SECARB “Early Test” at Cranfield
DE-FC26-05NT42590

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Gulf Coast Carbon Center
Bureau of Economic geology
Jackson School of Geoscience
The University of Texas at Austin

Mastering the Subsurface through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting, August 1–3, 2017, Pittsburgh, Pennsylvania
Team Structure

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Denbury Resources
Field owner and injection system design, management, 4-D survey, HS&E

Sandia Technologies
Monitoring Systems Design, Installation, HS&E

50 Vendors
e.g. Schlumberger

Core Lab
UT DoG
Anchor QEA

MSU & UMiss
Hydro & hydrochem

Curtin University
3-D Seismic processing

MSU & UMiss
Hydro & hydrochem

Federal collaborators Via FWP

LBNL
Well-based geophysics, U-tube and lab design and fabrication

LLNL
ERT

USGS
Geochemistry

SECARB Anthropogenic Test At Plant Barry/Citronelle

Separately funded

NRAP
VSP deployment & analysis

NETL
Rock-water interaction

Model comparisons
LBNL SIM SEQ study

IPARS Modeling
CFSES M. Wheeler

4-D Seismic analysis
K. Spikes UT DoGS

Rock Mechanics
CFSES Sandia NL

Microseismic deployment
RITE, Japan

Groundwater controlled release
AWWA
Recent progress - Knowledge Transfer to Industry

Separately-funded work monitoring large scale commercial projects based on SECARB early test experience

Air Products Port Arthur industrial capture from SMRI at 1 MMT/year transported to Denbury’s Hastings Field.

Petra Nova and NRG /Hillcorp/JX capture up to 1.6 MMT/year and use for EOR at West Ranch field
## Commercialization of Monitoring

<table>
<thead>
<tr>
<th>Method</th>
<th>Mass balance</th>
<th>soil gas</th>
<th>groundwater chem</th>
<th>AZMI chem</th>
<th>AZMI pressure</th>
<th>3D seismic</th>
<th>VSP</th>
<th>ERT</th>
<th>EM</th>
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Synergies

Field data collection
- Microseismic -- RITE
- CO\textsubscript{2} Geothermal -- LBNL
- PIDAS – Sun
- CCP-BP gravity
- Microbes – U KY
- NRAP 3-D VSP
- Borehole seismic – Groundmetrics
- Nobles
- U. Edinburgh
- Fluid Chem – Ohio State
- Well integrity – Schlum/Battelle

Modeling efforts
- SIMSEQ – LBNL
  - 15 teams
- CFSES – UT/ SNL
- IPARS -- Wheeler
- NRAP
- NCNO
- LBNL
- CCP3
- UT- LBNL Zhang
- LLNL (yesterday)

Additional analysis
- NETL- EOR accounting
- Mei/Dilmore
- NETL- Rock-water reaction
- BES - LLNL
No detectable seismic

Makiko Takagishi, RITE
Magnitude 0.4 horizontal and .07 vertical
Early Test Motivation

- MIT report “Future of Coal” 2007
  - Set 1 MMT injection goal “proceed .. as soon as possible. Several integrated large-scale demonstrations with appropriate measurement, monitoring and verification are needed. ... establish public confidence for future.”

- In 2007 scale and timing of large-scale capture in region still uncertain
  - SECARB anthropogenic test (2011)

- Early Test design to progress in the gap
  - Piggy-back on soon-to-start EOR project
  - Permits, source and infrastructure in place
  - Direct injection – relevant to large scale saline CCS
Early Test goals

- Large-scale storage demonstration
  - 1 MMT/year over >1.5 years
    - Periods of high injection rates
    - Result >5 years with >5 MMT CO₂ stored

- Measurement, monitoring and verification
  - Tool testing and optimization approach
  - Deploy as many tools, analysis methods, and models as possible

- Stacked EOR and saline storage
Location
Major Contributions

• Early Test Developed monitoring approaches for later commercial projects
  – Process-based soil gas method
  – Effectiveness of groundwater surveillance
  – Pressure and fluid chemistry monitoring in Above-Zone Monitoring Interval (AZMI)
  – ERT for deep CO$_2$ plume
  – Limitations of 4-D seismic

• Published and propagated techniques for widespread application
Knowledge Transfer to Industry

93 publications
Site visits
Talks, workshops
exchanges

PBS News hour – Miles O’Brien
Limitations to 4-D seismic

(b) CO₂ saturation distribution estimate (Carter [18]) compared to fluid flow simulation
Limitations to 4-D seismic

(a) Acoustic impedance difference (Zhang et al. [17]) compared to fluid flow simulation

Alfi & Hossieni, BEG
Limitations to 4-D seismic

Alfi & Hossieni, BEG
Calculate time shifts resulting from CO$_2$ emplacement for reflections just below the reservoir.

D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin, LBL
Largest seismic time shifts in area with greatest velocity changes

D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin, LBL
• Biggest velocity changes due to the injection of carbon dioxide are in the water leg.

D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin, LBL
LLNL Electrical Resistance Tomography - changes in response with saturation

Time-lapse sequence of resistivity changes observed during injection

Injection began 1 Dec 2009
Initial CO₂ breakthrough
CO₂ plume growth
CO₂ plume growth
CO₂ plume grows wider and thicker
CO₂ plume growth

C. Carrigan, X Yang, LLNL
D. LaBrecque Multi-Phase Technologies

Lawrence Livermore National Laboratory
Site Characterization Approach

Seismically non-unique interpreted form lines

Detail Area Study DAS

H Zeng, BEG

10cm
Modeling Approach's

Reservoir characterization

Relative permeabilities

Single phase pressure

Multi phase pressure

Probabilistic realizations of reservoir architecture

Breakthrough time

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<th>Realization Number</th>
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<th>31F-3</th>
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Hosseini and others, 2013

Cranfield
Modeling

- Multiple models (119)
  - I-PARS
  - SIM-SEQ model approach comparison

- CGM GEM
  - Probabilistic approaches
  - Match 100 realizations to subset of modeled data
  - Forward model scenarios

Pre-injection forward model breakthrough times to design geochemical sampling

Jong Won Choi BEG
History Match Modeled and measured CO$_2$ breakthrough

![Graph showing breakthrough time comparison between simulation and real field data, with Alfi, BEG at the bottom right.]
CFU31F-2, 68 m away from injector

Travel time = 317 h

2nd SF6 on May 9
Arrive on May 20

CFU31F-3, 112 m away from injector

Travel time = 319 h

2nd SF6 on May 9
Arrive on May 20
Above-Zone Pressure Observations

3,200m

3,060m

68m

31F-2

120m

Confining layer

IZ

AZMI

3,200m

3,060m

68m

31F-2

120m

Confining layer

IZ

(not scaled)

S Hosseini, S. Kim BEG
Groundwater at the Cranfield Site: Sampling

- More than 12 field campaigns since 2008
- ~130 groundwater samples collected for chemical analysis of
  
  Cations: Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Pb, Se, Zn
  Anions: F-, Cl-, SO$_4^{2-}$, Br-, NO$_3^-$, PO$_4^{3-}$
  TOC, TIC, pH, Alkalinity, VOC, $\delta^{13}$C
  
  On-site: pH, temperature, alkalinity, water level

- ~10 samples for noble gases
- ~20 groundwater samples for dissolved CH$_4$
- 15 Water wells
Groundwater at the Cranfield Site
Single-Well Push-Pull Test

- Maximum concentrations of trace metals observed, such as and Pb, are much less than the EPA contamination levels;
- Single well push-pull test appears to be a convenient field controlled-release test for assessing potential impacts of CO₂ leakage on drinking groundwater resources;

Results were summarized in the following paper

International Journal of Greenhouse Gas Control

Single-well push–pull test for assessing potential impacts of CO₂ leakage on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi

Changbing Yang, Patrick J. Mickler, Robert Reedy, Bridget R. Scanlon, Katherine D. Romanak, Jean-Philippe Nicot, Susan D. Hovorka, Ramon H. Trevino, Totti Larson

- Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnett Road, Bldg 130, Austin, TX 78758, United States
- Department of Geological Sciences, The University of Texas at Austin, 2275 Speedway Stop C1000, Austin, TX 78712-1722, United States

C. Yang, BEG
CO$_2$ leakage from a P&A well is detected by a monitoring network if change in DIC, dissolved CO$_2$, or pH in any one of wells of the monitoring network is higher than one standard deviation of the groundwater chemistry data collected in the shallow aquifer over the last 6 years.

Changbing Yang
Process-Based Soil Gas Monitoring

- No need for years of background measurements.
- Promptly identifies leakage signal over background noise.
- Uses simple gas ratios \((\text{CO}_2, \text{CH}_4, \text{N}_2, \text{O}_2)\)
- Can discern many \text{CO}_2 sources and sinks
  - Biologic respiration
  - \text{CO}_2 dissolution
  - Oxidation of \text{CH}_4 into \text{CO}_2 (Important at CCUS sites)
  - Influx air into sediments
  - \text{CO}_2 leakage

Katherine Romanak BEG
Major Technical Accomplishments

- **Multiphysics CO₂ plume detection**
  - Surface 4-D; Azimuthal VSP, cross well, ERT, Pulsed neutron, fiber-optic thermal, sonic logs, PNC logs
  - Limits evaluated (depth, gas)

- **In-zone and Above-zone pressure method validation**
  - Casing deployed BHP with real-time readout

- **Minimal geochemical change in-zone, geomechanical softening**

- **Non-detect of microseismicity by RITE at >1000 psi pressure increase**

- **Reservoir response to heterogeneity – non-linear breakthrough**

- **Groundwater sensitivity assessment**
  - Value of DIC, sensitivity to carbonate in rock matrix
  - Value for incident or allegation

- **Process-based soil gas**
  - Reduced sensitivity to environmental fluctuation, not dependent on baseline.
  - Value of attribution
Rate of Progress

- All elements have been completed on plan
  - (three years injection + three “post closure”)
- Under budget
  - Major saving was not needing to purchase CO₂ to meet the project goal; commercial injection was high during early project stages
- Emphasis on publication and technical outreach
  - 93 technical papers published 2009-2017
- Leveraged by data-sharing

Coreflood micro CT J Ajo-Franklin LBNL
Lessons Learned (where is improvement needed?)

- Simplified AZMI completions
- Improved high temperature and pressure equipment
- Simplified ERT deep installation
- Remote tools for water and soil gas surveillance
- Maturation of monitoring design planning
  - Interaction with international community
Detailed Area Study (DAS)

Injector CFU 31F1

Obs CFU 31 F2

Obs CFU 31 F3

Closely spaced well array to examine flow in complex reservoir

Tuscaloosa D-E reservoir

Petrel model Tip Meckel
Time-lapse cross well
Schlumberger

Injection Zone

10,500 feet BSL

68m

112 m
Project Status

Million metric tons CO₂

Real-time monitoring – BHP, BHT, AZMI, DTS

Baseline

Start DAS injection

Repeat 3-D VSP Cross well

Baseline 3-D VSP Cross well

Start injection

Logging

Surface monitoring

Cumulative injection

Recycled

Cumulative volume stored

Geochemical monitoring

2008 2009 2010 2011 2012 2013