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

Phase III Demonstration: Farnsworth Unit

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We gratefully acknowledge the contributions of more than 50 SWP scientists and engineers!
Outline

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

Phase III Demonstration: Farnsworth Unit

CO₂ Sources
(Metric Tons/year)
- 0.1 MT to 0.7 MT
- 0.7 MT to 2 MT
- 2 MT to 4 MT
- 4 MT to 10 MT
- 10 MT to 20 MT

Oil Fields
(Distance from existing CO₂ pipeline)
- 0-20 km
- 20-40 km
- 40-60 km

CO₂ Pipeline

Southwest Regional Partnership on Carbon Sequestration
Project Goals

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

• General Goals:
  • One million tons CO₂ 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>
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<tr>
<td>Initial reservoir pressure</td>
<td>2218 PSIA</td>
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<tr>
<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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<tr>
<td>Drive Mechanism</td>
<td>Solution Gas</td>
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<tr>
<td>Primary Recovery</td>
<td>11.2 MMSTB (9.3%)</td>
</tr>
<tr>
<td>Secondary Recovery</td>
<td>25.6 MMSTB (21.3%)</td>
</tr>
</tbody>
</table>
Project Site: Farnsworth Unit

Anthropogenic CO$_2$ Supply:

500-600,000 Metric tons CO$_2$/year for four fields
Active and Currently Planned CO\textsubscript{2} Patterns

- 2010-11
- 2013-14
- 2017?

Detailed in SPE 180408
Outline

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Characterization Accomplishments

• Hydraulic flow units – can define units based on a refined version of Winland R35 method. These units can be distinguished at scales from microscopic to field scale. Eight defined for Morrow B; HFUs have been incorporated into the simulation model.

• 2D seismic lines tied to Booker Field provided insight into regional structure and suggest any potential regional CO₂ migration would be to northwest and risk of leakage appears low (many seals/ no faults to surface)

• Basin scale petroleum system modeling has shown that hydrocarbons are likely derived from Atokan black shales in the deeper basin

• Caprock integrity evaluated, with a thorough analysis of caprock from microscale through core scale

• 2nd VSP seismic data shot Dec 2016, and processed spring 2017. Time-lapse attributes such as NRMS (Normalized Root-Mean Square), Repeatability and Predictability were extracted for 1000 ft around the well 13-10A. From the aforementioned parameters, there is a clear anisotropy that runs NE-SW. This horizontal transverse anisotropy may indicate preferential flow of CO₂ in this orientation.
Example Characterization Result - Hydraulic flow units

HFU 1 associated with the lowest porosity and permeability values.

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

Ts, T – Thin Section
P – Routine Plug analysis
$P_c$ - Capillary pressure
2D seismic structural interpretations show regional migration is NW to NE

Migration risk to the surface is low due to a lack of regional scale faulting and lateral continuity of sealing stratigraphy

Hydrocarbons at FWU migrated hundreds of millions of years ago from the deeper basin Thirteen Finger and upper Morrow Black Shales.

FWU was discovered as an under pressured reservoir when it should be over pressured. This phenomenon is seen across Northwest Anadarko Basin reservoirs and is attributed to Laramide erosion and groundwater discharge.

Seal bypass is an area of active research, but is unlikely
Characterization Working Group Goals

Remaining goals

- Complete fluid substitution modeling
- Complete and publish results of caprock integrity studies
- Complete and publish results of micro-scale pore studies
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Monitoring (MVA) Working Group Goals

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
Tracers (Aqueous- and Vapor-Phase)

- Determine interwell connections, patterns and directions.
- Identify heterogeneities including faults/fractures.
- Fluid Velocities.
- Constrain and calibrate flow models; predict the fate of the injected CO₂.
- Detect and quantify CO₂/brine leakage to subsurface/atmosphere.
- Attempt to determine oil/CO₂ saturation levels and CO₂ storage capacity.
- Attempt to determine sweep efficiency (tracer concentration history).
- Confirm other verification methods (e.g. time-lapse seismic).
- Aqueous Phase: 8 unique naphthalene sulfonates; conservative tracers for injected water (Pete Rose – University of Utah).
- Vapor Phase: 7 unique perfluorocarbons; conservative tracers that follow gas phase (Sean Sanguinito – NETL).
Example MVA Result – Tracer Studies

• Tracers (Aqueous- and Vapor-Phase)
  • Since 2014, six unique aqueous-phase tracer injections and four unique vapor-phase tracer injections.
  • Mixed results for both.
    • Tracer by-pass and stunted migration (e.g. aqueous-phase tracer by-passed by CO₂ flood).
    • Rapid breakthrough (e.g. vapor-phase tracer by-passing nearby producers, to appear several patterns away). Likely the result of mapped faults in area.
  • High detectability makes a good analog for brine/CO₂ leakage monitoring (no leaks detected).
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Initial tracer breakthrough (days). Larger circles mark faster breakthrough from injection (inverted triangle). Faults seem to influence breakthrough times.
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Simulation Working Group: Main Goals

- MVA Design
- Storage Forecasts
- Risk Assessment Basis
- Selection of on-going Simulation work
  - Porosity and Permeability distribution
  - Fault Permeability
  - History Matching
  - Production Forecasting

![Porosity Distribution (Morrow Sand) and Permeability Distribution (Morrow Sand)](image)

![Fault Transmissibility](image)

**History Match - CO₂-WAG**

![Plots showing simulated vs observed data](image)
Simulation: Achievements

- Improved geological model with properties population based on eight distinct hydraulic flow units. **The current model has improved property distribution for caprock based on geomechanical and routine core analysis conducted by Characterization Working Group (esp NMT/SNL).**
- Analysis of relative permeability and capillary pressure curves based on distinct hydraulic flow units to understand uncertainty associated with CO2 storage potential within Morrow B
- Improved history matching efforts which encompasses the fault transmissibility modeling to better understand their effects on fluid flow within the Morrow B reservoir
- Pore-to log scale nuclear magnetic resonance log analysis, data processing, in house inversion and permeability calibration
- **Continuous improvement of history matching with tracer sampling results to increase our understand on potential CO2 migration paths and heterogeneity within Morrow B reservoir**
- Reactive transport simulations of water-CO2-rock interaction within Morrow B reservoir
Simulation: Active Goals

• Simulation of production/storage history matching of primary, secondary, and tertiary recovery;
• Calibrated predictions of current and future carbon dioxide storage (capacity) in the reservoir (e.g., for Atlas updates);
• Interpretation of MVA tracer experiments;
• Newly-calibrated fully-coupled, full-scale simulations used to calibrate reduced order models for uncertainty quantification, risk assessment and storage optimization
• Continued forecasting of potential impacts (e.g., risk FEPs) via coupled thermal, geochemical and geomechanical processes
Simulation Result: Reactive Transport

Reactive transport simulation of water-CO$_2$-mineral interactions in the Morrow B Sandstone in the Farnsworth Unit (TOUGHREACT and STOMP):

- Migration of CO$_2$ through the reservoir
- Partitioning of CO$_2$ between aqueous solution, an immiscible gas phase, and carbonate minerals
- Changes in formation water composition
- Mineral precipitation and dissolution
- Changes in reservoir hydraulic properties

Precipitated carbon is primarily near well-bores
Simulation Result: 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.
Simulation Result: Reactive Transport

Simulation to interpret reactive and conservative tracers

2x refinement in x- and y-directions around #13-10a, #13-6, #13-12, #13-14, #13-16 for aqueous tracer experiment with injection
Simulation Working Group: Achievements

- MVA Design
- Storage Forecasts
- Risk Assessment Basis
- Selection of on-going Simulation work
  - Porosity and Permeability distribution
  - Fault Permeability
  - History Matching
  - Production Forecasting

![Porosity Distribution (Morrow Sand) and Permeability Distribution (Morrow Sand)](image)

![Fault Transmissibility](image)

**History Match- CO₂-WAG**

![Graphs showing history match](image)
Outline

• Introduction to the SWP
• Introduction to Farnsworth Unit
• **Major tasks:**
  • Geologic Characterization
  • MVA
  • Simulation
  • Risk
• Conclusions and ongoing work
Risk Working Group Goals

- Risk Management Planning
- Risk Identification (Risk Registry)
- Qualitative Risk Analysis
- Quantitative Risk Analysis
- Risk Response Planning
- Risk Monitoring and Control

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
- Identification of specific risk: features, events, and processes (FEPs)
Risk Result - Risk Source Assessment (Task 2)

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

- 2014
  - Web-based online workshop (Jan. 13 and 16, 2014)
  - 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
  - Web-based online risk workshop on Sep. 1, 2016
  - 15 project experts and 5 students participated to re-rank 69 FEPs (2 new in 2016, 46 from 2015, and 21 from 2014 black swans)
  - Likelihood for avg. $S_{bg}$ was collected separately via email survey (September 2016)
  - Expertise of individual participants was identified in 7 FEP groups and used for ranking and analysis
Risk Result – Qualitative Analysis (Task 3)

- Provide quantitative information on the risk
- Explicit treatment of uncertainties
- Perform probabilistic assessment due to the uncertainty
- Response Surface Method combined with Monte Carlo samplings
- Polynomial Chaos Expansion (PCE)

Arsenic Mobilization due to CO₂ Leakage (Xiao et al., 2017)

Uncertainty Analysis of Trapping Mechanism at FWU using ROMs (Jia et al., 2016)

Risk Analysis and Response-surface-based Economic Model (Dai et al., 2016)

Xiao et al. (2017), Arsenic mobilization in shallow aquifers due to CO₂ and brine intrusion from storage reservoirs. Sci. Rep. DOI:10.1038/s41598-017-02849-z

Jia et al. (2016), Probabilistic Risk Assessment of CO₂ Trapping Mechanisms in a Sandstone CO₂-EOR Field in Northern Texas, USA. GHGT-13, 2016 November 14-18, Lausanne, Switzerland

Dai et al. (2016), CO₂ Accounting and Risk Analysis for CO₂ Sequestration at Enhanced Oil Recovery Sites. ES&T
Risk Assessment: Accomplishments

• Annual Risk Identification (2014, 2015, 2016)
  • 2014: Identified total 405 FEPs
  • 2015: Evaluated top 50 FEPs
  • 2016: Re-ranked FEPs, evaluated likelihood for avg. $S_{bg}$ (best guess severity)

• Qualitative Risk Analysis
  • Updated the risk registry and identify interactions between FEPS
  • Identified the risk factors for the quantitative risk analysis
  • Constructed the process influence diagram for quantitative risk analysis

• Quantitative Risk Analysis
  • Arsenic mobilization due to CO2 leakage
  • Uncertainty analysis of trapping mechanism at FWU using reduced order models
  • Risk analysis and response-surface-based economic model
Conclusions and Ongoing Work

- 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

- 620,000 tonnes stored since October 2013
- 1,050,000 tonnes stored since November 2010
- 92.2% of purchased CO₂ still in the system
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 quantitative assessment of PDFs and CDFs for top FEPs;
- Effective best practices for CCS include an effective 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.
Characterization Working Group

Milestones

Remaining Milestones:

Two remaining geomodel updates to include:
- refined characterization of faults from tracer studies and associated simulations
- Correlation of geologic facies to acoustic impedance inversion results of the baseline 3D surface seismic survey
- Results from fluid-rock interaction data from lab studies at NMT and Sandia
Geologic controls on Hydraulic Flow Units

[A] HU1
Porosity occluded by calcite cement

[B] HU3
Intra-granular porosity dominant, lacks interconnected pore networks

[C] HU5
Lack of inter grain cementation enables better flow paths

[D] HU8
abundant macroposity creates great flow paths
Characterization – Hydraulic Flow Units

HFU 8 – best single phase $\Phi$, $K$
- Porosity spaces are fairly unimodal in size and moderately well-sorted
- Pore networks are fairly well connected.

HFU 8 rendering from micro-CT scan

Skeletonized pore network – lines are through medial axis of pores.

HFU 1 – lowest single phase $\Phi$, $K$
- Porosity spaces are generally bimodal, with some large pores and much clay-filled microporosity
- Pore networks are poorly connected

HFU 1 volume rendering, with macropores (green) and clay-filled pores (blue)

Pore image skeletonized along medial axes showing macropores and clay-filled micropores
Characterization – HFUs ➔ Relative permeability

- Low apparent endpoint perm for the lower HFUs is likely due to change in capillary number. Viscous forces dominate under experimental conditions for higher HFUs; capillary forces for lower.
- Higher degrees of heterogeneity lead to higher amounts of residual trapped scCO₂. Residual CO₂ amounts range in saturation values from 10-15% in the tested HFUs.
- HFUs exhibit mixed-wettability and lower value HFUs contain most of the residual oil. Higher HFUs represent fast paths that may thwart efforts at broad sweep efficiency of EOR.
Characterization – Reservoir Modeling

Up-scaled porosity values extrapolated and modeled as a function of hydraulic flow units

Upper surface of the Morrow B zone showing distribution of hydraulic flow units binned using R35 values
Relative permeability experiments

Conducting experiments on cores from the eight different hydraulic flow units of the Morrow B Formation using brine-$\text{CO}_2$, oil-brine, and oil-$\text{CO}_2$ fluid pairs. Sandia National Laboratories is using synthetic fluids, and New Mexico Tech is using formation fluids = 71°C, 4200-4800 psi pore fluid pressure, ~7500 psi confinement pressure.

Fluid-rock experiments

Flow-through experiments at New Mexico Tech – $\text{CO}_2$-rich brine injected into Morrow B Formation cores with different carbonate cement compositions at 71°C, 4200 psi pore fluid pressure, and 5000 psi confinement pressure. Mechanical tests (ultrasonic and Brazilian tests) at Sandia National Laboratories are used to identify impact of fluid-rock interaction on core mechanical properties.
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 CO₂ 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.
Focus Area: Relative Permeability

- CMR inversion
  - Data processing
  - Bootstrapped error metric
  - Adaptive noise $T_2$ inversion

- CMR interpretation
  - Calibration for permeability
  - Pore-scale modelling using μCT
  - Multi-phase interpretation tool

- Relative permeability
  - Stress-dependent in triaxial instrument
  - Small plugs $\rightarrow$ small fluid volume
  - Effluent analysis using benchtop NMR
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](image1.jpg)

![Pore matrix threshold](image2.jpg)

**Example Result: Synthetic Relative Permeability Models**
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;
• 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.
### Example Risk Identification - Risk Source Assessment (Task 2)

#### Risk Rankings 2014, 2015, and 2016

<table>
<thead>
<tr>
<th>FEP No.</th>
<th>FEP</th>
<th>Rank 2016 5wWP</th>
<th>Rank 2015 5wWP</th>
<th>Rank 2014 5wWP</th>
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<tr>
<td>F22</td>
<td>Price of oil (or other related commodities)</td>
<td>1</td>
<td>1</td>
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<td>F63</td>
<td>CO2 legislation</td>
<td>2</td>
<td>18</td>
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<td>F66</td>
<td>Accidents and unplanned events</td>
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<td>18</td>
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<td>F19</td>
<td>CO2 supply adequacy</td>
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<td>Operating and maintenance costs</td>
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<td>F38</td>
<td>Simulation of fluid dynamics</td>
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<td>F23</td>
<td>EOR oil recovery</td>
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<td>F34</td>
<td>EOR injection and production well pattern and spacing</td>
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<td>F46</td>
<td>Blowouts</td>
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<td>26</td>
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<td>Severe weather</td>
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<td>Caprock lateral extent and continuity</td>
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<td>Reservoir exploitation</td>
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<td>On-road driving</td>
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<td>Competing project objectives</td>
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<td>F35</td>
<td>EOR early CO2 breakthrough</td>
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<td>Release of compressed gases or liquids</td>
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<td>F48</td>
<td>Injection well components</td>
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<td>F49</td>
<td>CO2 containing H2S</td>
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<td>13</td>
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<tr>
<td>F61</td>
<td>Leaks and spills (related to oil and chemicals other than CO2)</td>
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<td>23</td>
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<tr>
<td>F13</td>
<td>Reservoir heterogeneity</td>
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<td>Fault sealing and reactivation</td>
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<td>Execution strategy</td>
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<td>Well lining and completion</td>
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<td>F29</td>
<td>Competition</td>
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<td>F65</td>
<td>Fractures and faults (CO2 leakage through new or existing fractures or faults)</td>
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<td>#N/A</td>
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<td>Seismicity (natural earthquakes)</td>
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<td>Geomechanical characterization</td>
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<td>Operator training</td>
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<td>F16</td>
<td>Seismic method</td>
<td>39</td>
<td>25</td>
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</table>

- Triple-weighted expert ranking
- Most FEPs have maintained roughly consistent positions in multiple years.
- Top ranked FEPs are mostly programmatic/non-technical risks related to project management, permitting/safety, and site.
- Re-included FEPs (unlikely but high severity) from 2014 survey.

- Some of them shows high risk in 2016 (#10, #12 ~15)
- Project operations, progress, and experience over time
Example Risk Result – Qualitative Risk Analysis (Task 3)

- Update the risk registry and identify interactions between FEPS
- Identify the risk factors for the quantitative risk analysis
- Construct the process influence diagram (PID) used to develop scenarios for quantitative risk analysis
## Risk - Previous Work and Ongoing Studies

<table>
<thead>
<tr>
<th>Independent Variables (Uncertain Parameters)</th>
<th>FP, ZD</th>
<th>WJ</th>
<th>Dependent Variables</th>
<th>Comments /Suggestions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂ Storage</strong></td>
<td></td>
<td></td>
<td>Amount of CO₂ stored (or CO₂ recovered or Net CO₂ stored)</td>
<td>ZD</td>
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<tr>
<td>Reservoir properties (porosity &amp; permeability, Kᵥ/Kₜ ratio)</td>
<td>FP, ZD</td>
<td></td>
<td>Early CO₂ Breakthrough time</td>
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<tr>
<td>Relative permeability (e.g. irreducible water saturation)</td>
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<td>CO₂ Retention (or residence)</td>
<td>WJ</td>
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<tr>
<td>WAG (including well pattern and spacing, and injection rate)</td>
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<td>CO₂ Injectivity reduction (Net CO₂ injection amount)</td>
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<td>CO₂ miscibility (e.g. minimum miscibility pressure)</td>
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<tr>
<td>Boundary conditions</td>
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<tr>
<td>Model uncertainty (e.g. simulation of coupled processes, simulation of fluid dynamics)</td>
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<tr>
<td>CO₂ impurity</td>
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<tr>
<td>Reservoir depth and thickness</td>
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<tr>
<td>Initial water, oil and gas saturations</td>
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<tr>
<td>Mineralogical composition</td>
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<tr>
<td><strong>Oil Recovery</strong></td>
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<tr>
<td>Reservoir temperature</td>
<td>FP, ZD</td>
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<td>Reservoir pressure</td>
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<td>Oil composition, gravity</td>
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<td>Oil viscosity</td>
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<td><strong>Geomechanics</strong></td>
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<tr>
<td>Fault density and distributions</td>
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<tr>
<td>Stress and mechanical properties</td>
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<tr>
<td>Initial water chemistry</td>
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<tr>
<td>CO₂ migration {point &amp; non-pont source}</td>
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<td>Distributions of leaky wells</td>
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<td>Oil production</td>
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<td>Water cut (or net water injection)</td>
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<td>Gas (CH₄) production</td>
<td>ZD</td>
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**Comments /Suggestions**

- CO₂ storage capacity loss
  - Amount of CO₂ mineral trapping
  - Mineral alteration and porosity evolution
  - AOR (CO₂ plume size or pressure buildup)

- Ongoing Study
  - Induced seismicity (seismic magnitude)
  - Injection induced faults reactivation

- e.g. Probability of inducing an earthquake of magnitude 2

**Authors**

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SL: Si-Yong Lee  
TX: Ting Xiao  
WJ: Wei Jia  
ZD: Zhenxue Dai
Risk - Risk Response Planning (Task 5)

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

Established risk prevention and mitigation treatments for 69 FEPs

<table>
<thead>
<tr>
<th>FEP</th>
<th>2016 Ranking</th>
<th>2015 Ranking</th>
<th>2014 ranking</th>
<th>Risk Prevention</th>
<th>Risk Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of oil (or other related commodities)</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>Analyze trends in commodity prices.</td>
<td>Control costs.</td>
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<td>Plan for worst case scenarios.</td>
<td>Shut in wells until prices recover.</td>
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<td>Hedge oil prices.</td>
<td>Shift to backup CO2 supplier.</td>
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<td>Establish a CO2-EOR economical model to predict the possible profit and lost and to evaluate the economical risk</td>
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<tr>
<td>CO2 legislation</td>
<td>2</td>
<td>18</td>
<td>29</td>
<td>Tie investment in CCS projects to passage of appropriate CO2 legislation.</td>
<td>Monitor CO2 legislation and analyze the impact of CO2 legislation on the project.</td>
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<td>Implement public outreach program to educate stakeholders on the legislative needs of the project.</td>
<td>Continue public outreach program.</td>
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<td>Shift from DSA to EOR or ECBM if CO2 legislation does not get passed, is insufficient or too onerous for DSA.</td>
<td>Comply with CO2 legislation.</td>
</tr>
</tbody>
</table>
MVA – Methods

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
  - Distributed temperature array
- 2D/3D seismic surveys
- VSP
- Cross-well seismic
- Passive seismic
- Fluid chemistry (target reservoir)
- Aqueous- & Vapor-Phase Tracers
- Gravity surveys (AIST)
- MagnetoTelluric (AIST)
• CO₂ & CH₄ Eddy Tower
  • Continuous, wide-area coverage and point-source leak detection.
  • FWU Eddy Tower deployed at 13-10A data shed in May 2015 (for ~1 month).
  • Continuous acquisition of CO₂ and CH₄ and wind data.
  • Exploratory statistics and data filtering methods.
  • Examination of diurnal and daily trends.
  • Probability estimates of leak source(s).

Example MVA Result – Flux Tower

Daily trends (aggregate hourly averages) of CO₂ (top) and CH₄ (bottom)
**Example MVA Result – Flux Tower**

- **CO₂ & CH₄ Eddy Tower**
  - Eddy covariance methods undergoing pre-deployment testing at Univ. of Utah.
  - Point source detection of CO₂ and CH₄.
  - Release from natural gas cooking vent (lunch) and methane-powered buses (evening).

- **University of Utah Experiment Site**

- **Jan 24, 2017**
  - (10 AM to 2 PM; CH₄)
  - Natural Gas Stove During Lunch

- **Jan 26, 2017**
  - (8 PM to midnight; CH₄)
  - Natural Gas Buses Idling

**Conditional Bivariate Probability Functions (CBPF):**
- 99th percentile concentration.
- Plots probability that high concentrations occurred in a specific direction or “bin” of degrees at different wind speeds.
Southwest Regional Partnership on Carbon Sequestration

3D VSP conducted in 2014 (baseline), 2015 (repeat 1), 2016 (repeat 2)
- Detailed Characterization near injectors
- Monitor the evolution and image CO₂ plume.
- Contribute to model verification.

Processed VSP: NRMS amplitude attribute (7600 - 8100 ft)

Baseline VSP to 2015 VSP
- ~30,000 tonnes CO₂

Baseline VSP to 2016 VSP
- ~80,000 tonnes CO₂
FWU storing approximately 10,000-20,000 metric tons per month

Over 90% of purchased CO₂ has been stored (balance due to upsets and flaring)