Site Selection Insights from the SECARB Citronelle Project

Robert C. Trautz
Principal Technical Leader
California Air Resource Board
CCS Technical Discussion Series: Site Selection
September 26, 2016
Outline

- Putting CO$_2$ emission from power stations in the proper context
- SECARB Anthropogenic Test (Citronelle, Alabama)
  - Project overview
  - Project status
  - Regional storage assessment
  - Citronelle Dome and the Paluxy Formation
  - Fluid sampling
- Brine Extraction Storage Test (BEST)
  - Early lessons learned from a LCA of brine extraction & treatment
Putting CO₂ Emissions from Power Stations into Perspective

- Ave. U.S. emission intensity for coal fleet is 1.007 metric tonnes of CO₂ per megawatt-hour (tCO₂/MWh)
- 1,000 MW coal-fired plant generates ~8.8 MtCO₂/yr at full capacity
- U.S. regulations require existing coal plants reduce emission intensity to 0.592 tCO₂/MWh
- Based on this scenario 41% capture is required and ~3.6 MtCO₂/yr would need to be stored per 1,000 MW

Average U.S. coal fleet requires CO₂ capture and storage equal to ~3.6 MtCO₂ / yr per 1,000 MW

Natural gas fleet requires ~18% capture or ~0.68 MtCO₂ / year per 1,000 MW
Global CCS Project Experience

- Equivalent emissions from two 1,000 MW Coal Power Plants
- 1½ 1,000 MW Natural Gas Power Plants
- One-third of a 1,000 MW Coal Power Plant
- One 1,000 MW Coal or Six Natural Gas Power Plants

**Note:**
- = 1 Mtpa of CO₂ (areas of circle are proportional to capacity)

(Courtesy of GCCSI)
SECARB Anthropogenic Test Overview (Citronelle, AL)

- DOE and industry funded research project
- Largest integrated CO₂ capture, transportation and storage project on a coal-fired power station using advanced amines in the U.S.
- Southern Co. and MHI captured over 240,900 metric tons of CO₂ from a 25 MW slip stream from Unit 5 at Plant Barry
- SECARB transported, injected and stored over 114,104 metric tonnes at Citronelle
SECARB Citronelle Status

- Three deep wells drilled in 2011–2012
- Injection started on August 20, 2012
- Injection ended September 1, 2014
- Three year Post-Injection Site Care Period started in September 2014

Currently in our third and final year of post-injection monitoring
Regional Geologic Assessment of Storage Reservoirs and Seals

Potential CO₂ Storage Units
- Eutaw Sand (U. Cretaceous)
- Lower Tuscaloosa Massive Sand Unit (U. Cretaceous)
- Dantzler Sand (L. Cretaceous)

Confining Units (Seals)
- Marine Tuscaloosa
- Austin Formation (Fm.)
- Selma Chalk/Navarro Fm.
- Midway Shale

Regional Assessment of Porosity was Used to Estimate Storage Capacity and Project Feasibility

<table>
<thead>
<tr>
<th>Stratigraphic unit</th>
<th>n</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>All data</td>
<td>3,648</td>
<td>8.7</td>
<td>40.0</td>
<td>24.8</td>
<td>25.1</td>
</tr>
<tr>
<td>Eutaw Formation</td>
<td>493</td>
<td>10.2</td>
<td>39.7</td>
<td>24.8</td>
<td>24.3</td>
</tr>
<tr>
<td>upper Tuscaloosa Group</td>
<td>162</td>
<td>13.8</td>
<td>35.1</td>
<td>25.2</td>
<td>25.1</td>
</tr>
<tr>
<td>Pilot sand</td>
<td>2,172</td>
<td>8.7</td>
<td>40.0</td>
<td>24.6</td>
<td>25.2</td>
</tr>
<tr>
<td>Massive sand</td>
<td>498</td>
<td>12.5</td>
<td>38.6</td>
<td>26.1</td>
<td>26.3</td>
</tr>
<tr>
<td>Washita-Fredericksburg interval</td>
<td>94</td>
<td>15.1</td>
<td>32.0</td>
<td>24.6</td>
<td>25.2</td>
</tr>
<tr>
<td>Paluxy Formation</td>
<td>229</td>
<td>12.3</td>
<td>29.4</td>
<td>23.3</td>
<td>24.1</td>
</tr>
</tbody>
</table>


Lower Tuscaloosa Massive Sand core, Plant Daniel MS
Areal Extent of the Lower Tuscaloosa Massive Sand Wedge is Extensive (High Capacity)

SECARB saline CO₂ storage resource capacity estimates

- Range 1,376–14,089 billion metric tons

Reservoir Area (mi²)
- Yellow: 26,000
- Green: 46,000

Lower Tuscaloosa Contours Modified From:
- AAPG Bull 1974 V.58 No.7 p.1272
- AAPG Bull 1990 V.74 No.6 p.857
- Geologic Map of Alabama (GSA 1970)
- Gas Fields Source: Atlas of Major Central and Eastern Gulf Coast Gas Reservoirs (GRI, 1992)

KS-6A = L. Tusc. Fluvial Deltaic Play
KS-6B = L. Tusc. Deltaic-Marine Play
Regional Assessment of Permeability Showed High Injectivity Storage Targets

<table>
<thead>
<tr>
<th>Stratigraphic unit</th>
<th>n</th>
<th>Maximum (mD)</th>
<th>Mean (mD)</th>
<th>Median (mD)</th>
<th>Standard deviation (mD)</th>
<th>Mean log x</th>
<th>Standard deviation log x</th>
</tr>
</thead>
<tbody>
<tr>
<td>All data</td>
<td>3,638</td>
<td>5,470</td>
<td>213</td>
<td>77</td>
<td>366</td>
<td>1.73</td>
<td>0.87</td>
</tr>
<tr>
<td>Eutaw Formation</td>
<td>491</td>
<td>5,470</td>
<td>184</td>
<td>35</td>
<td>500</td>
<td>1.54</td>
<td>0.84</td>
</tr>
<tr>
<td>upper Tuscaloosa Group</td>
<td>161</td>
<td>1,520</td>
<td>225</td>
<td>76</td>
<td>353</td>
<td>1.71</td>
<td>0.94</td>
</tr>
<tr>
<td>Pilot sand</td>
<td>2,172</td>
<td>2,840</td>
<td>206</td>
<td>74</td>
<td>331</td>
<td>1.69</td>
<td>0.90</td>
</tr>
<tr>
<td>massive sand</td>
<td>491</td>
<td>1,773</td>
<td>269</td>
<td>125</td>
<td>339</td>
<td>1.97</td>
<td>0.81</td>
</tr>
<tr>
<td>Washita-Fredericksburg interval</td>
<td>94</td>
<td>863</td>
<td>184</td>
<td>164</td>
<td>169</td>
<td>1.96</td>
<td>0.67</td>
</tr>
<tr>
<td>Paluxy Formation</td>
<td>229</td>
<td>3,950</td>
<td>236</td>
<td>131</td>
<td>451</td>
<td>1.93</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Structural Contour Map of the Top of the Rodessa Formation Near Plant Barry

- Mobile Graben located immediately east of Plant Barry
- Location of spill point near Plant Barry was uncertain !!!
- Moved injection site to Citronelle

Source: Geological Survey of Alabama and Esposito et al., 2008

Modified from: Pashin et al., 2008
Citronelle Oilfield and the Paluxy Formation

Plant Barry pipeline and Citronelle storage site near Mobile AL

CO₂ storage is in the Paluxy Formation at 9,400 ft (2,865 m)

<table>
<thead>
<tr>
<th>Stratigraphic Unit</th>
<th>Major Sub Units</th>
<th>Potential Reservoir and Confining Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eocene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuscaloosa Group</td>
<td>Marine Shale</td>
<td>Confining Unit</td>
</tr>
<tr>
<td></td>
<td>Pilot Sand</td>
<td>Saline Reservoir</td>
</tr>
<tr>
<td></td>
<td>Massive sand</td>
<td></td>
</tr>
<tr>
<td>Washita-Fredericksburg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Washita Shale</td>
<td>Primary Confining Unit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paluxy Formation</td>
<td>'Upper'</td>
<td>Injection Zone</td>
</tr>
<tr>
<td></td>
<td>'Middle'</td>
<td></td>
</tr>
<tr>
<td></td>
<td>'Lower'</td>
<td></td>
</tr>
</tbody>
</table>

Salt-cored dome with 4-way closure

Moving to Citronelle Created its Own Set of Challenges (production, injection and data gaps)
Assessment of Paluxy Formation Storage Properties (Permeability, Porosity)

Over 430 wells at Citronelle, but no core data for the Paluxy

Only two wells 4 miles away have porosity logs

Vintage logs available for remaining wells (SP, resistivity)

Alabama core data for the Paluxy Fm were used to develop a cross-plot of porosity versus permeability

Regional Cross-Plot of Porosity vs. Permeability

Formation data are typically lacking for most saline reservoirs
Initial Reservoir Simulation Results
(Optimizing Storage Capacity and Injectivity)

- Simulated 17 homogeneous sands
- Detailed reservoir architecture was built into the model
- After 10 years of injection, areal extent of CO₂ was estimated to be ~1,000 ft
- Low formation dip and relatively uniform reservoir properties creates a near-circular CO₂ plume

Results were uncertain because of lack of site-specific data
Reservoir Characterization

- Characterization Well D9-8#2
  - Total depth 11,817 ft (3,602 m)
  - Collected whole and side wall cores
    - ~200 ft of whole core
    - 45 percussion sidewall cores
  - Modern geophysical well logs (Triple Combo, MRI, mineralogy, dipole sonic, CBL)
- Well was later re-purposed for use as an observation well

Characterization well was needed to provide site-specific data
Prior to this project no core from the Paluxy Formation had been collected from the region.

Cored Top and Basal Paluxy Sands:
- Fluvial System: Sand and Shale sequence in both upper and lower core
- Fining upward units suggest channel fill
- ‘Sandy’ intervals are typically between ~ 2–10 ft
- Sharp base of medium-coarse grained sand grading upward to finer sand and then shale
Confirming Storage Injectivity for the Paluxy Formation

Lab measurements on core demonstrated exceptional reservoir properties
Refinement of the Reservoir Model

3D View of CO₂ Plume End of Injection

Original Model

Updated Model

• Original model predicted 1,000 ft CO₂ plume radius

• Updated model showed plume extent nearly 1,700 ft

• Plume is elongated up dip due to higher permeability in upper Paluxy Sandstones
In-zone Fluid Sampling to Confirm Water Chemistry

- USDW <10,000 mg/L TDS
- Quantifying deep brine chemistry can be challenging due to depressurization of samples


Reactive species concentrations are sensitive to the sampling method. Care must be taken during sampling to get meaningful results.

USGS collecting in-zone groundwater samples using:
A. gas-lift; B. electric submersible pump; C. Kuster sampler; and D. u-tube sampler
Brine Extraction Storage Test (BEST)—Managing CO\(_2\) Injection Pressures is Important for CO\(_2\) Storage Facility Integrity
EPRI conducted a life cycle analysis of extracting and treating brine, transmitting treated water

- Used Plant Smith waters as the basis for the analysis
- Performed techno-economic assessment of a hypothetical CCS water extraction project
  - Extraction
  - Transportation
  - Pre- and primary-treatment assuming zero liquid discharge
  - Residual waste disposal
- Computed power required over 30 years of operation
- Calculated CapEx/OpEx costs for entire system

Cost of water treatment can be significant adding another variable when selecting a site
Summary of Technical Siting Criteria (CCIS)

- **Capacity**
  - Sufficient volume (porosity & areal) = feasibility + safety

- **Containment**
  - Caprock free of transmissive fractures, faults and leaking well penetrations = CO\(_2\) isolation + safety
  - Geologic structure, caprock permeability and areal extent

- **Injectivity**
  - Rate and pressure maintenance (permeability) = feasibility + safety

- **Salinity**
  - Protection of Underground Sources of Drinking Water = resource protection + mitigation
Together…Shaping the Future of Electricity
EPRI’s Mission

Advancing **safe, reliable, affordable**, and **environmentally responsible** electricity for society through global collaboration, thought leadership and science & technology innovation
Three Key Aspects of EPRI

**Independent**
Objective, scientifically based results address reliability, efficiency, affordability, health, safety, and the environment

**Nonprofit**
Chartered to serve the public benefit

**Collaborative**
Bring together scientists, engineers, academic researchers, and industry experts
Our Members…

- 450+ participants in more than 30 countries
- EPRI members generate approximately 90% of the electricity in the United States
- International funding – nearly 25% of EPRI’s research, development, and demonstrations