Update on Results of SECARB Test of Monitoring Large Volume Injection at Cranfield

Mississippi River
Natchez
Mississippi

3,000 m depth
Gas cap, oil ring, downdip water leg
Shut in since 1965
Strong water drive
Returned to near initial pressure

Illustration by Tip Meckel
**Cranfield “Early” Field Test Collaboration**

**Gulf Coast Carbon Center Industrial Associates**

<table>
<thead>
<tr>
<th><strong>Gulf Coast Carbon Center Staff</strong></th>
<th><strong>BEG staff</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Susan Hovorka</td>
<td>Tongwei Zhang</td>
</tr>
<tr>
<td>Ramon Trevino</td>
<td>Jeff Paine</td>
</tr>
<tr>
<td>Tip Meckel</td>
<td>Bob Reedy</td>
</tr>
<tr>
<td>Changbing Yang</td>
<td>Robert Reed</td>
</tr>
<tr>
<td>Jiemin Liu</td>
<td>Kitty Millikan</td>
</tr>
<tr>
<td>Katherine Romanak</td>
<td></td>
</tr>
<tr>
<td>Rebecca Smyth</td>
<td></td>
</tr>
<tr>
<td>Sigrid Clift</td>
<td></td>
</tr>
<tr>
<td>Masoumeh Kordi</td>
<td></td>
</tr>
<tr>
<td>Stuart Coleman</td>
<td></td>
</tr>
<tr>
<td>Yihua Cai</td>
<td></td>
</tr>
<tr>
<td>Hamid Lashgari</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Institutional Affiliations**

- LBNL
- LLBL
- USGS
- ORNL
- NETL
- Schlumberger Carbon Services
- QEA
- BP
- U Mississippi Miss State
- UTPGE
- UT DoG
- University Tennessee
- Princeton
- Stanford
- University Edinburgh
<table>
<thead>
<tr>
<th>Theory and lab</th>
<th>Sensitivity of tools; saturated-vadose modeling of flux and tracers</th>
<th>Lab-based core response to EM and acoustic under various saturations, tracer behavior</th>
<th>Advanced simulation of reservoir pressure field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field experiments</td>
<td>Above-zone acoustic monitoring (CASSM) &amp; pressure monitoring</td>
<td>3-D time lapse surface/VSP seismic Tomography and change through time</td>
<td>Dissolution and saturation measured via tracer breakthrough and chromatography</td>
</tr>
<tr>
<td>Hypothesis tested</td>
<td>Surface monitoring: approach verification Groundwater program Gas variation over time</td>
<td>CO₂ saturation measured through time – acoustic impedance + resistivity Tomography and change through time</td>
<td>Microseismic test, pressure mapping Acoustic response to pressure change over time</td>
</tr>
<tr>
<td>Contingency plan</td>
<td>CO₂ retained in-zone document no leakage to air-no damage to water</td>
<td>CO₂ saturation correctly predicted by flow modeling</td>
<td>Pressure (flow plus deformation) correctly predicted by model</td>
</tr>
<tr>
<td>Commercialization</td>
<td>Parsimonious public assurance monitoring</td>
<td>Subsurface perturbation predicted</td>
<td></td>
</tr>
</tbody>
</table>
Natural CO₂ Available Now in large Volumes Shipped via Sonant Pipeline to Test Lower Part of the Gulf Coast Wedge

Cranfield test site

Relatively young sandstones with shale seals
Heterogeneous, high porosity sediments
Salt tectonics and growth faults
Characteristics of the Gulf Coast wedge

Galloway et al
Cranfield Progress

Phase II Site selection
First cored well, brine samples
baseline seismic

Characterization

Phase II Site development
Soil gas baseline

Phase III NEPA

Drill Phase III
3 DAS wells
Monitoring

Phase III injection

Phase II injection

End SECARB Early

May 1 million tones injected
P II + III

December 20
Last well for 1 million
tones/year rate

Projected 1.5 million
tons phase III
Characterization of the Reservoir

Based on log annotation and recent side-walls

Tuscaloosa Fm
Tuscaloosa D-E reservoir
Tuscaloosa confining system
Phase II
Oil-water contact

3D Denbury - interpretation Tip Meckel BEG
Reservoir heterogeneity from surface seismic

- Stratal slicing for facies
- 90-degree phase
- AVF for thickness/flow
- AVO for fluid/OWC

Denbury 3-D survey interpretation Hongliu Zeng, BEG
Baseline Cross Well tomogram

West

F3

F2

East

112 m

F1

Z-Seis & Tom Daley Jonathan Franklin in review at LBNL
Upward fining fluvial sandstone and conglomerates of the lower Tuscaloosa Fm
Go to the field to test

- Injector
- Producer (monitoring point)
- Observation Well

Key:
- Structure Contour
- Access roads
- Tuscaloosa Wells

- P II Obs well
- HiVIT
- Psite
- GMT
- Phase II
- Pipeline head & Separation facility
Model – history match pressure at real-time monitoring well

Results of 1 year model continuous pressure data

Injection rates

Pressures (psi)

Modeled pressure
Measured pressure

7/2008  12/2009

JP Nicot Jong Won Choi BEG

Rock and fluid properties in simulator

Obs well EGL7
Using pressure to show no leakage

Surface casing cemented in

Non-cemented long string

AZMI
Cement to isolate

Production/injection zone

Add CO₂ for EOR

Remaining open annulus between rock and casing= Potential leakage path for CO₂ or displaced brine?

Injection zone

Pressure

AMZI

Time

Seal = No fluid communication

Add CO₂ for EOR in injection zone
Look in Detail at Flow Detailed Study Area (DAS)

- **Injector**
- **Producer** (monitoring point)
- **Observation Well**

Key:
- Structure Contour
- Access roads
- Tuscaloosa Wells

GIS base Tip Meckel

Pipeline head & Separation facility

DAS

HiVIT

Psite

Phase II

GMT
DAS Monitoring

Closely spaced well array to examine flow in complex reservoir

Petrel model Tip Meckel
Phase III Research Observation
well construction for both wells

- 2 7/8” tubing
- U-tube sampler 1/4 “SS
- Seismic sources/receivers
- BHP+ T
- Cross well array in two wells
- High injection volumes
- Far-field monitoring microseismic, P&T, chemistry, surface seismic

- Casing-conveyed pressure sensor
- ERT – 20 electrodes
- Fiberglass non-conductive casing
- Distributed temperature and heater loop

BEG LBNL LLNL USGS ORNL Sandia Technologies
Probabilistic realization of permeability

Jong-won Choi and JP Nicot BEG
First breakthrough time at well F2 for each of the 10 permeability fields

Jong-won Choi and JP Nicot BEG
Start injection at DAS Dec 1, 2009
175 kg/min step up to 350kg/min
Start injection at DAS Dec 1, 2009
175 kg/min step up to 520 kg/min

It’s all about pressure
Today at DAS

- Mass flow increased to 507 kg/min above 327 kg/min average
- Injection well BHP 5,818 psi above 5793 psi
- BPT injection well 162 degrees F (252 F original)
Measuring distribution of CO$_2$ in the reservoir

- Well-based methods
  - Wireline logs in time lapse - RST
  - Temperature
- Cross well methods
  - Time- lapse ERT
  - Time – lapse acoustic (seismic)
<table>
<thead>
<tr>
<th>GR Washouts</th>
<th>Resistivity</th>
<th>OH Porosity</th>
<th>Sigma</th>
<th>RST Porosity</th>
<th>CO2 Volume</th>
<th>CO2 Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/12/09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/15/09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/31/09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bob Butch
What happened at the wells?

- Dec 1 CO2 flows into formation
- Dec 1 pressure changes right away, but no CO2
Day 9

Dec 9 CO₂ detected in top of well interval

Observation well F2

CO₂ flows into formation

Injection Well F1

Dec 9 well F2

Observation well F3

packing
Day 13

Dec 13 still minor amounts of CO$_2$ detected in top of well interval and maybe some thin zones

Dec 13 CO$_2$ detected in top of well interval and maybe some thin zones
Day 31

Dec 30 large amounts of CO₂ detected in well interval and some thick zones in lower part of formation

Dec 31 large amounts of CO₂ detected in well interval upper part of formation

Injection Well F1

Well F2

Well F3

may injection log large flow in upper part

packer

packer
Cross Well ERT tells us how flow occurred

- Resistive plume = CO2 in reservoir
- Conductive plume = workover fluids?

Observation well F2 electrodes

Direction of CO2 plume

Second Resistive plume out of section migration

50ft

Operation

Charles Carrigan, LLNL
High frequency fluid sampling via U-tube yields data on flow processes

Small diameter sampler with N₂ drive brings fluids quickly to surface with tracers intact.

CO₂ dissolution into brine liberates dissolved CH₄.

BEG, LBNL, USGS, ORNL, UTDoG,

data compiled by Changbing Yang BEG
HiVIT Is it possible to find leakage at P Site? P-Site tests

Phase II

GMT

Pipeline head & Separation facility

DAS

Is it possible to find leakage at surface? P-Site tests

Injector

Producer (monitoring point)

Observation Well

Key
Structure Contour
Access roads
Tuscaloosa Wells
Assessment of near surface techniques
“P Site”

Clear-cut, right-of-way for empty pipe

Pit
Pad
Plants
P&A well

1950’s pit
Preliminary Soil Gas data

CO2 (vol %)

CH4 (vol %)

O2 (vol %)

Pressure (inches H2O)

Katherine Romanak and Changbing Yang, BEG
Interim Conclusions of Study at Cranfield

- Phase III 1 million ton/year rate achieved Dec 20, 2009, 2 Million tones monitored since July 2008
- Rate to be maintained >15 months
- Monitored with standard and novel approaches
  - History match pressure response
  - No leakage into Above-Zone Monitoring Interval
  - Fluid flow measured/monitored with multiple tools in complex flow field
  - First US use of Electrical Resistance Tomography (ERT) for sequestration
  - Quantification of dissolution
- Export to commercial EOR/sequestration projects