Surface and Airborne Monitoring Technology for Detecting Geologic Leakage in a CO$_2$-Enhanced Oil Recovery Pilot, Anadarko Basin, Texas

Project Number DE-FE0012173

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Oklahoma State University

U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting
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Presentation Outline

• Benefit to Program
• Goals and Objectives
• Project Team
• Technical Status
• Accomplishments to Date
• Synergy Opportunities
• Summary
Benefit to the Program

• Develop and validate technologies to ensure 99 percent storage permanence.
• Develop technologies to ensure containment effectiveness.
• Develop Best Practice Manual for monitoring, verification, accounting.
• This project is developing next-generation surface and airborne (UAV) technologies that perform well and can be deployed rapidly and at reasonable cost. Technology to be deployed at the Southwest Regional Carbon Sequestration Partnership’s Farnsworth Pilot Site.
Project Motivation

- Surface monitoring integral to pilot programs; facilitates public acceptance.
- Major spatial sampling issues with current technology.
- Questions whether current technology is capable of detecting leaks.
- Deployment labor-intensive, expensive.
- New surface-based and UAV-based technology has potential to solve spatial sampling issue, reduce project costs.

Sample grid above oil seeps
Project Overview:
Goals and Objectives

• Evaluate low-cost sensors for carbon dioxide and methane.

• Develop ground-based and airborne (UAV-) based sensor platforms that minimize the labor cost associated with long term monitoring.

• Collect data from an active injection site for a period of at least one year.

• Develop monitoring strategies that minimize the need for ground-based monitoring while preserving the quality of the monitoring effort.
Project Team, Roles, Responsibilities, Project Organization

- Project Team: Oklahoma State University
  - Chemical Engineering
    - Peter E. Clark, PI
  - Geology
    - Jack Pashin, Co-PI, Geological Evaluation
  - Chemistry
    - Nicholas Materer, Co-PI, Sensor Development
  - Civil Engineering
    - Tyler Ley, Co-PI Sensor Development
  - Mechanical Engineering
    - Jamey Jacobs, Co-PI, UAV
    - Girish Chowdhary, Co-PI, Data Analysis
Technical Status

- Geological characterization and assessment of leakage risks.
- Sensor evaluation and deployment using surface and airborne platforms.
- UAV evaluation and testing; and deployment at Farnsworth Oil Unit.
- Application of advanced data analysis techniques.
Farnsworth Oil Unit

Operator: Chaparral Energy
Reservoir: Morrow Sandstone (Penn.)
Oil Production: > 36 MMbbl
CO₂-EOR operations since 2010
SWP Phase III CCUS project underway
# Stratigraphic Column

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<thead>
<tr>
<th>Depth (ft)</th>
<th>Rock type</th>
<th>Stratigraphy</th>
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<td>Doxey Formation</td>
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<td>Castille-Salado evaporites</td>
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<td>Rush Springs Sandstone</td>
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<td>Whitehorse Group</td>
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<td>Simpson Group</td>
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<td>8000</td>
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<td>Ellenburger Group</td>
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<td>Basement</td>
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- **USDW**
- **Regional seal**
- **Stacked sinks and seals**
- **Farnsworth EOR target**

**Rock types**
- Variegated sandstone
- Sandstone
- Variegated mudstone
- Black Shale
- Gray shale
- Limestone
- Dolomite
- Igneous-metamorphic

- Caprock
- Ogallala Fm.
Surface Formations

- **Caprock**
  - Chert breccia
  - Well jointed

- **Ogallala Fm.**
  - Joints in indurated layers
  - Silty sand with caliche nodules
  - Caliche nodules
Joint Networks

Satellite image
Chert caprock

Outcrop photo
Ogallala sandstone
Joint Orientation

Joint measurements

Modern stress indicators

Focal mechanism
Borehole breakouts
Hydrofractures
Geological Findings

- Multiple seals between reservoir and USDW.
- Natural fractures influence flow in USDW and chert caprock.
- Abundant natural sources of CO$_2$ and microbial CH$_4$ near surface.
**Goal:** Develop a reliable and cost-effective distributed sensor network to monitor CO$_2$ and CH$_4$ emissions (solar powered, minimal maintenance).

Eight CO$_2$ and six CH$_4$ sensor elements investigated.

Three sensors were chosen based on their price and accuracy.

Lessons learned:
- Almost none arrived correctly calibrated
- Automatic background/baseline corrections lead to inaccuracies
- Datasheets were incomplete; significant effort to get them to work properly
Sensor Elements

**CO₂ Sensor:**
Senseair K-Series selected for Sensor Nodes and UAV
Best performance for cost

**CH₄ Sensor:**
Edinburgh GasCard performed very well for CO₂ & CH₄.
Most expensive.
Sensor Node
Sensor Grid

- Many different configurations possible—Used cluster tree layout
- Used ZigBee Technology
- Real time collection can be used
- Sensor Nodes (Routers + End Devices)
- Coordinator Nodes will have high accuracy sensors and cell modem
Farnsworth Injection Well Site

Deployed in Farnsworth Oil Unit

- One subnet is deployed and two more are being installed this week!
- Response is steady and reliable
- Some variation in gas concentration can be detected
Airborne Sensor System

Airborne CO₂ Sensor Requirements
» Quick response
» Low cost
» Good accuracy
» Low SWAP (Size, Weight and Power)
» Non-Dispersive Infrared preferred option

<table>
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<th>Sensor Model</th>
<th>Measurement Range</th>
<th>Accuracy</th>
<th>Response Time</th>
<th>Cost</th>
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<td>±100 ppm</td>
<td>120 sec</td>
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Unmanned Aircraft System

- Skyhunter UAS; 7 foot wingspan; handlaunched
- 15 lb GTOW, 45-60 min endurance
Example Flight Path
Stabilis Autopilot

- OSU Stabilis: Mission flexibility and accuracy
  - Waypoint-driven flight planning
  - Interfaces with a variety of planners
- Modular sensor and power integration
  - Parallel embedded Linux modules
- "Plug and play" autopilot
  - Adapts to mission needs and minimizes tuning of control gains

Stabilis interfaces with a Beaglebone Black

http://beagleboard.org/Products/BeagleBone%20Black
Test Results

- Wind tunnel tests for flow rate and response time
- OSU low speed wind tunnel
  - 3’ x 3’ test section
  - 55 knot max speed
CO₂ Sensor – Flow Rate

- No Funnel
- Funnel
- Funnel, Prop
- No Funnel, No Filter

Airspeed (m/s)

Flow Rate (LPM)

Test Results

Wind tunnel conditions

Aircraft
Validation Flight Tests

» CO₂ tank point sources
» 2.5 mph SSE, 5 mph gust
» Low altitude passes only
» 0.5 LPM
» 7 sec data latency
Validation Flight Tests

- ~5 lb heated CO₂ tank
- 125 g release for 30 s on upwind passes
- 3 kg for 12 min on crosswind passes
- Correlation with ground network
Information Fusion using GP

- Gaussian Process: Bayesian Nonparametric model for spatially correlated distributions
- Distributed static and dynamic heterogeneous agents learning parts of the CO₂ and CH₄ models
- Naïve data sharing can overwhelm the network, how to minimize communication for distributed inference?
- Transmit compressed generative GP models instead of transmitting data
- **Value-of-Information** metrics utilized to minimize network clutter

Distributed network topology with static and dynamic agents

GP-Fusion with adaptive Value of Information (VoI) thresholds minimizes error with less communication

Gaussian processes model correlated data as distributions over functions
Accomplishments to Date

- Field site at Farnsworth Oil Unit.
- Geologic framework characterized; hypotheses formulated to help guide field operations.
- Robust and cost-effective near-surface and airborne sensors identified.
- UAV platform selected, instrumented, field-tested.
- Data management and processing techniques evaluated and tested.
- Deployment at Farnsworth underway.
Synergy Opportunities

• Limitless opportunities for collaboration.
• Sensor technologies deployable for a broad range of geological and operational monitoring applications.
• Sensor development and application fertile ground for collaborative research.
• UAV monitoring technology has utility at virtually all storage sites and can perform multiple tasks simultaneously (i.e., flux monitoring plus checking on status of operations).
• Wider deployment of technology helps define applicability, limitations, and best practices.
Summary

- Numerous shale and evaporite seals make Farnsworth a favorable storage site.

- Abundant natural fractures and natural CO$_2$ and CH$_4$ sources near surface; facilitate heterogeneous gas flux.

- Identifying robust and cost-effective options for near-surface and airborne CO$_2$ and CH$_4$ sensors required compromises.

- UAVs instrumented, tested, being deployed.

- Gaussian Process viable approach to data manipulation and modeling.

- Field deployment underway at Farnsworth.
Appendix

– These slides will not be discussed during the presentation, but are mandatory
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Total BP1 $977,304 Total BP2 $625,713 Total BP3 $654,948

Current Status:

Per sub task $2,257,965

Axelrod, Chowdary, Karaman. Exploitation by Informed Exploration between Isolated Operatives for Data Harvesting, CDC, Osaka, Japan.

Axelrod, Learning to Exploit Time-varying Heterogeneity in Distributed Sensing using the Information Exposure Rate, MS Thesis, OSU, Stillwater, USA.


Rakshit Allamraju & Girish Chowdhary, Multiagent Game Emulator(MAGE) for collaborative Autonomy Research, R4Sim workshop at the Robotics Science & Systems 2015, Rome Italy.