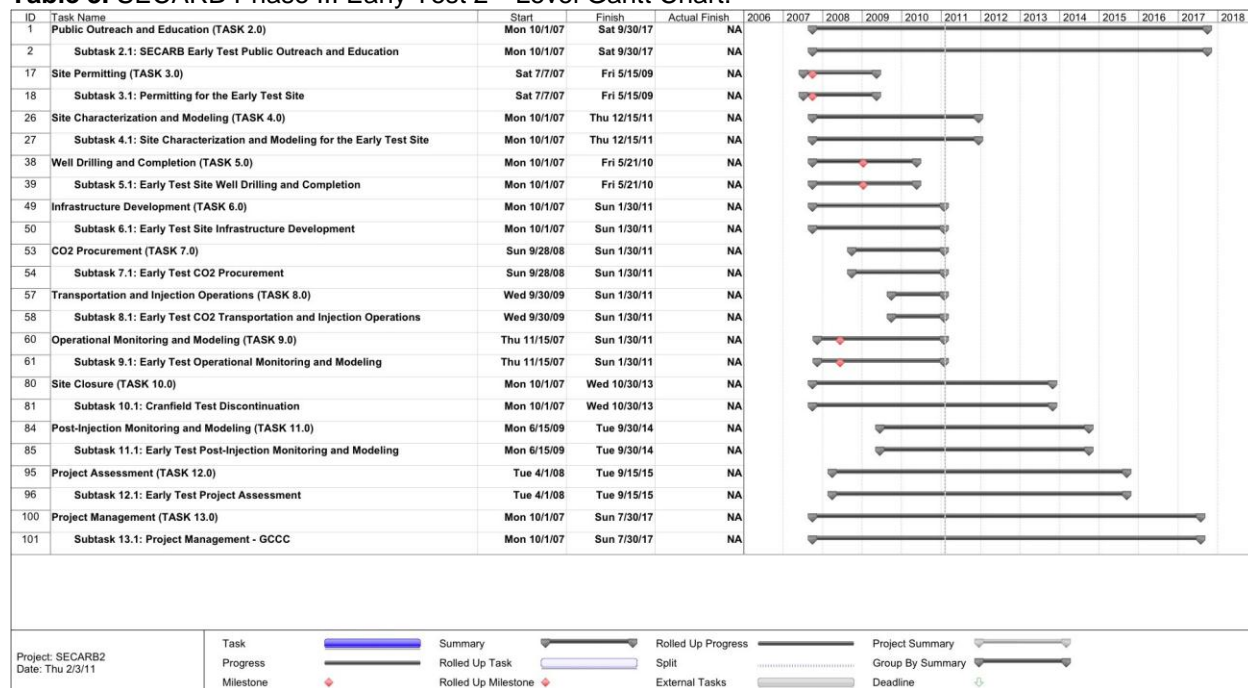
(Source: Modified from 2010 Carbon Sequestration Atlas of the United States and Canada, NETL, November 2010)

Saline Formations	State	CO ₂ Storage Capacity			
		Trillion Cubic Feet		Billion Metric Tons	
		Low Estimate	High Estimate	Low Estimate	High Estimate
Gulf Coast Basins (Pliocene)	Multiple States*	2,571	35,345	136	1,870
Gulf Coast Basins (Miocene)	Multiple States*	7,582	104,173	401	5,512
Gulf Coast Basins (Oligocene)	Multiple States*	2,488	34,215	132	1,810
Gulf Coast Basins (Eocene)	Multiple States	2,959	40,684	157	2,153
Gulf Coast Basins (Tertiary Undivided)	Multiple States	323	4,435	17	235
Gulf Coast Basins (Olmos)	TX**	8	116	0.4	6
Tuscaloosa Group	Multiple States	103	1,412	5	75
Woodbine and Paluxy Formations	TX**	96	1,324	5	70
TOTAL		16,130	221,704	853	11,731

14. FIELD TEST SCHEDULE AND KEY DECISION POINTS

(Paste Gantt Chart into the space below)

SECARB's Phase III Project Management Plan utilizes a Work Breakdown Structure (WBS) index and element dictionary, which fully defines the project scope, integrating it with allocated resources, and translating them into a project schedule for performance. A detailed Gantt chart has been developed for the ten-year SECARB Phase III program. Details of each task/subtask specific to the Early Test have been rolled up to a second level Gantt chart (**Table 3**) for the purpose of this report. The Early Test team has developed milestones (**Table 4**) for each budget period of the project to indicate progression toward project goals. These milestones are sorted by the WBS number associated with the appropriate Task or Subtask. Note that the Early Test will be discontinued by Budget Period 5, prior to 10/1/2014). Therefore, no milestones are defined after September 30, 2014. The SECARB Early Test is currently through Subtask 11.1 of its schedule.

Table 3. SECARB Phase III Early Test 2nd Level Gantt Chart.**Table 4. SECARB Phase III Early Test Milestones, sorted by the WBS number.**

Southeast Regional Carbon Sequestration Partnership Phase III Early Test

WBS	Start Date	Planned Date	Completion Date	Budget Period	Milestone	Verification Method
3.1.1	7/7/2007	10/1/2007	10/1/2007	3	Environmental Questionnaire Submitted to NETL	Work Product 3.1.1.a
5.1.2	3/1/2008	1/12/2009	1/12/2009	4	Decision Point on Well Plans and Costs	Work Product 5.1.2.a
7.1	9/28/2008	9/28/2008	9/28/2008	3	Decision Point for CO ₂ Injection	Work Product 7.1.a
9.1.1	5/15/2008	12/31/2008	12/31/2008	3	Subsurface Monitoring Plan	Work Product 9.1.1.g
9.1.3	11/15/2007	6/12/2008	6/12/2008	3	Surface Monitoring Plan	Work Product 9.1.3.a
11.1.2	1/30/2011	1/30/2012	future	4	Finalize, Distribute and Archive Subsurface Data	Work Product 11.1.2.b
11.1.2	6/1/2010	6/1/2014	future	4	Final History Match: Subsurface Plume Development,	Work Product 11.1.2.c
11.1.3	8/1/2014	9/30/2014	future	4	Finalize, Distribute and Archive Data Compilation	Work Product 11.1.3.b

** Work Products are deliverables/reports sent to the NETL COR that document completion of the milestone. The Work Product number directly corresponds to the Subtask under which it is completed.*

15. COST TARGETS AND/OR BRIEF ECONOMIC ANALYSIS

The high value of the SECARB Early Test is in preparation for monitoring anthropogenic CO₂ injection which is planned in a number of Gulf Coast sites. Substantive knowledge sharing is underway with these high value projects, which include the SECARB Anthropogenic Test at Citronelle, NRG's capture project at the Parrish, Louisiana plant, Air Products and Leucadia capture projects with storage at Hastings, Texas. These projects all have immediate or long-term value for EOR, with substantive resultant economic benefits. The Early Test itself however set no economic rules other than low cost-high value research monitoring, which were achieved by operator collaboration. For example Denbury did the well engineering, surveying, and permitting, road construction and maintenance, CO₂ pipeline at no cost to the project.

16. POTENTIAL PROJECT RISKS

Project risks and risk mitigation strategies are divided into five categories:

- (1) Economic project risks. Issues such as commercial investment, CO₂ availability at the site, injection permits, surface access rights, subsurface injection rights, and any project delays related to these risks are managed by the site operator, Denbury Onshore LLC. The SECARB project risk management strategy was to coordinate closely with Denbury and adapt as needed. In fact, the project schedule and location was adjusted in response to the recession in late 2008.
- (2) Federal funding issues. One major risk has been co-ordination of federal funding and commercial project build out. An unexpectedly long NEPA process while the commercial project advanced required restructuring of the research project. Funding cycles required project adaptation and rescheduling, especially for the national labs, which are on a different funding cycles.
- (3) Health, safety, and environmental (HS&E) risks. Denbury is an experienced and professional CO₂ injection company and operated the CO₂ transportation and injection under state permits and under their in-company best practices. Denbury staff provided this oversight for all research elements also, constructing and operating the DAS wells compatibly with their in-company experiences. Mitigation of any field-wide HS&E issues are the responsibility of Denbury. Sandia Technologies LLC provided supervision of HS&E elements of the research program using a written manual.
- (4) Failure of research program to collect data of quality needed. Because the project design pushed the envelope on tools, tested more tools and at greater depth than any previous test, the project team expected some tools to fail. Post-mortem analysis was collected on all tools and will be part of reported learning. Because of the tool-testing goals, redundancy was built in to the monitoring program. For example, when CASM receivers failed, two data sets collected with cross-well seismic "bookends" partly filled the need for comparison with ERT.
- (5) Failure of long term storage via leakage is considered unlikely. However it is not a project risk, because the CO₂ is contained within a unitized EOR field where long-term movement of CO₂ in the water leg is updip and towards the oil ring. The long-term ownership of CO₂ and any attached risk belongs to the site operator.

17. KEY FINDINGS FROM PHASE II AND THEIR SIGNIFICANCE

The SECARB monitoring program for Phase II Stacked Storage at Cranfield began in the spring of 2008 prior to CO₂ injection and continues as part of Phase III. A novel test element is a dual completed observation well to allow monitoring pressure in two zones: the lower Tuscaloosa injection zone and an aerally continuous, 12 ft thick, 100 mD sandstone above the thick middle Tuscaloosa mudstone that serves as an above-zone monitoring interval (AZMI). Over 2 1/2 years, pressure in the injection zone increased as much as 1200 psi. Pressure measurement at an idle well completed in the injection zone proved to be an effective tool for injection surveillance. Pressure at the observation well responded rapidly and with high sensitivity to injection and shut-in at distant wells documenting hydrologic continuity of the reservoir, as well as the corroborating effective cross-fault sealing performance predicted on the basis of production history of one of the crestal graben-bounding faults. Slow onset of production by natural lift was more difficult to separate from response to reservoir heterogeneity. Additional monitoring undertaken to constrain the model and thereby document the capacity under the conditions at the site includes intermittent flowing and shut in pressure measurements at selected producers using memory gauges, selected injection and production profiles, and wireline behind-casing estimates of fluid changes measured with Schlumberger's Reservoir Saturation Tool (RST) at selected observation wells. Change in well-head pressure because of lower fluid column density was effective in documenting arrival of CO₂ at the observation well where breakthrough of CO₂ occurred in 2010, about a year later than predicted by modeling.

Pressure changes in the AZMI showed a more complex response than predicted, but document that the AZMI is mostly isolated from the injection zone. A slight decrease at the start of injection, followed by an increase is attributed to a combination of near-well bore effects, geotechnical effects, and minor fluid migration along well completions. It is difficult to isolate the effects of these similarly-trending processes. In future projects we plan to reduce complexity by installing single-use AZMI wells to reduce the near-well bore effects. At project end, fluid sampling to test the AZMI for geochemical evidence of leakage is planned. This test assessed the adequacy of established Mississippi well integrity standards for retaining CO₂ for greenhouse gas mitigation.

18. ADDITIONAL PROJECT INFORMATION

The Early Test is one half of SECARB's Phase III program, and is focused on increasing technical confidence in large volume geologic storage. The Early Test is in many ways a unique program where abundant diverse measurements of many aspects of the perturbation produced by injection of large volumes of CO₂ can be made. The project team has completed major monitoring and is in process of in-depth modeling the injection to test predictive capabilities and preparing results for publication. This research-oriented early project will lead to improved confidence in storage security in following more commercially-oriented projects through knowledge sharing.

Phase III Early Test results:

A large amount of interim project results have been collected. An additional two years of data analysis and project integration are planned, to sufficiently analyze the large amounts of data collected. Much of this analysis is being conducted collaboratively (for example modeling teams at BEG, LBNL, LLNL, EFRC, SIMSEQ are all working on model approaches, some unique and some duplicative).

- Pressure response is most sensitive to boundary conditions. Open boundary conditions predicted during characterization are demonstrated by good model match.
- CO₂ moved down dip at the scale of the test (buoyancy did not dominate).
- Significant percentage of CO₂ dissolved in brine and methane exsolved. This methane contamination is a significant new finding.
- The plume continued to thicken over time.

18. ADDITIONAL PROJECT INFORMATION

- Tracer performance shows that with increased injection rates new parts of the reservoir were accessed: storage efficiency improved.
- Rock-brine integration shows slow and minor changes following introduction of CO₂.
- The repeat VSP can show change in seismic reflection strength at specific spatial locations. This will be used for interpretation/calibration of the repeat 3D surface seismic. The 3D-VSP could show spatial distribution of the CO₂ induced seismic reflection change at a resolution up to an order of magnitude better than surface seismic.
- ERT appear to be sensitive to introduction of CO₂ and highlighted lateral heterogeneity between DAS wells. Cross well seismic includes an analogous assessment of the heterogeneous vertical and lateral distribution of CO₂ in the Tuscaloosa and should provide a detailed (~2m) image of lateral and vertical distribution of CO₂ within the reservoir, allowing calibration of the detailed flow model. Multiple scale seismic measurements will allow quantification of the seismic velocity change induced by CO₂ (used for interpretation/calibration of 3D seismic) and improved understanding of scaling of seismic properties from core to well-log to VSP to surface seismic.
- CASSM sources remained operational until removal. CASSM receiver failure (after about 1 month of operation, but before injection) was caused by failure of internal seals in the pressure compensated components. The seals, which had pressure differential, apparently maintained seal due to deformation from the pressure. This is an important lesson for future monitoring design utilizing removable fluid-coupled sensors.

19. BIBLIOGRAPHY (PHASE I, II, AND III)

(Bold Items are Peer Reviewed)

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