Unconventional (Coal/Organic Shale) Small-scale CO₂ Injection Tests in the Central Appalachian Basin

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Research Partners

- Virginia Center for Coal and Energy Research (Virginia Tech) \(^1,2,3,4,5\)
- Cardno \(^2,3\)
- Gerald Hill, Ph.D. \(^1,4\)
- Southern States Energy Board \(^1,5\)
- Virginia Dept. of Mines, Minerals and Energy \(^3\)
- Geological Survey of Alabama \(^3\)
- Sandia Technologies \(^3\)
- Det Norske Veritas (DNV) \(^4\)
- Consol Energy (Research Group) \(^2,3\)

1 Project management
2 Operations
3 Research
4 Risk management
5 Outreach

Industrial Partners

- Consol Energy (CNX Gas)
- Harrison-Wyatt, LLC
- Emory River, LLC
- Dominion Energy
- Alpha Natural Resources
- Flo-CO2

Collaborators

- Schlumberger
- Global Geophysical Services
- Oak Ridge National Laboratory
- University of Tennessee
- University of Virginia
- Southern Illinois University
- Oklahoma State University
Project Objectives

• Test the CO$_2$ storage potential of coal and organic shale reservoirs:
  – Injection target of approximately 20,000 metric tons (total)
  – **Coal test**: one year period
  – **Shale test**: “huff and puff”

• Assess the potential for enhanced gas recovery from coal and shale reservoirs

• Major tasks:
  – Phase I: site characterization, well coring, injection design
  – Phase II: site preparation, injection operations
  – Phase III: post-injection monitoring, data analysis, reservoir modeling

DE FOA 0000441 objectives:

• Characterize both unconventional reservoirs (basalts, organic shale, coal) and conventional saline reservoirs
• “increase our understanding of the potential for these formations to safely and permanently store CO$_2$”
• “determine the usefulness of potential geologic storage sites”
Previous Work of VCCER Team

• **SECARB Phase I:**

• **SECARB Phase II**
  – **Task II:** Performed Pilot CO$_2$ Injection Field Tests in Virginia (1,000 tons) and, under the direction of the GSA, in Alabama (300 tons) (2005-2011)
Coalbed Methane Production (CBM)

(i) Dewatering: pressure ↓, effective stress ↑, fracture apertures ↓, permeability ↓

(ii) CH₄ release → matrix shrinkage and zero volume change condition, fracture apertures ↑, permeability ↑

- Net Permeability:
  Competing effects (i)-(ii)

Enhanced Coalbed Methane Production (ECBM)

(i) CO₂ greater affinity to coal than CH₄

(ii) Depending on coal rank coal matrix can adsorb twice to as much as ten times more CO₂ as CH₄

(iii) When CO₂ is adsorbed matrix swells; under zero volume change condition, fracture apertures ↓, permeability ↓
Previous Experience in Huff and Puff Test in Russell County, Virginia (2009)

Production curve for huff-and-puff test well, Russell County, Virginia, 2009

- 1000-ton CO₂ injection
- Stacked coal reservoir
- Evidence of preferential adsorption: elevated N₂ and CH₄
- Enhanced CH₄ recovery at two offset wells, no CO₂ breakthrough
- 30% CO₂ in flowback over 5 years
- EUR of test well has increased by 48 percent
CBM CO₂ Injection Test in Buchanan County, Virginia

- Oakwood coalbed methane field
- Stacked coal reservoir, 15-20 seams
- Tight shale and sandstone confining units
- 20,000-tonne CO₂ injection over one year in three legacy production wells
- CO₂ storage + Enhanced gas recovery (EGR)
- Permitting finalized including US EPA Class II UIC Permit
- Current status: final site preparations
CBM CO₂ Injection Test in Buchanan County, Virginia
Reservoir Modeling

Stratigraphic cross section through injection wells

Modeling Considerations:

- 15-20 coal seams in injection zone
- Average seam thickness of 1.0 feet
- Depth range: 800-2200 feet
- Variable lateral continuity
- Intermediate and overlying seals
- Integrity of perforations
- Dynamic reservoir properties (active production operations)
- Multi-phase flow
CO₂ Injection simulations used to define Area of Review (AOR) for monitoring program
CBM CO₂ Injection Test in Buchanan County, Virginia
Monitoring, Verification, and Accounting (MVA)

Oakwood Field Demonstration Site

MVA Focus Area
• Injection wells
• CBM production wells
• MVA boundaries
• Roads
• Monitoring and characterization wells
• Microseismic array (28 stns)
• GPS array (20 monuments)
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Well logging

• **Injection wells**
  – Borehole camera
  – CO₂ injection logging: flow rate (spinner test), pressure, temperature

• **Monitoring and characterization wells**
  – Gamma Ray
  – Deviation
  – Temperature
  – Caliper
  – Density

• **Characterization well only**
  – Sonic log (surface to TD)
  – Formation MicroImager (FMI)
  – Ultrasonic Borehole Imager (UBI)
  – Neutron Porosity
  – Resistivity

Temperature logging from injection test in Russell County, Virginia (2009)
Perfluorocarbon Tracer Study

Considerations:

- Multiple injection wells
- Multiple coal seams
- Variable hydraulic fracture success by perforation/seam
CBM CO₂ Injection Test in Buchanan County, Virginia
Monitoring, Verification, and Accounting (MVA)

Microseismic Array and Tomographic Fracture Imaging™ (TFI)
From Global Geophysical Services, Inc.

- Well-suited because of its high sensitivity
- Semblance-based algorithm
- Records microseismic events and “slow earthquakes”
- Can locate events within the context of the mapped 3-D fracture network
- Low CO₂ injection rates are likely to produce only weak seismic energy.
- Baseline monitoring recorded no microseismic events

Map-View Slice at 1700 feet. The “hit count” number represents how many times a voxel was activated.
CBM CO$_2$ Injection Test in Buchanan County, Virginia
Monitoring, Verification, and Accounting (MVA)

Surface Deformation Measurement

Combination of technologies:
- **InSAR** acquisition: TerraSAR-X satellite
- **ISBAS** (intermittent small baseline subset) processing for InSAR
- **GPS** array: 20 stations

Additional subsidence responses from gas extraction and active and abandoned mine workings

**Advantages:**
- shallow injection targets
- coal swelling

**Challenges:**
- terrain
- tree cover
CBM CO₂ Injection Test in Buchanan County, Virginia
Monitoring, Verification, and Accounting (MVA)

MVA Approach

Borehole-scale technologies:
- Pressure/Temperature
- Gas composition
- Tracers
- Formation logging

Technologies deployed over large areal extents:
- Microseismic/TFI
- Surface deformation measurement (GPS + InSAR)

- Combination of technologies will provide data sets with overlapping spatial and temporal scales.
  - Data will help distinguish signals from CO₂ operations vs. active CBM operations
  - Data sets will cross validate each other

- Selected technologies to address/overcome challenges of reservoir geometry and terrain
Shale CO$_2$ Injection Test (510 tons)
Morgan County, Tennessee

- Horizontal well in Chattanooga Shale formation, drilled in 2009
- Legacy producing gas well permitted under TDEC
- 510 tons for “huff and puff” injection test
- **Injection period**: March 18-31, 2014 (14 days)
- **Shut-in period**: March 31- July 29, 2014 (~4 months)
- **Flowback period**: July 29, 2014- present (~8 months)
- **Current status**: post-injection monitoring
Shale CO₂ Injection Test in Morgan County, Tennessee
Reservoir Modeling

Depth at heel: 2600'

Depth at toe: 3600'

2600’ lateral length, drilled up-dip

Hydraulically fractured in 4 stages with N2-Foam
Shale CO$_2$ Injection Test in Morgan County, Tennessee
Reservoir Modeling

Modeling stimulated reservoir volumes (SRVs):
- Shape based on nearby microseismic data
- Variable permeability
- Input for sensitivity analysis, history matching

Modeling predictions:
- CO$_2$ injection flow rate: 50 tons/day
- Wellhead pressure: ~800 psi
- Closed system behavior
Shale CO₂ Injection Test in Morgan County, Tennessee
Monitoring, Verification, and Accounting (MVA)

MVA Overview:
• Gas and water sampling
  – Commenced: 4/2013
  – Injection Well: HW-1003
  – 13 Offset Monitoring Wells
    • 3 Horizontal / 10 Vertical
    • 11 In-zone / 2 Out-of-zone
• Perfluorocarbon tracer study
• Surface water sampling

Monitor for:
• Injection Phase: % Composition, Tracer Arrival
• Soaking Phase: Pressure, % Composition
• Flowback Phase: Flowrate, % Composition, Tracers
Shale CO₂ Injection Test in Morgan County, Tennessee
Operations Overview
Shale CO$_2$ Injection Test in Morgan County, Tennessee

Operations Overview

- Storage Vessel
- Propane Heater
- Tracer Injection Tee
- Check valve
- Ball valve
- Gate valve
- CO$_2$ Inlet
Shale CO₂ Injection Test in Morgan County, Tennessee
Injection Summary

- 510 tons CO₂ injected
- Avg. Flow Rate: 40 tons/day (predicted: 50 tons/day)
- Avg. Wellhead Temp: 50°F
- Max Wellhead Pressure: ~500 psi (Gas Phase) (predicted: ~800 psi) – (Liquid Phase)
Shale CO₂ Injection Test in Morgan County, Tennessee
Monitoring, Verification, and Accounting (MVA)

Perfluorocarbon Tracers
Injected with CO₂ stream

- **Sulfur Hexafluoride (SF₆)**
  - 0.574 kg at 50-ton mark
  - Booster Pump and Air Compressor

- **Perfluoromethylcyclopentane (PMCP)**
  - 0.854 kg at 50-ton mark
  - Syringe Pump

- **Perfluoromethylcyclohexane (PMCH)**
  - 0.894 kg at 350-ton mark
  - Syringe Pump
Shale CO₂ Injection Test in Morgan County, Tennessee
Injection Summary

- CO₂ injected in gas phase (predicted: gas/liquid)
- SF6 injected in gas/liquid phase (predicted: liquid)
- PFTs injected in liquid phase (predicted: liquid)
Shale CO$_2$ Injection Test in Morgan County, Tennessee
Results to Date

Injection period:
- No increased concentration of CO$_2$ at offset wells *
- No detection of tracers at offset wells *

Shut-in period:
- Wellhead pressure leveled out at 260 psig for 3 months *
- No liquids downhole
- All gas phase in wellbore
Shale CO$_2$ Injection Test in Morgan County, Tennessee

Results to Date

Injection period:
- No increased concentration of CO$_2$ at offset wells*
- No detection of tracers at offset wells*

Shut-in period:
- Wellhead pressure leveled out at 260 psig for 3 months*
- No liquids downhole
- All gas phase in wellbore

*Indications of closed system behavior
- Consistent with modeled predictions
- CO$_2$ confinement $\rightarrow$ storage option
Shale CO$_2$ Injection Test in Morgan County, Tennessee

Flowback Results to Date
Shale CO₂ Injection Test in Morgan County, Tennessee

Results to Date

- EGR: An increase of 2.76 MMCF (108%) versus baseline production in early flowback (*shut-in losses not included)

- Correlated production of hydrocarbons and CO₂
- 34 percent of injected CO₂ produced to date (173 tons)
- Current CO₂ production rate of 0.22 tons/day
Shale CO$_2$ Injection Test in Morgan County, Tennessee
Results to Date

Production of heavy hydrocarbons elevated from baseline values:

- Role of pressure, viscosity and adsorption/desorption processes
- Enhanced recovery $\rightarrow$ implications for other shale plays
Project Wrap-up

– Project status
  • CBM test: final site preparation, currently drilling, logging and installing pipeline, start injection spring 2015 (injection pressure management to offset coal-swelling), 1-year of post-injection monitoring
  • Shale test: injection completed, ongoing monitoring, approaching site closure phase

– Key Findings to Date
  • CBM test: developed monitoring program well-suited for stacked injection zones, within mountainous terrain;
  • Shale test: Closed reservoir system, enhanced heavy hydrocarbon production
Acknowledgments

- Financial assistance for this work was provided by the U.S. Department of Energy through the National Energy Technology Laboratory’s Program under Contract No. DE-FE0006827.
- Advice and guidance of the NETL project management team is appreciated.