Commercial & Experimental Monitoring
at SECARB's Anthropogenic Test Site

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Presentation Outline

• Site Overview

• MVA Plan
  – Surface
  – Shallow
  – Deep
  – Experimental

• Lessons learned
Storage Overview

Project Schedule and Milestones

The CO₂ capture unit at Alabama Power’s (Southern Co.) Plant Barry became operational in 3Q 2011.

A newly built 12 mile CO₂ pipeline from Plant Barry to the Citronelle Dome completed in 4Q 2011.

A characterization well was drilled in 1Q 2011 to confirm geology.

Injection wells were drilled in 3Q 2011.

100k – 300k metric tons of CO₂ will be injected into a saline formation began 3Q 2012.

3 years of post-injection monitoring.
Project Objectives

1. Support a fully integrated, commercial prototype CCS project (e.g. coal fired power generation capture, transport and storage)
2. Test the CO$_2$ flow, trapping and storage mechanisms of a regionally extensive Gulf Coast saline formation.
3. Test the adaptation of commercially available oil field tools and techniques for monitoring CO$_2$ storage (e.g., VSP, cross-well seismic, cased-hole neutron logs, tracers, pressure, etc.)
4. Document the permitting process for all aspects of a CCS project
5. Begin to understand the coordination required to successfully integrate all three components of the project
Good Geology, Model, & Design

- Proven four-way closure at Citronelle Dome with existing logs
- Injecting into Paluxy @ 9,400 feet
- >260 net feet of “clean” sand
- Average porosity of 19% (ranges from 14% to 24%)
- Average permeability of 300 md (ranges from 30md to 1,000 md)
- No evidence of faulting/fracturing (2D)
- Max. injection rate 500 tonnes/day
- Plume area in topmost sand is 0.35 mi² (225 acres)
- Modeled for UIC Area of Review (AoR)
# D9-7#2 Injector Completion

<table>
<thead>
<tr>
<th>Sand Name</th>
<th>Top Depth (ft, log)</th>
<th>Net Thickness (ft)</th>
<th>Log porosity (%)</th>
<th>Permeability (md) from porosity - permeability cross plot</th>
<th>Total Perf Footage</th>
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| Total Net Thickness: 263 | Weighted Average: 18.2 | Weighted Average: 208 |

Total Perf Footage: 28
CO₂ Injection
Constraints, Restrictions, and Toolkit additions to down-select MVA Program

• **Constraints**
  – Active EOR field
  – Water disposal
  – Eliminate surface change measurements

• **Class VI UIC aspects added**
  – Soil flux measurements
  – AoR via modeling

• **Experimental MVA techniques**
  – Reservoir fluid sampling
  – MBM VSP & OVSP
  – Heat pulse decay
Down-select from Cranfield & Frio Experience

**Motivation:**
- Sequestration sites will use dedicated monitoring wells.
- Maximize efficient use of available boreholes for semi-permanent monitoring

**Measurements of Interest:**
- Pressure*
- Temperature
- Fluid Sampling*
- Wireline logs
- Geophysical Monitoring
  - Seismic: active source and passive monitoring
  - Electrical

* Requires perforations and packer for zonal isolation when deployed inside casing
Defined Elements of the MVA Program

• **Shallow MVA**
  – Groundwater sampling (USDW Monitoring)
  – Soil Flux
  – PFT Surveys

• **Deep MVA**
  – Reservoir Fluid sampling
  – Crosswell Seismic
  – CO₂ Volume, Pressure, and Composition analysis
  – Injection, Temperature, and Spinner logs
  – Pulse Neutron Capture logs
  – Vertical Seismic Profile

• **MVA Experimental tools**
MVA Sample Locations

- One Injector (D-9-7 #2)
- Two deep Observation wells (D-9-8 #2 & D-9-9 #2)
- Two in-zone & above zone Monitoring wells (D-4-13 & D-4-14)
- One PNC logging well (D-9-11)
- Twelve soil flux monitoring stations
MVA Frequency

- **Shallow MVA**
  - Groundwater sampling (USDW Monitoring)
  - Soil Flux
  - PFT Surveys

- **Deep MVA**
  - Reservoir Fluid sampling
  - Crosswell Seismic
  - Mechanical Integrity Test (MIT)
  - CO₂ Volume, Pressure, and Composition analysis
  - Injection, Temperature, and Spinner logs
  - Pulse Neutron Capture logs
  - Vertical Seismic Profile

- **MVA Experimental tools**

Baseline
- 1 year
  - APR 2011 to AUG 2012

Injection
- 2 years
  - SEPT 2012 to SEPT 2014

Post
- 3 years
  - OCT 2014 to SEPT 2017
Shallow MVA

- Shallow water sampling – Quarterly
- Soil Flux sampling – continuous
- PFT Surveys – annually
Deep MVA

- Reservoir Fluid sampling - *annually*
- Crosswell/VSP Seismic – *Base/Post Inj*
- CO₂ Volume, Pressure, & Composition analysis - *continuous*
- Injection, Temperature, & Spinner logs - *annually*
- Pulse Neutron Capture logs - annually
- MBM Vertical Seismic Profile - *annually*

D 4-14 Observation Wellbore
Experimental MVA

- Compare sampling methods:
  - $N_2$ gas lift
  - Pumping
  - Kuster Sampler (wireline)
  - U-tube sampler
- Deploy MBM system
- Compare MBM VSP & OVSP seismic
Tools Deployed with MBM:

- Discrete Pressure & Temperature
  (2 Quartz Gauges)
- Distributed Temperature Sensing
  (DTS) with Heater (Heat-Pulse)
- Fluid Sampling (U-tube)
- Seismic monitoring 18 clamping geophones
- Distributed Acoustic Sensing (DAS)

The Citronelle MBM Improvement over Cranfield = Flatpack and Geophone Cable (one line deployment vs. 7)
MBM Design: Flat-Pack & Geophone

Flat-pack replaces 7 lines

Geophone clamp hydraulic line

Hybrid copper fiber-optic cable

Geophone TEC

Tube-in-tube U-tube sampler

Coax PIT monitoring cable

DTS, Heater, DAS
Hybrid 6-copper, 4-fiber-optic cable

SIX 20 AWG CONDUCTORS & FOUR FIBER FINT STAINLESS STEEL TUBE

Components:
A. 6 x 20 AWG [2660 ft] copper [coat] outer [coat] outer [coat]; O.D.: 0.39 mm (0.012") Nominal
B. Coated T.I. (FRP); O.D.: 1.73 mm (0.068") Nominal
C. JIC EMT [threading gel and 2" x PVC or 6" x 1/16""] & another dual-foam fiber; T.F.: 1.8 mm
D. PVF Tape (0.005""); "Pipesaver" Wrap over Cabled Core
E. White T-I-J, O.D.: 7.73 mm (0.30") Nominal
F. 3 HI. Nummer [threaded tube, half thickness]: 6.88 mm (0.27") O.D.: 9.53 mm (0.37") Nominal

Welded Geophone Line
Deployment of MBM

Tubing Deployment allows for wireline access:

- 4-element flatpack
- 18-level Geophone cable
  - Hydraulic clamps for Geophones
  - Clamp in tubing/casing annulus
- Dual mandrel hydraulic packer
- Non-rotating overshot connection for coupling to 450’ bottom assembly
- Avoids splices at packer
Deployment of MBM

**RUN-IN DATA**

- Bundling 7 control lines in a polypropylene-jacketed flatpack
- Non-rotating off-center overshot to couple the uphole, dual-mandrel hydroset packer assembly
- Packer landed at ~9,400 feet (2,865 m)
- Completion depth was 9,850 feet (3,002 m)
- Required four – 24 hour-a-day operations to install.
Key Results

- PTF Survey
- Seismic
- Reservoir Response
PFT Survey

Site was inoculated August 2012, prior to injection and retested in June 2013

<table>
<thead>
<tr>
<th>Well/Sample</th>
<th>Inoculation</th>
<th>Testing</th>
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<td>D-9-2</td>
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<tr>
<td>System Blank</td>
<td>No Sample taken</td>
<td>ND</td>
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</table>
Seismic: Baseline Crosswell

Survey Parameters

- Source Type: Piezoelectric
- Receiver type: Hydrophone – 10 levels
- Source & Receiver interval: 10 feet
- Sweep length: 2.6 sec (record length 3 sec)

Survey Results

- High resolution image between injection well & observation well (~10 feet vertical resolution)
- No reservoir or confining unit discontinuities observed
- Good CO₂ confinement
MBM Geophone Array: Baseline VSP, OVSP and Walkaway

Next Step:

Resolution Comparison

- Crosswell ~ 10 feet
- Full VSP ~ 25 – 30 feet
- MBM VSP~ 50 feet
- Establish “fence post”
- Collect time lapse seismic events
- Collaborative analysis of varying resolutions
Reservoir Response

- 630,000 data points
- 11 month deployment

SECU D-4-13/14 Pressure

- Pressure spike JAN 2012 across all 4 gauges
- Small pressure spike observed consistent with the MIT’s
- Downhole pressure quickly stabilized to pre-test levels, indicating no residual effects & packer integrity.
• Consistent & expected pressure increases in zone
• At 9,441 feet and at 9,416 feet

Discretely identified MVA activities

• System remains elastic – bouncing back when shut in
• Reservoir responds to MVA activities
Pressure & Injection Rate Response
Lessons Learned

• Time and cost reductions, but not yet commercial
• Data, data, and more data
• MVA systems can impact injection and vice versa
• We have a good capacity, injectivity, and no apparent formation damage
Office Locations

**Washington, DC**
4501 Fairfax Drive, Suite 910
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http://adv-res.com/
Extra & Supporting Slides
## CO$_2$ Stream Composition

<table>
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<tr>
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<th>CO2 Stream composition data (%)</th>
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<td><strong>average</strong></td>
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# MVA Tests and Their Frequencies (1)

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<th>Measurement Technique</th>
<th>Measurement Parameters</th>
<th>Application</th>
<th>UIC Required Frequency</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Reservoir and above-zone pressure</td>
<td>downhole pressure gauges</td>
<td>Key measurement for assessing the injection pressure field and for regulatory compliance. Above-zone monitoring to detect leakage through the confining unit</td>
<td>Constant during injection operations, annually post-injection</td>
<td>(2) Panex gauges run D-9-8#2 with MBM in March 2012; MRO gauges run in D-9-13 and D-4-14 in June 2012</td>
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<tr>
<td>Cased-hole pulsed neutron logging</td>
<td>Neutron capture as a function of CO₂ saturation buildup</td>
<td>CO₂ saturation buildup near new and existing wellbores. Demonstrates CO₂ plume migration and monitor for above-zone leakage</td>
<td>One baseline deployment, annually during injection, bi-annually post-injection</td>
<td>Baseline logs run on D-4-13, D-4-14, D-9-7#2, D-9-8#2 and D-9-9#2.</td>
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<td>Time-lapse seismic (crosswell and/or vertical seismic profiling)</td>
<td>CO₂ induced change from baseline sonic velocity and amplitude</td>
<td>Distribution of CO₂ plume vertically and horizontally</td>
<td>One baseline deployment, once post-injection</td>
<td>Baseline VSP acquired in Feb 2012; baseline crosswell acquired in Jan 2012</td>
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<td>Reservoir fluid sampling</td>
<td>Pressurized fluid samples taken from the injection zone. Analyze for pH, and selected cations and anions</td>
<td>Geochemical changes to injection zone that occur as a result of CO₂ injection</td>
<td>Semi-annually during injection phase, annually post-injection</td>
<td>D-9-8#2 Baseline samples taken via U-Tube on June 12 2012; Kuster samples taken in March and June 2012</td>
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## MVA Tests and Their Frequencies (2)

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<tr>
<td>Drinking water aquifer (USDW)</td>
<td>Alkalinity, DIC, DOC, selected cations and anions</td>
<td>Monitoring of USDWs for geochemical changes related to shallow CO₂ leakage.</td>
<td>Quarterly during and post-injection</td>
<td>Baseline USDW samples acquired and analyzed in Feb, March and July 2012</td>
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<td>Injection well annular and</td>
<td>Pressure gauges located on the wellhead to monitor casing annular and tubing pressure</td>
<td>Annular pressure is an indication of wellbore integrity. Tubing pressure</td>
<td>Constant during injection operations and post-injection</td>
<td>Gauges installed, to be tied into Denbury’s data acquisition system</td>
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<tr>
<td>tubing pressure</td>
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<td>assures regulatory compliance with maximum injection pressure.</td>
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<tr>
<td>Soil CO₂ Flux</td>
<td>Mass of CO₂ emitted from the soil per unit time and area</td>
<td>Monitor for anomalous increases in the amount of CO₂ that is emitted from the soil surface as an indication of CO₂ leakage</td>
<td>Quarterly during and post-injection</td>
<td>(12) soil flux stations in place. Monitoring began in Dec 2011. Eleven field deployments to date</td>
</tr>
<tr>
<td>Perfluorocarbon tracers (PFTs)</td>
<td>Measure tracer levels near the ground surface around new and pre-existing oilfield wells</td>
<td>Monitor for the presence of tracer buildup near wellbores which would suggest leakage of CO₂</td>
<td>Single baseline, annually during and post-injection</td>
<td>Baseline sampling on Sept 11, 2012 at the D-9-1, D-9-2, D-9-3, D-9-6, D-9-7, D-9-8, D-9-9, D-9-10 and D-9-11 well locations</td>
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</table>
Groundwater Sampling: Context

- Above zone groundwater monitoring may be used as a compliance tool to detect CO$_2$ leakage
- Samples undergo geo-chemical transformation when collected from deep wells, e.g.,
  - Exsolution of dissolved gases
  - Changes in dissolved CO$_2$ concentrations that control pH
  - Exposure to atmosphere causes changes in redox
- Industry needs best available practices for compliance
Groundwater Sampling Comparison

- **Purpose:**
  - Compare sampling methods to identify significant differences in groundwater quality results
  - Compare costs/benefits of each method

- **Scope:** Collect and analyze groundwater samples using four artificial lift techniques
  1. $\text{N}_2$ gas lift
  2. Pumping
  3. Kuster Sampler (wireline)
  4. U-tube sampler

Photo Courtesy of the USGS: Fluid Samples from Gas Lift
USGS Groundwater Sampling Comparison Findings

- The U-Tube samples a larger volume (tens of Ls), is at high pressure at surface, and once installed, it is easier to operate; but can be contaminated with brine, N\textsubscript{2} and organics, and is fixed at one location.

- N\textsubscript{2} gas lift can be used to clean the well and produces large brine volumes, but removes dissolved volatiles and gases, significantly raising brine pH that may cause mineral precipitation and other chemical changes before sampling and is good only for major and unreactive solutes.

- Submersible pump can also be used to clean the well and produces large brine volumes, but dissolved volatiles and gases are lost by lowered fluid pressures, significantly raising brine pH that may cause mineral precipitation and other chemical changes before sampling and is good only for major and unreactive solutes.

- Results of reactive solutes and dissolved organics could prove most conclusive for monitoring and therefore for the selection of method of sampling formation water.

Baseline USDW Monitoring

- Three new wells and one existing well drilled in Nov-Dec 2011
  - New well pair at primary injection well (D-9-7#2); one completed in unconfined surficial aquifer (depth = 168’) and one completed in semi-confined deep aquifer (depth = 498’)
  - New well at backup injector (D-9-9#2) in semi-confined deep aquifer (depth = 167’)
  - Utilize existing water supply well at monitoring well site (D-9-8#2)
- Initial well development using gas lift to produce at least 3 well volumes of water in Jan 2012
- Low flow bladder pumps installed in new shallow wells for sampling
- New deep well sampled using Grunfos high flow pump (3 well volumes and stable parameters)
- Baseline unfiltered and filtered (0.45 um) samples taken 3 times (Jan, March and July 2012)
- High levels of turbidity in deep well complicates results – now taking 0.2 um filtered samples.
MVA Plan - Soil Flux Stations

- Twelve stations
- Baseline Monitoring Began in December 2011
- Eleven Baseline Deployments
MVA Plan - Soil Flux Results

The graph displays the soil flux results over time for different locations and temperatures. The x-axis represents the dates from December 3, 2011, to June 20, 2012. The y-axis on the left shows the flux in umol/m²/sec, ranging from 0 to 10, while the y-axis on the right shows the temperature in °C, ranging from 10 to 35.

Different symbols and colors are used to represent various locations and roads, with specific dates marked for each data point. The graph also includes a line indicating the mean temperature trend over time.
MRR Reporting Requirements

Illustrative Representation of Requirements

CO₂ received at the facility is the only reporting requirement under Subpart UU.
MMR RR Monitoring (MRV) Plans

- Required for RR projects
- Unclear if they are required for R&D exemption projects (we submitted one for the Anthro Test…)
- Should complement Class VI UIC MVA plan
- Required components:
  - Delineation of the maximum monitoring area (MMA)
  - Delineation of the active monitoring areas (AMA)
  - Identification of potential surface leakage
  - Surface leakage detection strategy
  - Surface baseline monitoring strategy
  - Well ID number(s)
  - Date to begin collecting data