Southwest Regional Partnership on Carbon Sequestration (SWP)
DE-FC26-05NT42591

PHASE III DEMONSTRATION: FARNSWORTH UNIT

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Mastering the Subsurface through Technology Innovation & Collaboration:
Carbon Storage & Oil and Natural Gas Technologies Review Meeting
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OUTLINE

• Introduction to the SWP
• Status of Milestones
• 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 (BP4) priorities
• Post-Injection Period (BP4) workplan components
THE SOUTHWEST PARTNERSHIP AND FARNsworth UNIT
AREA COVERED BY THE SWP
Anthropogenic Supply: 500-600,000 Metric tons CO₂/year supply
ACTIVE AND CURRENTLY PLANNED CO$_2$ PATTERNS

2010-11

2013-14

2016

2012-13

2018?

Detailed in SPE 180408
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
- Phase III Budget Period 4 – “Post-Injection”


July 31, 2018
STATUS OF MILESTONES - PHASE III
SOUTHWEST PARTNERSHIP: MILESTONES MET

• Critical Milestones – 25
  • 23 completed
  • 2 ongoing
    • Tracer analysis (due Q2-FY17 – initial report delivered Q1-FY18)
    • Final injection period simulation (due Q3 of FY18)

• Technical Milestone – 73
  • 66 completed
  7 ongoing
    • Five tracer-related milestones
    • One risk mitigation plan update
    • One 3-phase reactive transport model
Cumulative CO2 Storage – Metric Tonnes

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

- **Stored Since 2010**
- **Stored Since SWP Monitoring Began**
- **Proposed Storage**
- **Goal**
ACCOUNTING - CO$_2$ AND INCREMENTAL PRODUCTION

- 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 CO$_2$ still in the system

- Average monthly oil rate increased from ~3,500 to ~65,000 BBL’s in first 4 years of CO$_2$ Flood
- Initial production response within 6 months
- ~3.8 million STB produced during CO2 flood

Monthly accounting since October of 2013

Monthly CO$_2$ Injection and Oil Production

- Oil Produced
- CO$_2$ Injected

- Purchased
- Net Stored
- Recycled
- Flared
SOUTHWEST PARTNERSHIP: BIBLIOGRAPHY

• >85 publications, major presentations, SPE DL

• Springer Book – 25 Papers covering multiple aspects
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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

Sample 2
7670.55"  
HFU3-4

Pore rendering
Medial axis (skeleton) of pore network
Cross-laminae with carbonate cement and little porosity serve as flow barriers
CHARACTERIZATION USING SEISMIC DATA

• Goal - characterizing reservoir architecture & facies distribution, mapping any faults, fractures, or structural features that could influence plume movement or reservoir integrity

• Tools – well logs, 3D surface seismic, 3D VSP’s, cross-well tomography

• Findings- A geologic model was generated using all available seismic and well log information available. Geologic information and fault-like features interpreted from 3D seismic were included into this model. (See animation). The reservoir does exhibit heterogeneity. Features that may be faults but are still open to interpretation were noted in seismic data, and there is variation in reservoir thickness and structure across the Farnsworth field

• Geological model updated annually > propagated to simulation model
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

Small-scale MEM Young’s modulus
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 CO₂ column height is in the cementstone lithology at 11000 m (36089 ft). The lowest CO₂ 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
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\textsubscript{2} and/or brine outside Reservoir:

- Groundwater chemistry (USDW)
- Soil CO\textsubscript{2} flux
- CO\textsubscript{2} & CH\textsubscript{4} Eddy Covariance
- Aqueous- & Vapor-Phase Tracers
- Self-potential (AIST)
- Distributed Sensor Network (Ok. State)

Tracking CO\textsubscript{2} Migration and Fate:

- \textit{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
MVA OVERVIEW – SUCCESSES

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 ($C_T$) = $[\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{CO}_2^{\text{aq}}]$ (Note: $\text{DIC}$ 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
Reservoir Tracers – Aqueous Phase

- Aqueous-phase tracer slugs (Naphthalene sulfonates) were injected into 5 well patterns to successfully evaluate fluid velocities, interwell connectivity and identify and characterize significant reservoir heterogeneities (faults).
  - The latest injection (FWU #13-3) yielded results indicating significant preferential fluid flow along two adjacent faults.
  - Relative tracer recovery along (#8-2 and #20-2) and across faults (#9-1) indicate variable transmissive versus sealed characteristics.
Reservoir Tracers – Vapor Phase

- Vapor-phase tracer slugs (Perfluorocarbons) were injected into 4 well patterns in an attempt to assess CO₂ migration in the reservoir.
  - An injection into FWU #13-1 yielded results suggesting preferential fluid flow along two adjacent faults.
  - However, vapor-phase tracer recovery is not as straightforward (multiple spikes) as the aqueous-phase tracers, leading to uncertainty in analysis.
  - Despite technological advancements made by NMT for the purpose of gas tracer collection, injection and sampling both require specialized equipment and procedures that increase on-site access, effort and costs.

GOST: Gas Oil Separation Tank for collection of vapor-phase tracers

Fluctuating vapor-phase tracer return curve for FWU well #8-2 is indicative of most wells sampled.
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
- Geological Model
- Field Historical data
- Fluid Samples
- SCAL data/Capillary pressure data
- Borehole NMR (CMR)
- Tracer injection/recovery data
- Lab derived data
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
• Incorporation of Geologic models from characterization
• UU’s model and NMT’s history matched model are in good agreement with historical data
• Used as the basis for relative permeability analysis, fluid substitution analyses, etc.
**SIMULATION: WHAT WORKED**

Exchange of field data, geologic models, and PVT data between disparate modeling / simulation software (e.g., for different capabilities, including Petrel, Eclipse, STOMP, TOUGHREACT)

TOUGHREACT simulation plots of the western FWU showing the SMCO2 parameter, i.e. the mass of injected CO$_2$ sequestered as carbonate minerals in kg/m$^3$ of porous medium at times of (a) 1 year and (b) 57 years

- CO$_2$ was injected continuously for the first 10 years of the simulation
What didn’t work and needs further evaluation

• Recover predictions for tracer 2,7-NDS at production well #20-8
• STOMP-EOR simulations require longer execution time than Eclipse, demonstrating difference between production and scientific software (and the need for parallelization)
SIMULATION: MAJOR FINDINGS

• 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 CO₂ storage and oil recovery framework which may be applied to other projects
SIMULATION: RECENT 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 Management Planning
Risk Identification (Risk Registry)
Qualitative Risk Analysis
Quantitative Risk Analysis
Risk Response Planning
Risk Monitoring and Control
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.
RISK ASSESSMENT: MAJOR FINDINGS

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 CO₂ 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.

CO₂ Storage and Economics:
• Hydrodynamic trapping sequesters the most injected CO₂ 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.
**RISK ASSESSMENT: NEEDS FURTHER EVALUATION**

- **Leakage Assessment**
  - Compare leakage risk for FWU in current EOR operations to FWU if it had been developed as a greenfield, CO$_2$-storage-only site
  - Enhance wellbore leakage models to include oil with the CO$_2$ and brine leakage.

- **Uncertainty Reduction**
  - Heterogeneity of groundwater (Ogallala) formation/caprock/reservoir could be included in simulations for further site characterization.
  - Further calibration of geochemical reactions/cement degradation of site-specific samples may be utilized to reduce uncertainty of forecasted key parameters.
  - Uncertainty may be reduced with more and/or higher-resolution characterization data.
POST-INJECTION PERIOD (BP4) PLANS
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
FOCUS AREA: PASSIVE SEISMIC

- 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 slated for installation in October 2018
FOCUS AREA: 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 CO₂ on cement and near-wellbore rock

• Take results from reduced order models back into full-scale simulation
FOCUS AREA:
DEPLETED OILFIELD (POST-EOR) STORAGE ANALYSIS

• 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
• 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

TIMELINE TO COMPLETE PROJECT – 4 YEARS

2018

2019

2020

2021

2022

Data acquisition, final geologic models
Integrate final models with simulations
Final quantitative risk assessments/storage
Staggered exit from site
Reports, wrap-up
Southwest Regional Partnership on Carbon Sequestration

Project DE-FC26-05NT42591

http://SWP.rocks