Southwest Regional Partnership on Carbon Sequestration (SWP)  
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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  
August 16-18, 2016
Outline

• Introduction to the SWP
• Introduction to Farnsworth Unit
• Major tasks:
  • Geologic Characterization
  • Simulation
  • Risk
  • MVA
• Conclusions and ongoing work
The Southwest Partnership

Phase III Demonstration: Farnsworth Unit
Project Goals

• SWP’s Phase III: large-scale EOR-CCUS demonstration

• General Goals:
  • One million tons CO$_2$ storage
  • Optimization of storage engineering
  • Optimization of monitoring design
  • Optimization of risk assessment

• Blueprint for CCUS in southwestern U.S.
Project Site: Farnsworth Unit

- Farnsworth field discovered in 1955.
- About 100 wells completed by the year 1960.
  - Field was unitized in 1963 by operator Unocal

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Initial water saturation</td>
<td>31.4%</td>
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<td>Initial reservoir pressure</td>
<td>2218 PSIA</td>
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<td>Bubblepoint Pressure</td>
<td>20-150 PSIA</td>
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<td>Original Oil in Place (OOIP)</td>
<td>120 MMSTB (60 MMSTB west-side)</td>
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<td>Drive Mechanism</td>
<td>Solution Gas</td>
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<td>Primary Recovery</td>
<td>11.2 MMSTB (9.3%)</td>
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<tr>
<td>Secondary Recovery</td>
<td>25.6 MMSTB (21.3%)</td>
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</tbody>
</table>
Project Site: Farnsworth Unit

Anthropogenic CO₂ Supply:

500-600,000 Metric tons CO₂/year for four fields
Active and Currently Planned CO₂ Patterns

- 2010-11
- 2013-14
- 2016
- 2012-13

Detailed in SPE 180408

Farnsworth Unit Well Classification
- CO₂ Injector
- Oil Producer
- Inactive
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Characterization

- Goals are to better understand geology of the storage system
- Deliver fine scale facies based models including hydraulic flow units to improve flow simulation and risk assessments
Characterization: Geologic Model

Incised Valley Depositional System

Rose-Coss 2015, after Puckette et al., 2008
Characterization: Role of Seismic Data

Detailed in SPE 180408
Characterization: Seismic Interpretation

Surface Seismic

VSP

Cross-Well

Surface Seismic Top Morrow Interpretation

Well 13-10A (GR)
Core porosity vs log of permeability was computed for 51 cored wells

- Over 750 feet of core were collected in three SWP drilled characterization wells
- Extensive logs from near surface through the reservoir were collected
- The data was inconclusive in relating porosity to permeability
The Winland equation relates porosity to permeability using variables that impact hydraulic flow (Kolodzie, 1980):

- \( \log R_{35} = 0.732 + 0.588 \log K_{air} - 0.864 \log \phi \) core

- Hydraulic units were grouped into porosity/permeability categories based on similar pore throat sizes

Detailed in SPE 180375
Characterization: Core Correlation

HFU 1 associated with the lowest porosity and permeability values.

HFU 8 in green interval highlighted indicates the highest porosity and permeability values.

Yellow boxes indicate sample locations chosen to be used in core flood experiments intended to capture variability in relative permeability within the core and Hydraulic flow units (HFU).

Ts, T – Thin Section
P – Routine Plug analysis
$P_c$ - Capillary pressure
Characterization: Geologic Models

- SWP evaluates and updates fine-scale geologic models at least annually for use in simulation modeling and risk assessment
  - Goal is to integrate, and honor, seismic and well data
  - Includes fault planes picked from seismic
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Simulation: Design, Forecasts, Risk

- Simulation of production/storage history matching of primary, secondary, and tertiary recovery provides some calibration
- Calibrated simulation used for predictions of future and CO$_2$ storage in the reservoir;
- Uncertainty estimates are critical for forecast context and risk assessment; relative permeability is paramount
- Forecasting potential impacts (risk FEPs) via coupled thermal, geochemical and geomechanical processes;
- Fully-coupled, full-scale simulations used to calibrate reduced order models for uncertainty quantification, risk assessment and optimization for ongoing forecasts.
Simulation: Design, Forecasts, Risk

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Essential Task: History Matching

Field Oil production rate

Oil production rate [STB/d]

Date


Primary
Secondary
Tertiary

FWU Oil Production Simulated
FWU Oil Production Observed

Detailed in SPE-180376
Simulation: Design, Forecasts, Risk

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Focus Area: Relative Permeability

Uncertainty Estimation: Impact of choice of three-phase relative permeability model on storage forecasts

Morrow Sandstone relative permeability curve from the Unocal 1988 reservoir simulation study.

Six targeted synthetic relative permeability curves each assigned to hydraulic flow units.
Focus Area: Relative Permeability

Example Result: Synthetic Relative Permeability Models

Pore-scale modeling
- Relative permeability information
- Inputs for reservoir simulation
- Compliment laboratory studies
- Flexible for statistical analysis

Micro CT imaging as input
- Extract pore matrix
- Cost-effective
- Multi-thresholding for pore matrix
- Alternative to network approximation

Raw CT image

Pore matrix threshold
Simulation: Design, Forecasts, Risk

• Simulation of production/storage history matching of primary, secondary, and tertiary recovery provides some calibration
• Calibrated simulation used for predictions of future and carbon dioxide storage in the reservoir;
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• Forecasting potential impacts (risk FEPs) via coupled thermal, geochemical and geomechanical processes;
• Fully-coupled, full-scale simulations used to calibrate reduced order models for uncertainty quantification, risk assessment and optimization for ongoing forecasts.
Focus Area: Reactive Transport

Precipitated carbon is primarily near well-bores
Focus Area: Reactive Transport

Simulation to interpret reactive and conservative tracers

Normalized aqueous tracer concentration between first CO2-water flood transition.

Gas saturation between first CO2-water flood transition.
2x refinement in x- and y-directions around #13-10a, #13-6, #13-12, #13-14, #13-16 for aqueous tracer experiment with injection on 02 May 2014.

Simulation to interpret reactive and conservative tracers
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Risk Assessment Workflow

Task 1
Overall risk management plan including
- Coordination with other working groups.
- Roles and responsibilities of each personnel
- Budget assignment
- Timing & frequency of risk assessment tasks
- New elements for the risk registry and its potential impacts
Task 2 – Risk Identification

• Identification of specific risk: features, events, and processes (FEPs)

• 2014
  • Web-based online workshop (Jan. 13 and 16, 2014)
  • Expert-weighted risk for ranking
  • Total 405 FEPs identified
  • 23 project experts evaluated 79 initial FEPs, and generated & evaluated 24 new FEPs

• 2015
  • Email survey during (May ~ August 2015)
  • 15 project experts evaluated top 50 FEPs of 2014

• 2016
  • In progress, risk review meeting at end of August
### 2015 vs. 2014 FEP’s Ranking

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<td>Price of oil (or other related commodities)</td>
<td>12.26</td>
<td>1</td>
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<td>EOR oil recovery</td>
<td>11.07</td>
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<td>Operating and maintenance costs</td>
<td>10.26</td>
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<td>4</td>
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<td>EOR injection and production well pattern, spacing</td>
<td>9.19</td>
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<td>EOR early CO2 breakthrough</td>
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<td>20</td>
<td>5.88</td>
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<td>Simulation of geomechanics</td>
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<td>3</td>
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<td>Accidents and unplanned events</td>
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<td>10</td>
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<td>Release of compressed gases or liquids</td>
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<td>7.80</td>
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<td>Seafloor failure</td>
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<td>Seismic surveys</td>
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<td>17</td>
<td>5.28</td>
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</table>

- Triple-weighted expert ranking
- Two major things causing the changes
  - ✓ Oil price
  - ✓ Project operations, progress, and experience over one year
- Rankings in EOR activities \(↑\)
- Rankings in Modeling/simulation parameters and Geomechanical characterization \(↓\)
- 14 FEPs changing at least 20 positions \(→\) requires comprehensive evaluation in 2016
Quantitative Risk Analysis (Task 4)

Risk Assessment of CO₂ Storage and Oil Recovery in FWU using RSM

Uncertainty Analysis of Trapping Mechanism using PCE

Risk Analysis and Response-surface-based Economic Model

(Pan et al., 2016)

(Jia et al., 2016)

(Dai et al., 2016)
Quantitative Risk Analysis (Task 4)

Forecasted water quality impacts (as \( f(\text{time}) \)) to the Ogallala USDW, via conventional reactive transport simulation.

Probabilistic Analyses - NRAP’s AIM Tool

Cumulative distribution function of impacts on aquifer (pH, TDS) due to three levels of leakage

Forecasted water quality impacts (as CDFs) to the Ogallala USDW, via NRAP’s AIM tool.
Established risk prevention and mitigation treatments for top 50 FEPs and 10 black swans.

As NRAP moves into its Phase 2, collaboration on mitigation plans will be critical!
Risk Monitoring and Control (Task 6)

- Keep tracking of existing and new risks
- Review of mitigation activities (response plan) and their effectiveness
- Iterative process

As NRAP moves into its Phase 2, collaboration on mitigation plans will be critical!
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Monitoring (MVA)

As a demonstration project a comprehensive monitoring strategy is in place:

• **Monitoring** – understand CO\(_2\) plume movement over short and long time periods
  
  • *Direct monitoring* tests repeat air and water samples for seeps, leaks, and well-bore failures
  
  • *Seismic MVA* utilizes time lapse seismic data at a variety of scales to image the CO\(_2\) plume over time

• **Verification** – assurance that CO\(_2\) stays in target reservoir, doesn’t make it back to atmosphere

• **Accounting** – Accurately measure amount of stored carbon including storage mechanisms
Direct Monitoring Strategy

Detecting CO$_2$ at Surface:
- Surface soil CO$_2$ flux
- Atmospheric CO$_2$/CH$_4$ eddy flux
- Gas phase tracers

Detecting CO$_2$ and/or other fluid migration in Target/Non-Target Reservoirs:
- Groundwater chemistry (USDWs)
- Water/gas phase tracers

Tracking CO$_2$ Migration and Fate:
- *In situ* pressure & temperature
- 2D/3D seismic reflection surveys
- VSP and Cross-well seismic
- Passive seismic
SWP CO₂ Flux – Soil Flux Results

[Graph showing carbon dioxide flux with data points and box plots for different months from 2013 Oct to 2016 Apr.]
SWP CO₂ Flux – Eddy Covariance

• FWU Data
  • Top: All data. Looking at 90%–100% concentration CO₂ (left) and 99% CO₂ (right)
  • Bottom: 6/1/2015. Looking at 90%–100% concentration CO₂ (left) and 99% CO₂ (right)
Southwest Regional Partnership on Carbon Sequestration

SWP MVA Overview – Near Surface Monitoring

- **USDW**
  - Quarterly sampling of Ogallala aquifer to monitor for brine, oil and/or CO₂ leakage from depth.
  - Major Cations/Anions
  - pH
  - Conductivity
  - Alkalinity
  - Oxidation and Reduction Potentials (ORP)
  - Inorganic Carbon (IC) and Organic Carbon (OC)
  - Trace Metals
  - Isotopes (¹³C, ¹⁸O, and D)
**SWP MVA Overview – Near Surface Monitoring**

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- Isotopes (\(^{13}\)C, \(^{18}\)O, and D)
SwP MVA Overview – Tracer Studies

• Tracers – Aqueous- and Vapor-Phase
  • Aqueous Phase: naphthalene sulfonates; conservative tracers that follow water phase (Pete Rose – University of Utah).
  • Up to 8 unique aqueous-phase tracers available.
  • Vapor Phase: perfluorocarbons; conservative tracers that follow gas phase (Rod Diehl – NETL).
  • Up to 7 unique vapor-phase tracers available.
  • Oil Phase: Not planned at this time.

Tracer suite available for use at the FWU; green highlighted tracers already injected at FWU.

Aqueous Phase (n=8)
- 1-naphthalenesulfonic acid, sodium salt
- 2-naphthalenesulfonic acid, sodium salt
- 1,5-naphthalenedisulfonic acid, disodium salt
- 1,6-naphthalenedisulfonic acid, disodium salt
- 2,6-naphthalenedisulfonic acid, disodium salt
- 2,7-naphthalenedisulfonic acid, disodium salt
- 1,3,5-naphthalenetrisulfonic acid, trisodium salt
- 1,3,6-naphthalenetrisulfonic acid, trisodium salt

Vapor Phase (n=7)
- Perfluoro-dimethylcyclobutane (PDCB)
- Perfluoro-methylcyclopentane (PMCP)
- Perfluoro-methylcyclohexane (PMCH)
- Perfluoro-ethylcyclohexane (PECH)
- Perfluoro-1,2-dimethylcyclohexane (o-PDCH)
- Perfluoro-1,3,5-trimethylcyclohexane (PTCH)
- Perfluoro-isopropyl-cyclohexane (i-PPCH)
SWP MVA Overview – Aqueous Tracers

- **Tracers – Aqueous-phase Injection #1**
  - Three FWU wells (on water flood) tagged with unique tracers in May, 2014
  - Additional ~3 days of water injection, followed by CO₂ flood
  - Never observed breakthrough!

- **Tracers – Aqueous-phase Injection #2**
  - FWU well (on water flood) tagged with tracer in October, 2015
    - Well #14-1: 2,7-Naphthalenedisulfonic acid, disodium salt
    - 2 to 4 times the amount of NPT injected into previous wells
  - No switch to CO₂
  - Breakthrough for FWU #20-8
Southwest Regional Partnership on Carbon Sequestration

**SWP MVA Overview – Aqueous Tracers**

- **Aqueous Tracers**
  - **Injection #1**
    - Three FWU wells (on water flood) tagged with unique tracers in May, 2014
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  - **Injection #2**
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    - Well #14-1: 2,7-Naphthalenedisulfonic acid, disodium salt
    - 2 to 4 times the amount of NPT injected into previous wells
    - No switch to CO$_2$
    - Breakthrough for FWU #20-8

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**Graph**

- **Well 13-14**
- **Well 13-19**
- **Well 20-2**
- **Well 20-8**

**Legend**

- Blue circle: producer
- Blue triangle: Water tracer injection
- Dashed line: Probable Fault

**Dates**

- 11/10/15
- 11/24/15
- 12/8/15
- 12/22/15
- 1/5/16
- 1/19/16
- 2/2/16
- 2/16/16
- 3/1/16
- 3/15/16
- 3/29/16
- 4/12/16
- 4/26/16
- 5/10/16
- 5/24/16
- 6/7/16
- 6/21/16

**2,7 NDS CONCENTRATION (PPB)**

- Well 13-14
- Well 13-19
- Well 20-2
- Well 20-8
SWP MVA Overview – Gas Phase Tracers

- Tracers – Vapor-Phase Injection #1
  - FWU well (on CO₂ flood) tagged with tracer in May, 2015
  - Well #13-13: PTCH (2 kg)
  - Additional ~30 days of CO₂ injection
  - Every other week to weekly sampling of production wells
  - “Breakthrough” after 2 to 4 weeks! (fast path or “short circuit” between 13-13 and 11-2)
SWP MVA Overview – Gas Phase Tracers

- Tracers – Vapor-Phase Injection #2
  - FWU well (on CO₂ flood) tagged with tracer in November, 2015
    - Well #13-10A: PDCB (1kg)
  - Additional ~30 days of CO₂ injection
  - High frequency sampling (wells & recycled CO₂)
  - Modification of sampling procedures
  - Waiting for breakthrough
SWP MVA Overview – Gas Phase Tracers

- **Tracers – Vapor-Phase Injection #3**
  - Two additional FWU wells (on CO₂ flood) tagged with tracer in May, 2016
    - Well #13-1: PMCH (0.5kg)
    - Well #13-3: PECH (0.5 kg)
  - Evaluate influence of faults.
  - High frequency sampling (12 wells & recycled CO₂)
  - No breakthrough after 2 months
Data Acquired February 2014 and January 2015

- Processed by WesternGeco and delivered June 2015
- Processing 1st and second 13-10a VSPs with ~30,000 Metric tonnes CO2 injected
- Excellent repeatability
- Acquired calibration VSP data for micro-seismic array
- Cursory differencing inconclusive
**SWP MVA Overview – Time Lapse 3D VSP**

- **Model can be populated with fluids for multiple cases**
  - Post waterflood
  - Post 30,000 tonnes injection, etc.

- **Fluid filled models can have synthetic seismic generated from them**
  - Can difference to find expected response at varying CO2 injection levels
  - Useful for determining detection thresholds
  - Help determine timing of future VSP repeats

**IMAGE DIFFERENCE SLICES AT SRD DEPTH 7800 FT.**
Fluid Substitution modeling – work flow

I. Modeling begins by development of a static geologic model using all available data such as logs, core, inversion, and seismic stratigraphy and structure.

II. The fine scale geologic model is history matched, and then used to predict the fluid state of the reservoir at various times corresponding to different CO2 injection volumes.

III. The fluid substitutions can change the elastic properties of the rock, which can then impact the seismic response.
SWP MVA Overview – Time Lapse 3D VSP

Property Changes – CO₂ Saturation

2015 Monitor

Proposed 2017 Monitor
SWP MVA Overview – Time Lapse 3D VSP

Property changes - % Acoustic impedance
SWP MVA Overview – Time Lapse 3D VSP

Property changes - % fluid modulus

2015 Monitor

Proposed 2017 Monitor
SWP MVA Overview – Time Lapse 3D VSP

Modeled (synthetic) seismic survey

75 Hz

125 Hz
SWP MVA Overview – Time Lapse 3D VSP

Proposed 2017 Monitor Survey (75 HZ)

CO₂ Saturation
Monthly accounting since October of 2013

92.2% of purchased CO₂ still in the system

Cumulative CO₂ storage since December 2010

92.1% of purchased CO₂ has been stored
SWP MVA Overview – Accounting

CUMULATIVE CO₂ UTILIZATION THROUGH 7/2016

Cumulative
Purchased 499,100 978,278
Produced 383,771 470,338
Recycled 346,665 394,570
Flared 38,059 76,721
Injected 845,765 1,372,848
Net Stored 461,040 901,556

*all figures in tonnes
MONTHLY OIL PRODUCTION THROUGH 7/2016

Monthly Oil Production and CO2 Injection, 2010-2016

Start of SWP project
Conclusions and Ongoing Work

- The Southwest Partnership’s demonstration project at Farnsworth field highlights enhanced recovery with ~92% carbon storage
- Extensive characterization, modeling, simulation, and monitoring studies have demonstrated long term storage security
- Continuous geologic characterization;
- Annual updated geo-model;
- Continuous history match;
- Continuous monitoring (ongoing);
- New risk registry and assessment;
- Effective best practices for CCS must include an adequate MVA program
- *To date and after nearly 3 years of monitoring no leaks to the atmosphere, ground water, or secondary reservoirs have been detected at Farnsworth using a wide array of detection technologies*
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