MONITORING CCUS AT AN ACTIVE EOR SITE: 
AN OVERVIEW OF A LARGE SCALE CARBON CAPTURE, 
UTILIZATION, AND STORAGE DEMONSTRATION AT 
TEXAS, USA

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OUTLINE

• Introduction to the SWP
• Status of SWP at end of Injection Period Monitoring
• Effort divided into four groups
  • Characterization effort and lessons learned
  • Simulation effort and lessons learned
  • MVA effort and lessons learned
  • Risk Assessment effort and lessons learned
• “Post-Injection Period” priorities
THE SOUTHWEST PARTNERSHIP AND FARNSWORTH UNIT
AREA COVERED BY THE SWP
Anthropogenic Supply: 500-600,000 Metric tons CO$_2$/year supply

Legend
- Green: Utilization & Storage
- Blue pentagon: Carbon Capture
- Red: Transportation
- Gray: Oil Fields

Other CO$_2$ Sources
- Yellow circle: 0.1 to 0.7 MT/yr
- Yellow circle: 0.7 to 1.8 MT/yr
- Yellow circle: 1.8 to 4 MT/yr
- Yellow circle: 4 to 10 MT/yr
- Yellow circle: 10 to 20 MT/yr

Farnsworth Unit
- Arkalon Ethanol Plant
- Camrick Area
- Booker Area
- Agrium Fertilizer Plant

Map showing regions in Kansas, Oklahoma, and Texas with transportation and oil fields marked.

http://www.conestogaenergy.com/arkalon-ethanol

www.agrium.com
SOUTHWEST PARTNERSHIP: TIMELINE

• Phase I – regional sources and sinks,
  • ID Phase II studies
• Phase II – pilot scale studies
  • ID Phase III study site
• Phase III Budget Period 3 – Large Scale demonstration
  • Pre-injection
  • Injection Monitoring
• Phase III Budget Period 4 – “Post-Injection”


July 31, 2018
PROJECT STATUS – END OF PHASE III
SOUTHWEST PARTNERSHIP: CO$_2$ STORAGE

Cumulative CO2 Storage – Metric Tonnes

- **Total injection volume monitored**: 1,428,046
- **Target storage**: 918,333
- **Actual storage**: 739,862

- Stored Since 2010
- Stored Since SWP Monitoring Began
- Proposed Storage
- Goal
ACCOUNTING - CO₂ AND INCREMENTAL PRODUCTION

- Average monthly oil rate increased from ~3,500 to ~65,000 BBL's in first 4 years of CO₂ Flood
- Initial production response within 6 months
- ~3.8 million STB produced during CO2 flood

- 739,863 tonnes stored since October 2013
- 688,183 tonnes recycled since October 2013
- 1,180,379 tonnes stored since November 2010
- 92.7% of purchased CO₂ still in the system
SWP CHARACTERIZATION EFFORTS AND LESSONS LEARNED
CHARACTERIZATION – GEOLOGICAL UNDERSTANDING

• Goal: Reservoir & caprock description – depositional setting, reservoir architecture, lithologies, fracture potential, geomechanical properties

• Tools: Cores & core analyses, thin section, microprobe, log & seismic data, geomechanical, borehole image logs, CT scanning
CHARACTERIZATION – GEOLOGICAL UNDERSTANDING

• Findings:
  • Incised valley model fits well, reservoir can be divided into lithofacies based on core descriptions
  • Lithofacies provide a record of marine transgressive/regressive sequences that have effects on reservoir diagenesis
  • Reservoir can also be characterized by Hydraulic Flow Units (HFU) determined from porosity and permeability data using Winland R35 approach, these have different pore structure and interconnectivity
  • Caprock is a sequence of interbedded mudstones/shales and diagenetic limestones
  • Better understanding of fluid/rock interactions, relative permeability data
CHARACTERIZATION OF GEOLOGY AT MULTIPLE SCALES

Facies model – reservoir scale

MicroCT Imaging – pore scale, can differentiate between HFUs defined by R35 method

1-3 Sample E2, well 13-10A, 7684.75 ft bgs

Medial axis, macro-pores and clay-filled pores

Volume rendering, macro-pores (green) and clay-filled pores (blue)

3-4 Sample 2 7670.55” HFU3-4

Pore rendering

Cross-laminae with carbonate cement and little porosity serve as flow barriers
CHARACTERIZATION: SEISMIC DATA

Annually updated
Geological model

Planar features may be faults, fractures, and/or facies changes, paleovalley walls – remains to be determined
CHARACTERIZATION: MECHANICAL EARTH MODEL

- Goal: Create a mechanical earth model that could be used to model rock behavior under a variety of scenarios
- Tools: Well logs, mechanical tests, geophysical studies
- Results: A small scale (5000 ft. by 5000 ft.) mechanical earth model centered on 13-10A. Utilized 1D geomechanical model generated by Schlumberger at 13-10A from sonic logs and post stack 3D seismic inversion to calculate geomechanical properties
CHARACTERIZATION: CAPROCK INTEGRITY

• Goal: Caprock Integrity – how good is the seal?
• Tools: Core analysis, lithofacies & petrographic studies, mechanical testing, isotope analysis, mercury porosimetry, capillary pressure data
• Findings: Caprock The highest CO\textsubscript{2} column height is in the cementstone lithology at 11000 m (36089 ft). The lowest CO\textsubscript{2} column height for the caprock system is in the mudstone lithology within the upper Morrow Shale at 1100 m (3609 ft).
• Fracture gradients indicate that the Morrow B sandstone reservoir is weaker than the overlying lithologies, so any fractures initiated around the injection zone should be contained
SWP MVA EFFORTS AND LESSONS LEARNED

The MVA technologies deployed by the SWP are targeted to provide the data necessary to track the location of CO$_2$ in the study area, including migration, type, quantity and degree of CO$_2$ trapping. Monitoring data is used to facilitate simulation and risk assessment, particularly with respect to USDWs, the shallow subsurface, and atmosphere.
Detecting CO$_2$ and/or brine outside Reservoir:

- Groundwater chemistry (USDW)
- Soil CO$_2$ flux
- CO$_2$ & CH$_4$ Eddy Covariance
- Aqueous- & Vapor-Phase Tracers
- Self-potential (AIST)
- Distributed Sensor Network (Ok. State)

Tracking CO$_2$ Migration and Fate:

- *In situ* pressure & temperature
- 2D/3D seismic surveys
- VSP’s
- Cross-well seismic
- Passive seismic
- Fluid chemistry (target reservoir)
- Aqueous- & Vapor-Phase Tracers
- Gravity surveys & MagnetoTelluric (AIST)

MVA relational database:
- All SWP non-seismic MVA data in one central location
- Collection of related tables that can be readily queried
- Efficient, Fast
- Complex searching
- Web ready
- Secure
USDW Monitoring

- Quarterly sampling of groundwater wells in/around FWU (n≈22) to monitor for brine, hydrocarbon and/or CO₂ leakage from depth.
  - Includes Major Cations/ Anions, pH, Conductivity, Alkalinity, Oxidation and Reduction Potentials (ORP), Inorganic Carbon (IC) and Organic Carbon (OC), Trace Metals and Isotopes (13C,18O, and D).
- Total/Dissolved Inorganic Carbon (DIC) increasing “field wide” (>18 USDW wells).
  - DIC ($C_\text{T}$) = [CO₂] + [HCO₃⁻] + [CO₃²⁻]
  - DIC is a measure of CO₂ in an aqueous system
  - However! No other indicators of CO₂ leakage yet measured (pH steady, Alkalinity decreasing, ORP increasing)
- More data needed, but increasing DIC values likely due to regional recharge and/or groundwater contamination from the surface (e.g. fertilizers)
- Technology validates spatial and temporal sampling as a means to monitor USDW for potential leakage
MVA MAJOR FINDING: COUPLING OF GEOPHYSICS, MODELING & TRACERS

Geophysical modeling & structural interpretation using 3D reflection seismic
- Seismically resolvable faults/fault-like features interpreted by seismic attributes
- Implies many smaller faults/fractures
- Faults probably act as sealing features rather than seal bypass systems
- Faults affect geologic properties in geomodel

Reservoir Tracers
- Reservoir tracer data yielded useful model development data, including verification of and characterization of faults and transport pathways.

Modeling & Simulation
- Numerical simulations of the aqueous-phase tracer injections were able to successfully predict fluid transport in specific well patterns and increased permeabilities along adjacent faults.
SWP SIMULATION EFFORTS AND LESSONS LEARNED
SIMULATION: TECHNOLOGIES AND APPROACH

SOFTWARE:
- Different software used to satisfy the full range of THMC processes
- STOMP-EOR (PNNL)
- Eclipse/Petrel (Schlumberger)
- Geochemist’s Workbench (U. Ill.)
- TOUGHREACT (LBNL)
- Other in-house codes for specialty applications (proxy/ROMs, resource analysis, economics, etc.)

CALIBRATION:
- Porosity & permeability inverted from logs
- Calibration with laboratory tests yields good results, e.g.
  - Slim tube experiment for MMP
  - Relative permeability tests

SOME HIGHLIGHTED GOALS:
- Computer assisted history matching
- Proxy Modeling (ROMs)
- Optimization framework
Simulation model showing Non-aqueous Liquid Saturation and impact of planar features on flow
• Successfully history matched several generations of geomodels provided by the Characterization group
• Successfully implemented proxy modeling technique to reduce computational time without compromising accuracy
• Successfully developed co-optimization of CO\textsubscript{2} storage and oil recovery framework which may be applied to other projects
SIMULATION: MAJOR FINDINGS

• For this field, injected CO$_2$ persists as an immiscible phase for only a few decades after injection ceases

• Calcite was predicted to be the most abundantly precipitated carbonate mineral over the entire study area (model domain)

• In the immediate vicinity of injection wells, dolomite was the most abundantly precipitated carbonate mineral

• Native reservoir minerals, albite, clinochlore, and illite, were predicted to dissolve, whereas quartz, kaolinite, and smectite were predicted to precipitate

• Dissolution and precipitation of minerals in the Morrow B Sandstone induce negligible changes in its porosity
SWP RISK ASSESSMENT EFFORTS AND LESSONS LEARNED
RISK ASSESSMENT: TECHNOLOGIES

• Qualitative Risk Analysis (MOSTLY COMPLETE)
  • Risk Registry via Failure Modes and Effects Analysis (FMEA)
  • Annual Risk Survey (2014-2017)
  • Process Influence Diagram (PID)

• Quantitative Risk Analysis (ONGOING)
  • Probabilistic Assessment
  • Geologic/reservoir models
  • Reduced Order Models (ROMs)
    • Response Surface Method
    • Polynomial Chaos Expansion (PCE)
  • NRAP tools: NRAP-IAM-CS, RROM-GEN
RISK ASSESSMENT: RECENT ACCOMPLISHMENTS


• Constructed process influence diagrams (PIDs) for quantitative risk assessment

• Developed apparently-robust ROMs for representing full-reservoir model simulation results, to save computational time and effort.

• Developed workflow from physics-based reservoir simulators to performing leakage calculations using NRAP-IAM-CS

• Developed integrated framework of combined batch experiments and reactive transport simulations to analyze mechanisms of trace metal mobilization.
Wellbore Leakage:

- Wellbore cement at the FWU will likely maintain its structure and integrity within 100 years, and is unlikely to provide leakage pathways.

USDW Impact:

- Toxic trace metals may be considered an insignificant long-term concern for the Ogallala formation: simulations indicate that clay adsorption mitigates impact of CO$_2$ and brine leakage from the reservoir.
- Increased salinity of USDW via leaked saline water may likely be a larger concern than associated trace metals release.

CO$_2$ Storage and Economics:

- Hydrodynamic trapping sequesters the most injected CO$_2$ at the FWU, followed by oil dissolution trapping, and aqueous dissolution trapping.
- ROMs analyses suggest that 31% of the 1000 realizations designed for FWU may be profitable.
POST-INJECTION PERIOD (BP4) PLANS
SOUTHWEST PARTNERSHIP: CO₂ STORAGE

Cumulative CO₂ Storage

Total Injected since 2013 1,759,497
Total Storage since 2013 840,709

CO₂ Thousands Metric Tonnes

- Stored Since 2010
- Proposed Storage
- Storage Goal
- Injected
- Recycled
- Stored Since SWP Monitoring Began

Total Injected since 2013 1,759,497
Total Storage since 2013 840,709

32
INCOMPLETE AND FINAL WORK ITEMS

Critical work that is incomplete

- Support work
  - Characterization
  - Simulation
  - Monitoring (MVA)
- Passive seismic
- Depleted oilfield storage analysis (post EOR storage)
- Risk assessment (quantitative things)
  - Storage security
  - Leakage pathways
  - Wellbore integrity

Risk relies on much input from prior tasks and thus significant work remains
FOCUS AREA: SUPPORT WORK

• Characterization
  • VSP, Xwell, geobodies, larger scale mechanical earth model
  • Fine scale VSP based models and time-lapse geomodels
  • Better understanding of fault/fault-like features

• Simulation
  • Incorporate all tracer data
  • Contribute to long-term storage and risk assessments
  • Incorporate lab generated data, especially hydraulic flow and facies

• Monitoring (MVA)
  • Continue monitoring efforts until project close
  • Continue to provide support, data, and feedback to model builders, simulators, and risk assessment
Major work left in:

• Storage security

• Leakage pathways – chemomechanical studies of rock/fluid interactions under reservoir PT conditions

• Wellbore integrity – inventory older wells for cement quality, do sidewall coring, study effects of CO$_2$ on cement and near-wellbore rock

• Take results from reduced order models back into full-scale simulation
• Capacity analysis – quantifying capacity for commercial storage when factoring in post-EOR storage.

• Portability to other Anadarko or SW basins (Morrow reservoirs in particular – screen other fields based on FWU criteria and results).

• Evaluate impacts of credits such as 45Q on future projects

• Provide example and operational procedures for future EOR operations utilizing storage credits
• Test of an inexpensive off the shelf system to monitor if activity existed was successful in that it identified microseismic activity related to injection

• The system ultimately failed due to hardware limitations and damage incurred during emplacement leading to increasing signal to noise ratio

• Utilization of passive seismic not only as a risk assessment but also characterization tool
  • example: Aneth faults for characterization/risk and
  • example: AZMi and BZMi for risk

• New system installed this year
  • Borehole array
  • 20 Surface seismic stations
PASSIVE SEISMIC: BOREHOLE ARRAY REPLACED

- GeoRes recording system
- 16 levels three components geophone array
- 100 ft geophone spacing
- Depth interval: 4,389 – 5,889 ft
- 1 ms sampling rate
- Each geophone is contained in a protector and clamped to production tubing
- Geophone housing and protector were redesigned for optimal coupling to casing and tubal noise reduction
- System was installed in December 2018
PASSIVE SEISMIC: SURFACE STATIONS INSTALLED

• Survey design and modeling was performed for optimal sensor placement

• Twenty Guralp 3T-120 Broadband sensors were deployed in the FWU

• Samples per second: 250

• All Sensors oriented to true North: Declination 5° East.

• Continuous recording data acquisition system (DAS) was deployed with each sensor
PASSIVE SEISMIC: SURFACE LOCATIONS
PASSIVE SEISMIC: BOREHOLE ORIENTATION
TIMELINE TO COMPLETE PROJECT – 4 YEARS

- 24-36 months data collection: Passive seismic installation, acquisition, processing, and assimilation; Hydrophone Cross-well baseline and repeat; tracer results to be acquired and assimilated
- Integration of new data into geologic, simulation, and risk models
- Quantitative risk estimates using final models
- SWP exits FWU site
- Final reports, best practices manuals, presentations

DATA ACQUISITION, FINAL GEOLOGIC MODELS

INTEGRATE FINAL MODELS WITH SIMULATIONS

FINAL QUANTITATIVE RISK ASSESSMENTS/STORAGE

STAGGERED EXIT FROM SITE

REPORTS, WRAP-UP

2018                             2019                             2020                                   2021                             2022
CONCLUSIONS

• Demand for CO₂ for EOR projects has outpaced natural supplies

• Carbon Capture can mitigate CO₂ emissions using geologic storage and is responsive to government interests in reducing carbon emissions, worldwide

• Costs for using anthropogenic CO₂ for EOR purposes is mitigated by existing oilfield infrastructure and increased oil production

• Case studies can provide “best practices” and demonstrate viability of the use of local anthropogenic sources

• The Farnsworth project highlights enhanced recovery with ~93% carbon storage

• Extensive characterization, modeling, simulation, and monitoring studies have demonstrated long term storage security
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http://SWP.rocks