EERC | UND UNIVERSITY OF NORTH DAKOTA

Critical Challenges. Practical Solutions.

Energy & Environmental Research Center (EERC)

CO_2 ENHANCED OIL RECOVERY IMPROVEMENT IN CONVENTIONAL FIELDS USING RICH GAS

DE-FE0031789

U.S. Department of Energy National Energy Technology Laboratory
2022 Resource Sustainability Annual Project Review Meeting
October 25, 2022

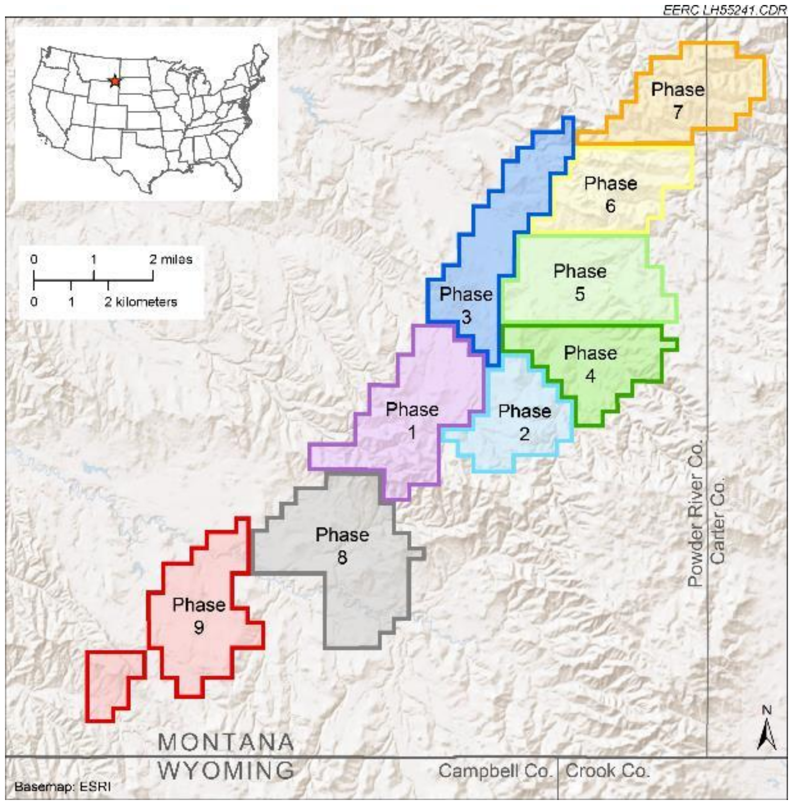
Bethany A. Kurz
Director of Analytical Solutions

CO_2 BLENDED WITH RICH GAS

Research Hypothesis: *The injection of a blend of rich hydrocarbon gas and CO_2 into an oil reservoir will reduce molecular weight (MW) selectivity, lower minimum miscibility pressure (MMP) and viscosity of the oil, and improve gas solubility, resulting in an overall improvement in enhanced oil recovery (EOR) performance.*

PROJECT GOAL AND OBJECTIVES

Project Goal: *Determine the effect of injecting blended CO_2 and rich gas into an active CO_2 EOR field to improve production performance.*



Project Objectives:

- Determine the rich gas quantity, transportation, compression, and injection needs for a field-based injection test.
- Inject blended CO_2 and rich gas in the Bell Creek Field for incremental recovery and associated CO_2 storage.
- Develop field-based data to determine the effects of rich gas additives in CO_2 on oil production.
- Use laboratory experiments and reservoir simulation to determine the potential for varying compositions of rich gas blended with CO_2 to improve oil recovery in other conventional reservoirs currently undergoing CO_2 EOR.
- Develop business case scenarios to assess the potential for using rich gas added to CO_2 at other EOR locations in the United States.

FUNDING AND PROJECT PERFORMANCE DATES

	BP1 ($) 10/1/2019–9/30/2021		BP2 ($) 10/1/2021–9/30/2024		Total	
	Federal	Nonfederal	Federal	Nonfederal	Federal	Nonfederal
DOE	$2,184,364	–	$5,789,517	–	$7,973,881	–
Schlumberger	–	$334,400	–	$501,600	–	$836,000
CMG	–	$212,993	–	$951,007	–	$1,164,000
Total	$2,184,364	$547,393	$5,789,517	$1,452,607	$7,973,881	$2,000,000
Total Cost Share %	80%	20%	80%	20%	80%	20%

*Note: **Denbury** – Additional collaboration in the form of field support, infrastructure development, design and implementation, gas supply, and injection/production operations.*

TECHNICAL APPROACH/PROJECT SCOPE

- Task 1.0 – Project Management and Planning

- Task 2.0 – Engineering Design (BP1)
  - 2.1 – Rich Gas Source, Compression, and Transportation Evaluation

  Go/no-go decision based on securing a rich gas source completed on 6/30/2021

  - 2.2 – Core and Fluid Laboratory Evaluations
  - 2.3 – Blended CO_2–Rich Gas Injection Modeling and Simulation
  - 2.4 – Injection/Monitoring Program Design

TECHNICAL APPROACH/PROJECT SCOPE (CONT.)

- Task 3.0 – Field Operations and Monitoring (BP2)
  - 3.1 – Field Preparation
  - 3.2 – Field Validation and Monitoring
  - 3.3 – Rich Gas Supply Monitoring
  - 3.4 – Sample Analysis
  - 3.5 – Field Validation Decommissioning Activities

- Task 4.0 – Business Case for Blended CO_2–Rich Gas Utilization (BP1 and BP2)
  - 4.1 – Laboratory Studies
  - 4.2 – Data Management and Machine Learning Studies
  - 4.3 – Modeling and Simulation
  - 4.4 – Business Case Analysis

BUDGET PERIOD 1 PROGRESS OVERVIEW

A series of activities were performed to accomplish the planned tasks in BP1:

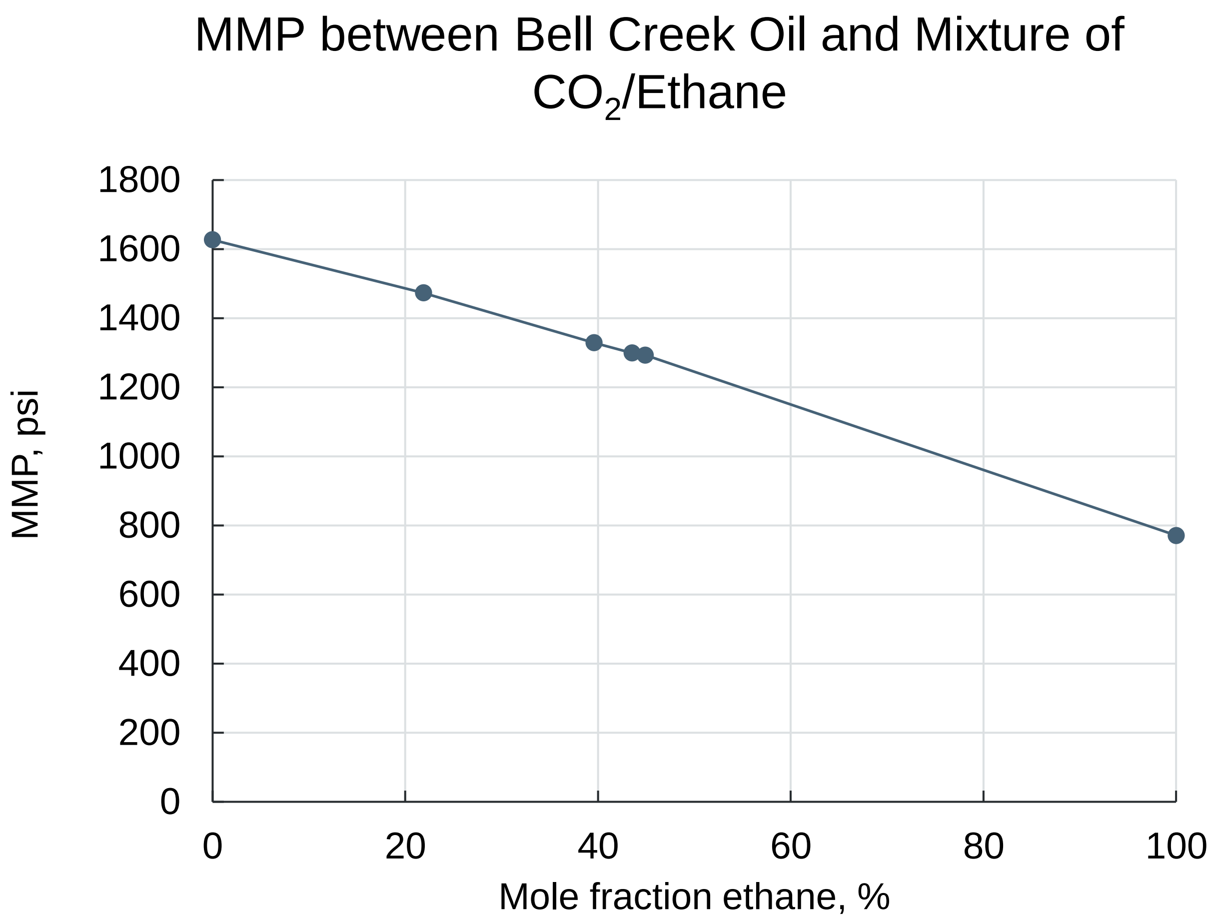
- Worked with Trimeric to design the surface injection and monitoring system.
- Performed detailed laboratory experiments to investigate the oil–gas interactions between rich gas components and oil samples collected from different oil fields.
- Designed and evaluated two pilot test plans in the Bell Creek Field based on the gas availability, facility configurations in the field, and Denbury’s budget to meet the project requirements.
- Performed an extensive simulation study to predict the possible EOR response in the Bell Creek Field and determine the optimal operational parameters for the pilot test.
- Designed a practical injection monitoring program based on the simulation results and operational schedule in the field.
- Worked with Denbury and vendors to secure the rich gas source for the pilot.
- Developed a workflow for conducting business case scenarios.
- Go/no-go decision based on whether rich gas source is secured was confirmed 6/30/2021.

Work performed during BP1 allowed the successful transition to begin BP2 activities.

LABORATORY TESTING DURING BP1

Subtask 2.2 -- Core and Fluid Laboratory Evaluations

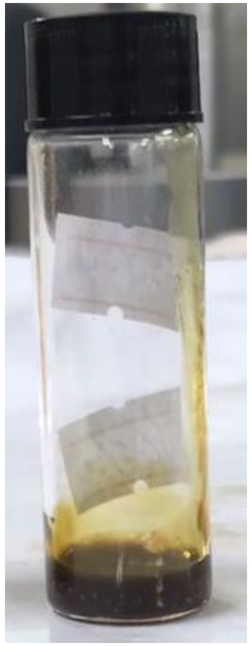
- Core and oil samples were collected for the Bell Creek Field.
- Testing was performed to determine:
  - Porosity/permeability.
  - Relative permeability of CO_2/ethane blends.
  - PVT data to describe the swelling and solubility of CO_2/rich gas blends in the presence of Bell Creek oil.
  - CO_2/rich gas MMP testing.



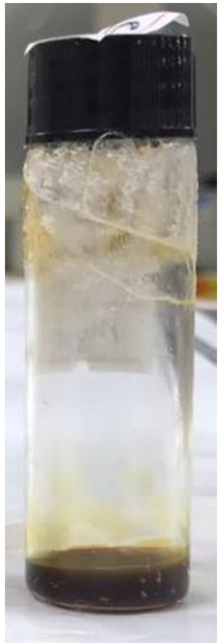
TECHNOLOGY BACKGROUND: CO_2 BLENDED WITH RICH GAS (BP1)

BP1 Flow-Through Testing: Example Results

CO_2-Flooded Oil, 2 mL

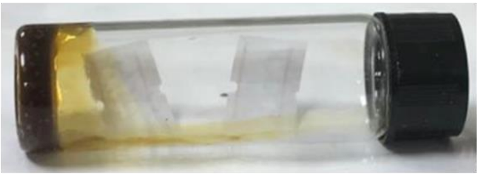


C2-Flooded Oil, Additional 1 mL

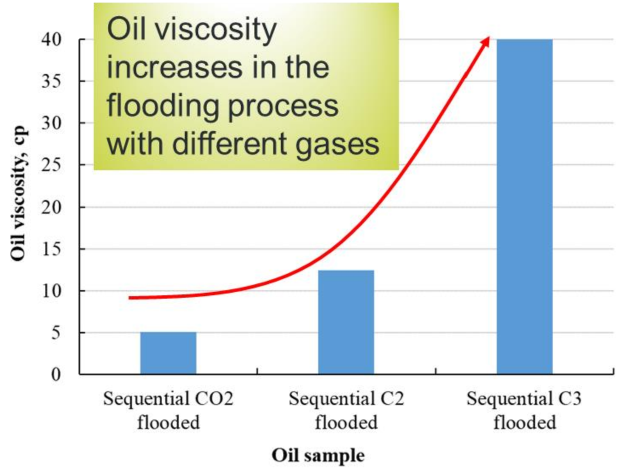


C3-Flooded Oil, Additional 0.95

CO_2-flooded oil, oil can flow under room temperature



C2-flooded oil after CO_2 flood, oil is difficult to flow under room temperature



C3-flooded oil after C2 flood, oil cannot flow under room temperature

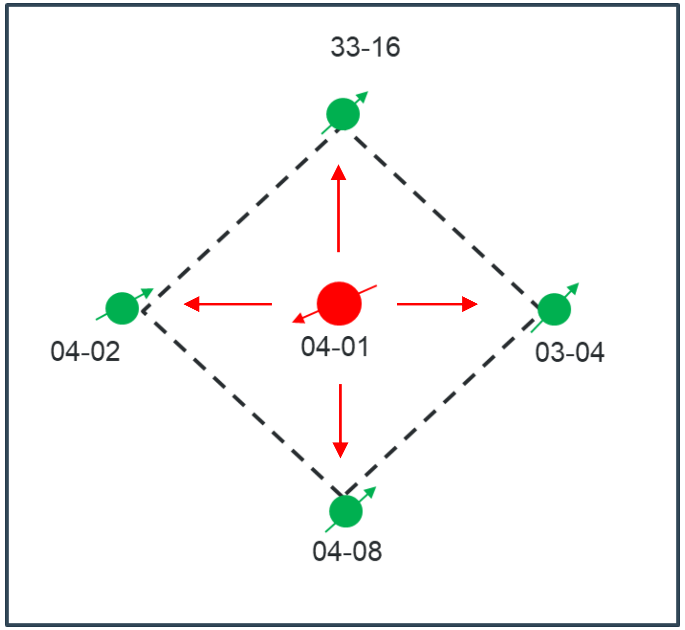
Laboratory tests demonstrated that the addition of C2 and C3 effectively drained higher viscosity oil from core plugs.

SELECTION OF EOR MODE FOR THE PILOT

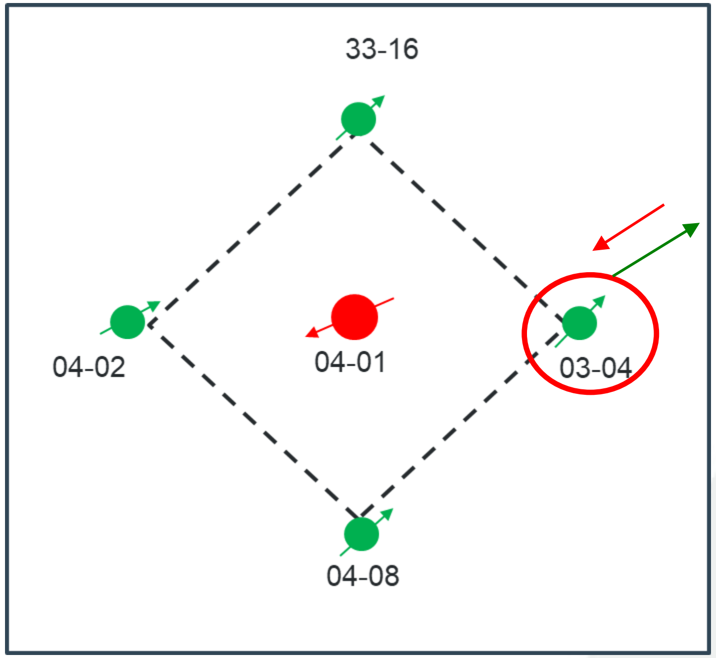
Subtask 2.3 – Blended CO_2–Rich Gas Injection Modeling and Simulation

- The goal of the project is to determine the effect of injecting blended CO_2 and rich gas into an active CO_2 EOR field to improve production performance.
- Continuous flooding and huff ‘n’ puff (HnP) were considered in this subtask to predict the potential EOR improvement by using rich gas in the selected pattern.

Continuous Flooding



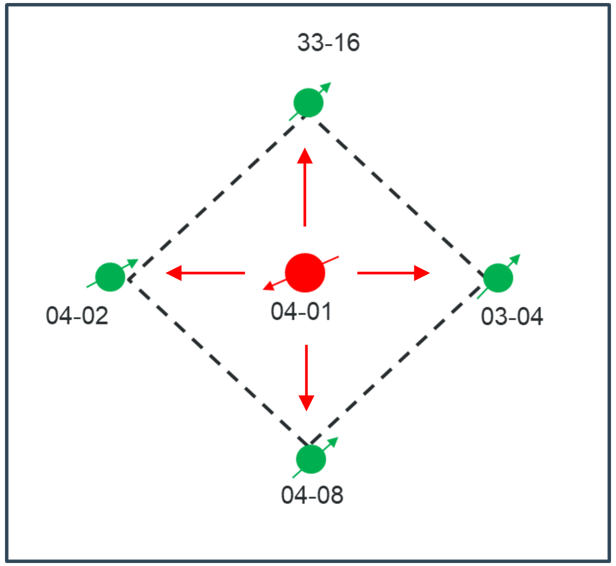
Huff ‘n’ Puff

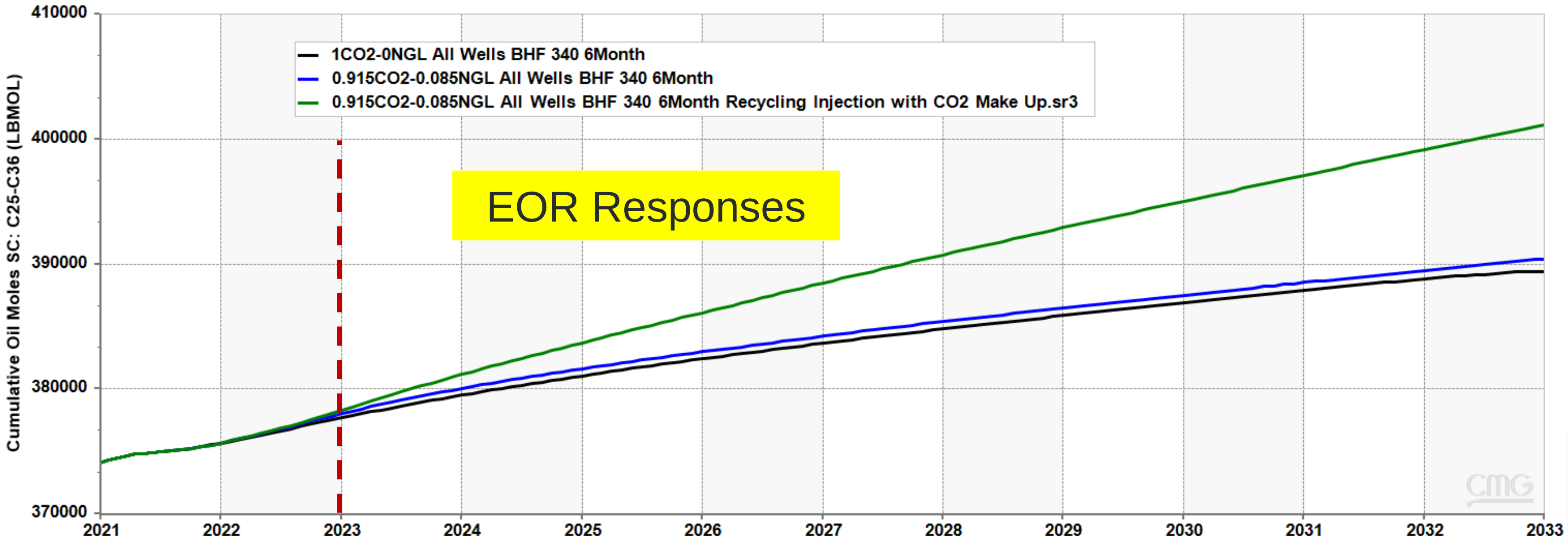


PREDICTION OF EOR RESPONSE FOR CONTINUOUS FLOODING

Scenario 1 – Continuous Flooding:

- CO_2–NGL blend of 8.5 mol% is injected through Well 04-01 while the other four wells are open for production during the pilot.
- The blend injection rate (1280 bpd downhole) is maintained consistently for 6 months.
- Simulation results indicate that the flooding may take 2 years to show the EOR improvement because of the low NGL concentration in the injected blend.



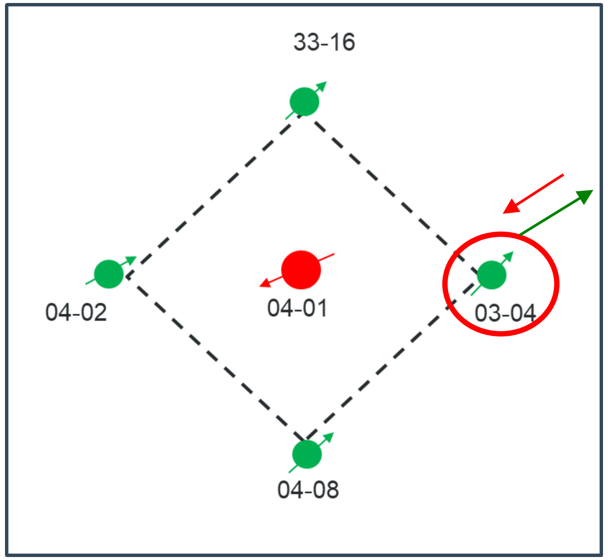


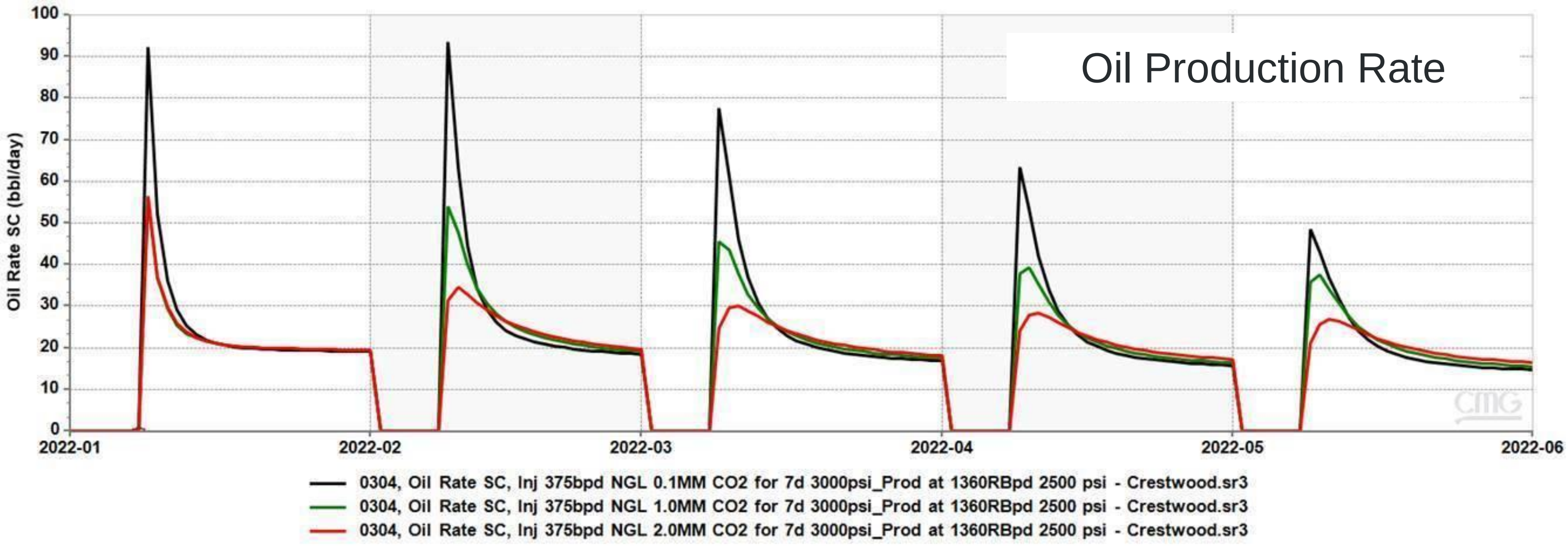
PREDICTION OF EOR RESPONSE FOR HUFF 'N' PUFF

Scenario 2 – Huff 'n' Puff:

- A boundary well (03-04) was selected for HnP in the pilot instead of flooding the whole pattern.
- HnP with 7 days of injection and 21–24 days of production per cycle could provide much quicker EOR responses than continuous flooding.
- HnP could solve both economic and technical challenges in the pilot by using less NGL while keeping high NGL concentration (83 mol%) in the blend.

Huff 'n' Puff

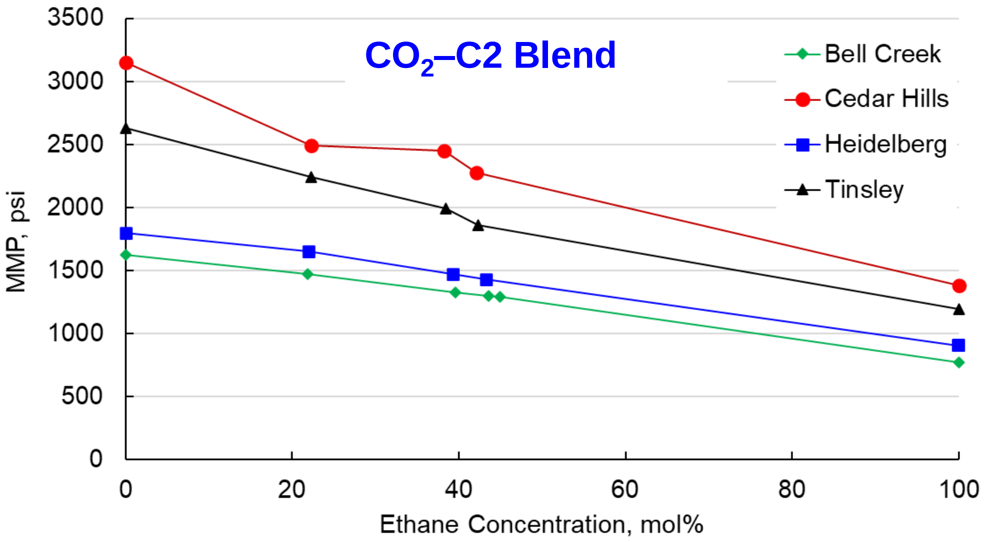


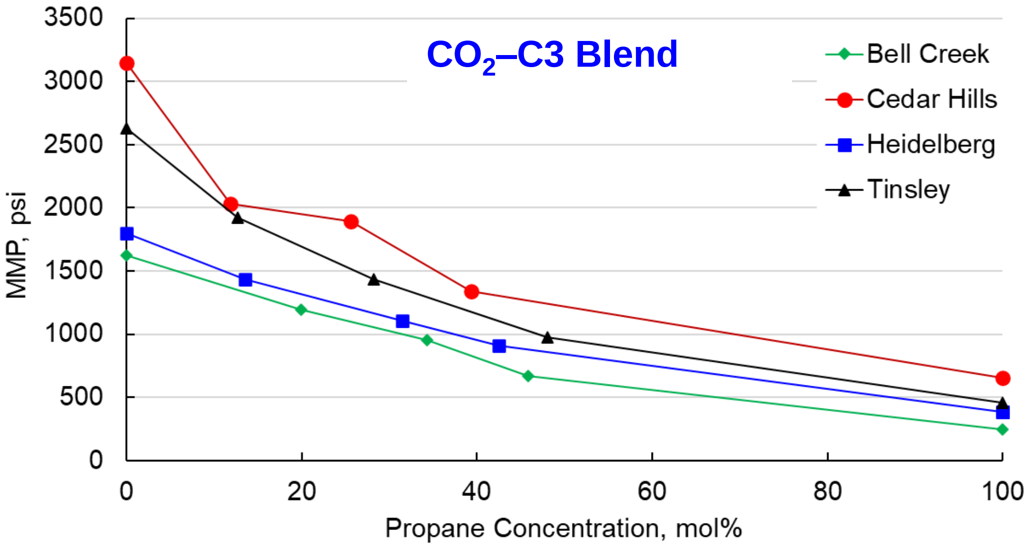


MINIMUM MISCIBILITY PRESSURE TESTS

Subtask 4.1 – Business Case Laboratory Studies (BP1)

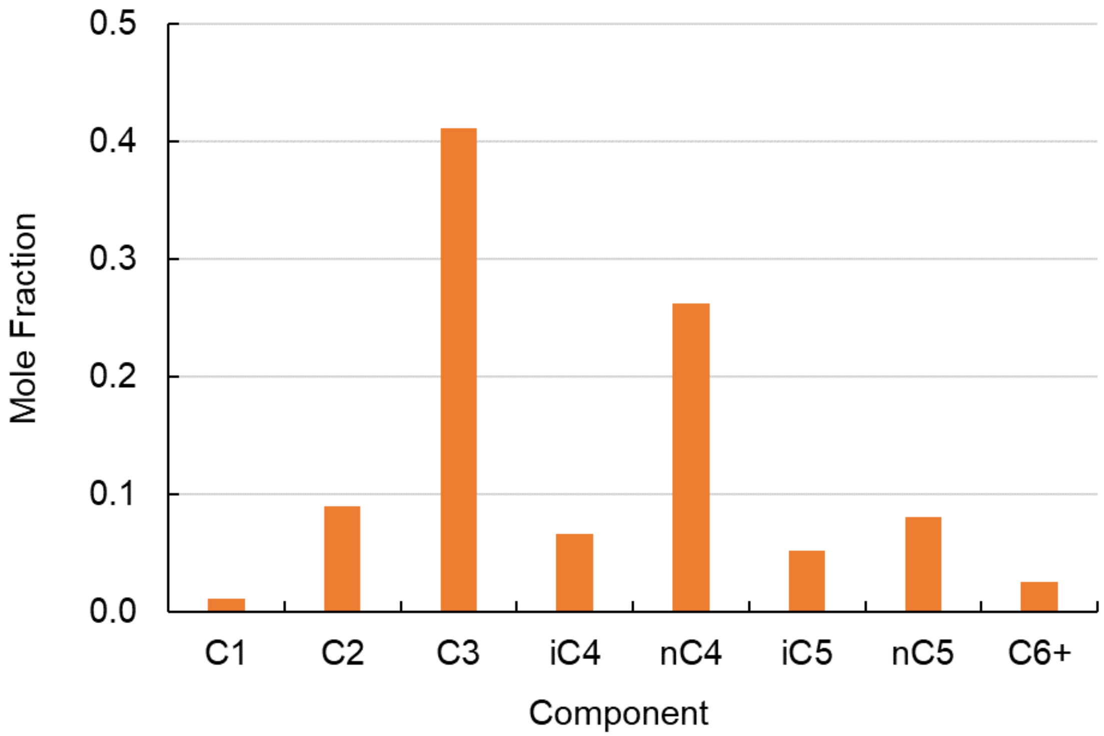
- Four fields were selected for developing business cases: two Rocky Mountain and two Gulf Coast region fields.
  - All have different geologic and oil properties and are currently operated by Denbury.
- MMP tests were completed for the four oil samples with CO_2–rich gas blends.
- Results showed that adding ethane or propane to the injection gas stream can significantly reduce the MMP.
- Test models and simulation of the four fields are under staged development. Results of the pilot at Bell Creek will inform potential sweep efficiencies and techno-economics for the business case scenarios.





GAS COMPOSITION TO BE USED FOR THE PILOT

- The gas sourced for the pilot has a high concentration of C3+ (~90 mol%).
- Additional laboratory testing and simulation is planned to better understand how butane will affect MMP and blended CO_2-rich gas performance.
- Initial simulations show that this is favorable for EOR using a HnP strategy.



Measured NGL Stream Composition

BP2 ACTIVITIES

Field Validation and Monitoring

- Blended gas injection
- Well production
- Fluid sampling (gas and oil)
- Monitoring (rate, pressure, temperature)

Pilot Test Evaluation

- Improvement in oil recovery factor
- MW shifting

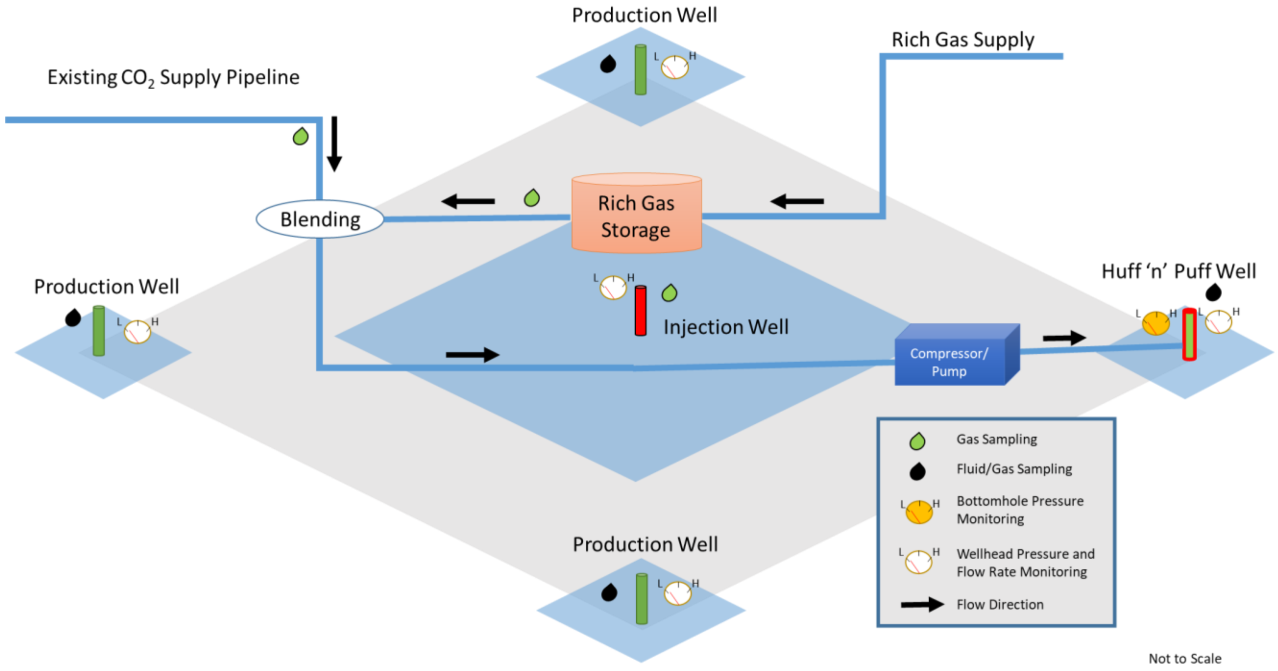
Business Case Evaluation for Other Potential Target Fields

- Additional laboratory testing
- Data management
- Modeling and simulation

TASK 3 – FIELD INJECTION AND MONITORING (BP2)

Huff-n-Puff Field Pilot Plan

- On-site storage of the rich gas product, with routine deliveries during the project to minimize the amount of on-site storage.
- NGL injection rate of 375 bbl/day.
- Total blended gas injection rate is 588,000 scf/day.
- Monitor rate of each gas injection stream, gas composition, well production, and production oil composition.



PROPOSED EQUIPMENT LAYOUT – DENBURY'S TEST SITE (T3)

System Arrangement:

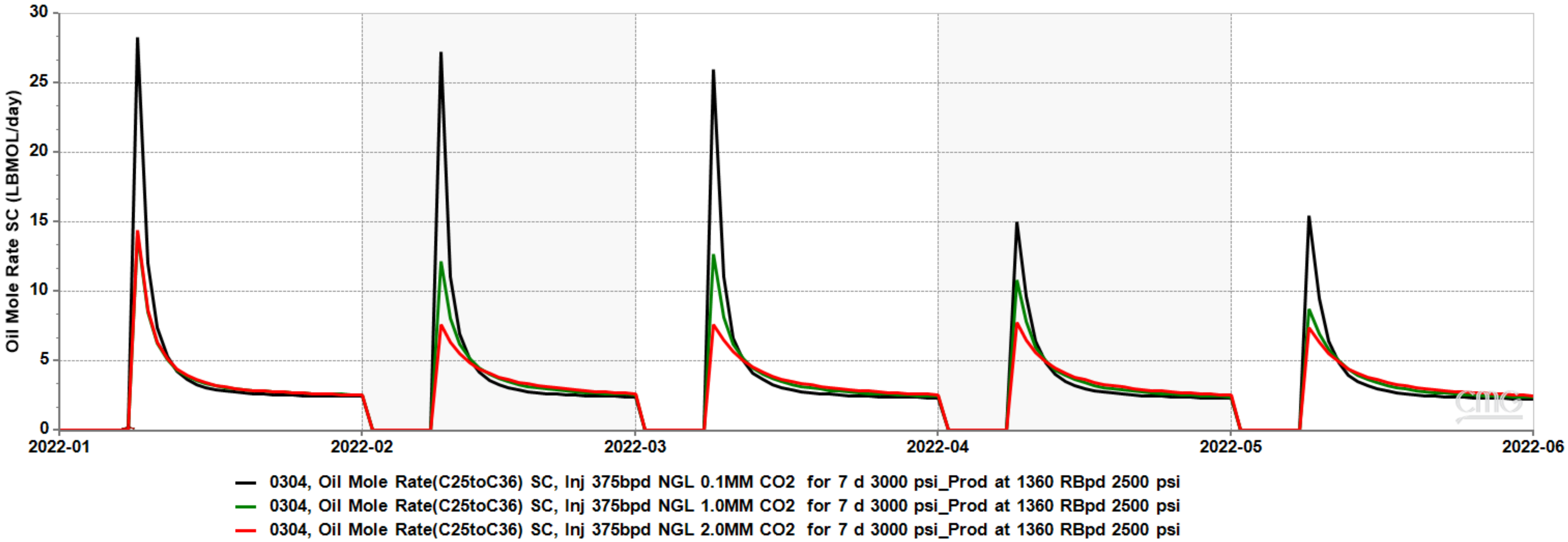
- Two storage vessels
- Pump system
  - Booster pump
  - Primary pump
- Metering
  - Rich gas: Coriolis meter
  - CO_2 stream: existing meter inside building
- Connections inside building to 03-04 line
- All equipment to be located within footprint of test site

BENEFITS OF SITING EQUIPMENT AT THE TEST SITE

- Installation of equipment at the test site allows for project monitoring through Denbury’s telemetry system.
  – Provides detailed monitoring of injection and production cycles.
- The updated monitoring system will be utilized to provide:
  – Daily monitoring of oil, water, and gas production for first week of production cycle.
  – Minimum of weekly tests after first week of production cycle.
- Routine sampling possible of all streams: oil, water, and gas streams.
- Utilities are already in place with adequate capacity available for additional loads, minimizing cost of installation.

Field Validation and Monitoring (T3)

- Well logs (Pulsed neutron logs – PNX) will be collected and analyzed from the HnP well before and after the pilot to compare the oil saturation change in the near wellbore region.
- Oil samples will be collected and analyzed throughout the pilot to monitor changes in the heavy hydrocarbon content of the produced oil.

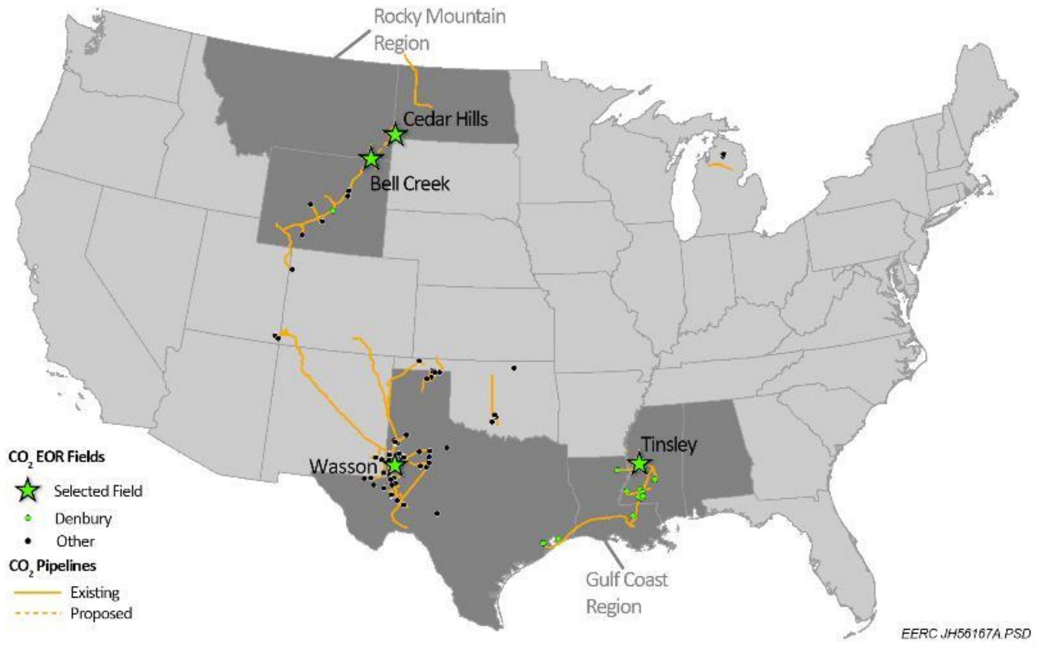


BUSINESS CASE ANALYSIS (T4)

- The EERC is working closely with Denbury on economic analyses to determine the potential for field-scale implementation of blended CO_2–rich gas EOR.
- After detailed consultation with Denbury, we will forego the business case analysis of the Heidelberg field due to conformance issues and reservoir complexity, which results in downhole commingling of multiple intervals in the CO_2 flood.
- The EERC decided to substitute the Wasson field for Heidelberg in business case analysis.
  - Voluminous published data exists on the Wasson field.
  - Wasson increases geological diversity of business case field group relative to Heidelberg.
  - Wasson analysis will be of greater interest to operators in largest CO_2-EOR province (Permian).

CHARACTERISTICS OF CO_2 EOR FIELDS TO BE USED FOR THE BUSINESS CASE ANALYSIS (T4)

Field	Basin	Zone	Dominant Lithology	Porosity Range, %	Permeability Range, mD	Thickness, ft	API Gravity
Bell Creek	Powder River	Muddy	Marine sandstone	25–35	150–1175	30–45	32–41
Cedar Hills	Williston	Red River	Dolostone	13–23	15	10	30
Tinsley	Mississippi Interior Salt	Woodruff	Shallow marine sandstone	26–28	1040–1300	80–90	32
Wasson	Permian	San Andres	Dolostone	15–25	1–150	200–500	33



BUSINESS CASE FOR POTENTIAL TARGET FIELDS (T4)

Subtask 4.1 – Laboratory Studies

- Detailed laboratory measurements will be performed to investigate the gas–oil–rock interactions for different oil fields.
- Test matrices were designed for interfacial tension and contact angle measurements.

IFT

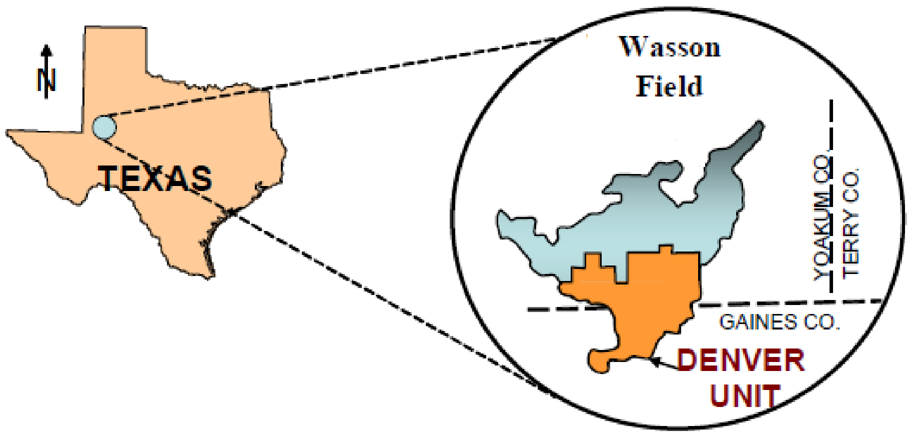
Surrounding Phase

Oil Sample	Gas Sample	Temperature, C°	Pressure, psi
Bell Creek	• CO_2 • Ethane (C2) • Propane (C3) • Butane (C4) • Mix of CO_2 & C2 • Mix of CO_2 & C3 • Mix of CO_2 & C4	42	1K, 3K, 5K, 7K
Tinsley		77	1K, 3K, 5K, 7K
Cedar Hills		104	1K, 3K, 5K, 7K

PROOF OF CONCEPT RESERVOIR SIMULATION (T4)

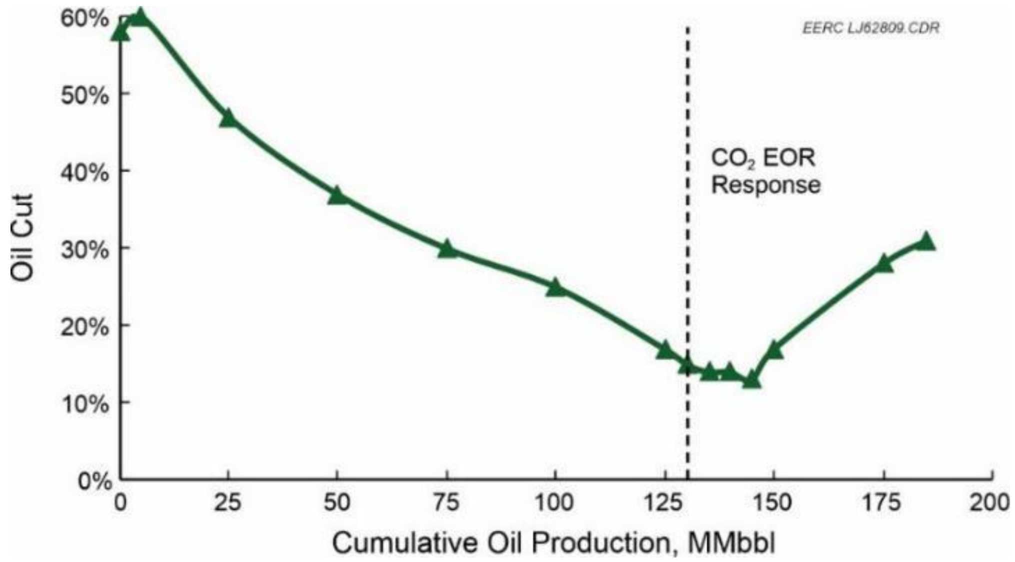
Subtask 4.3 – Modeling and Simulation

- Both experimental and field data showed that adding rich gas components to the CO_2 injection stream may improve the EOR performance in shallower/low-pressure reservoirs where miscible flooding is difficult to achieve using CO_2 alone.
- The Wasson Field of West Texas, which has undergone CO_2 EOR since 1983, was used as an initial test case for reservoir simulation because a wealth of publicly-available data exists for the field, including PVT data.



Location Map of the Denver Unit in the Wasson Field (Garcia, 2006).

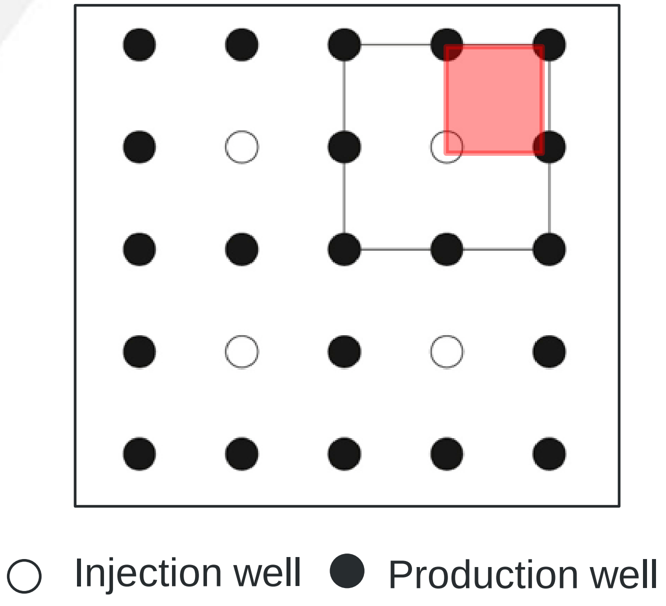
Garcia Quijada, M., 2006, Optimization of a CO_2 flood design Wesson Field, West Texas: Master's Thesis, Texas A&M University.



Oil Cut Response in the CO_2 EOR Process at the Denver Unit of the Wasson Field.

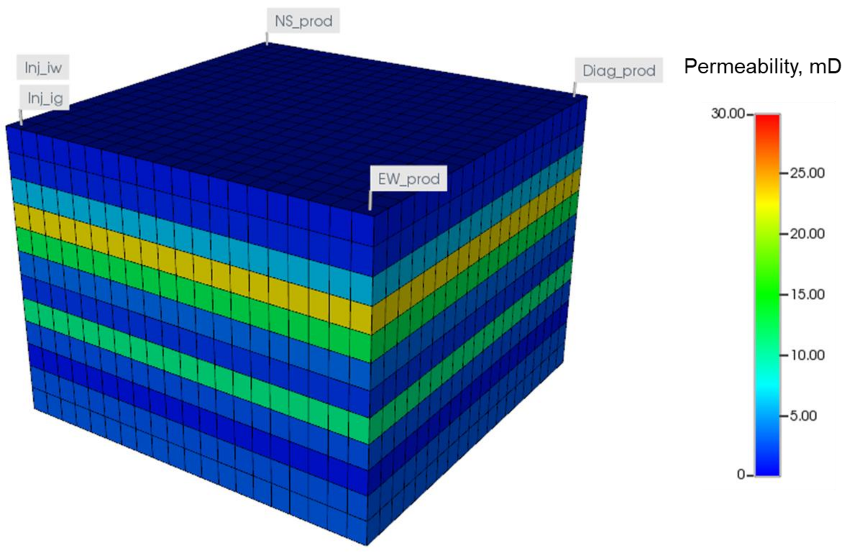
INITIAL SIMULATION MODEL DEVELOPMENT (T4)

- A quarter inverted nine-spot pattern simulation model was developed to investigate the feasibility of CO_2 EOR improvement by using rich gas components.
- The model includes four vertical wells: one injection well and three production wells. The pay zone depth was set at 1800 ft to reflect a shallower reservoir.



Schematic of Inverted Nine-Spot Patterns in the Wasson Field.

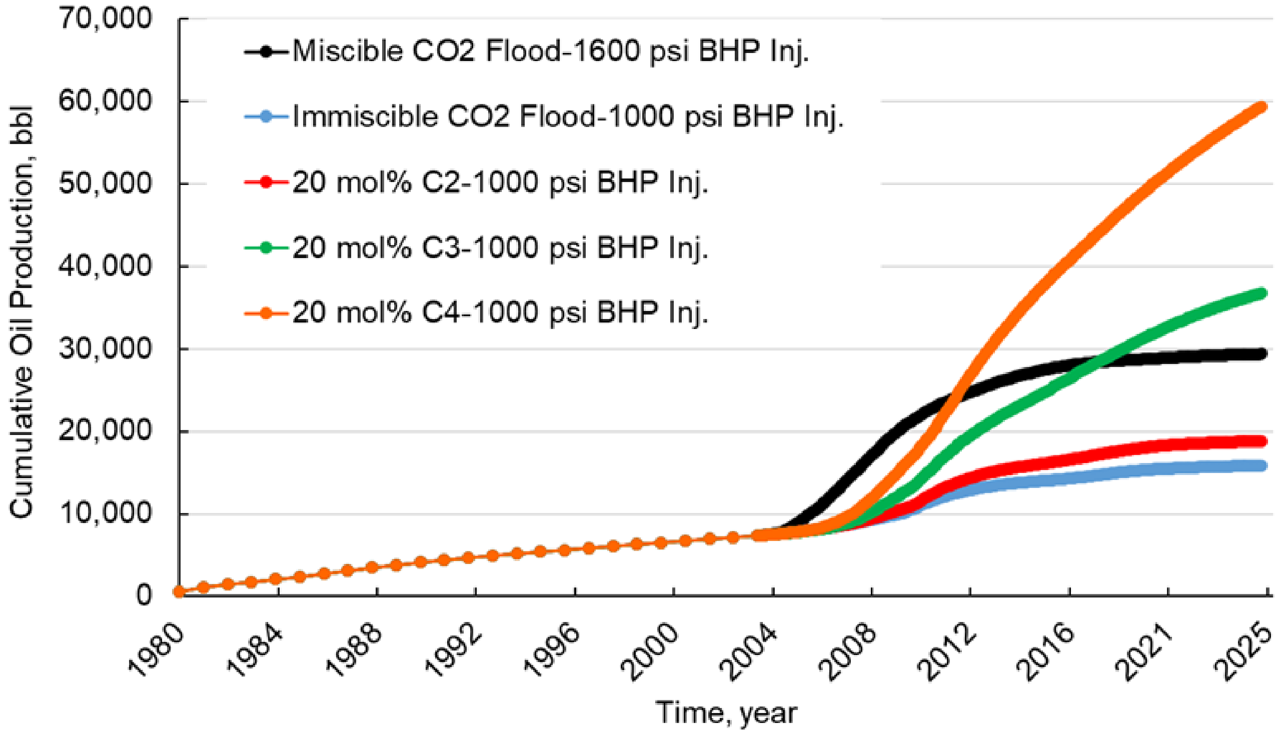
Parameter	Value
Avg. Permeability	5 mD
Avg. Porosity	12%
Reservoir Temperature	105°F
Pay Zone Depth	1800 ft
Max. Injection Pressure	1620 psi
Grids (I×J×K)	20×20×12 cells
Cell Dimension (I×J×K)	50 ft × 50 ft × 2 ft



Schematic of the Simulation Model.

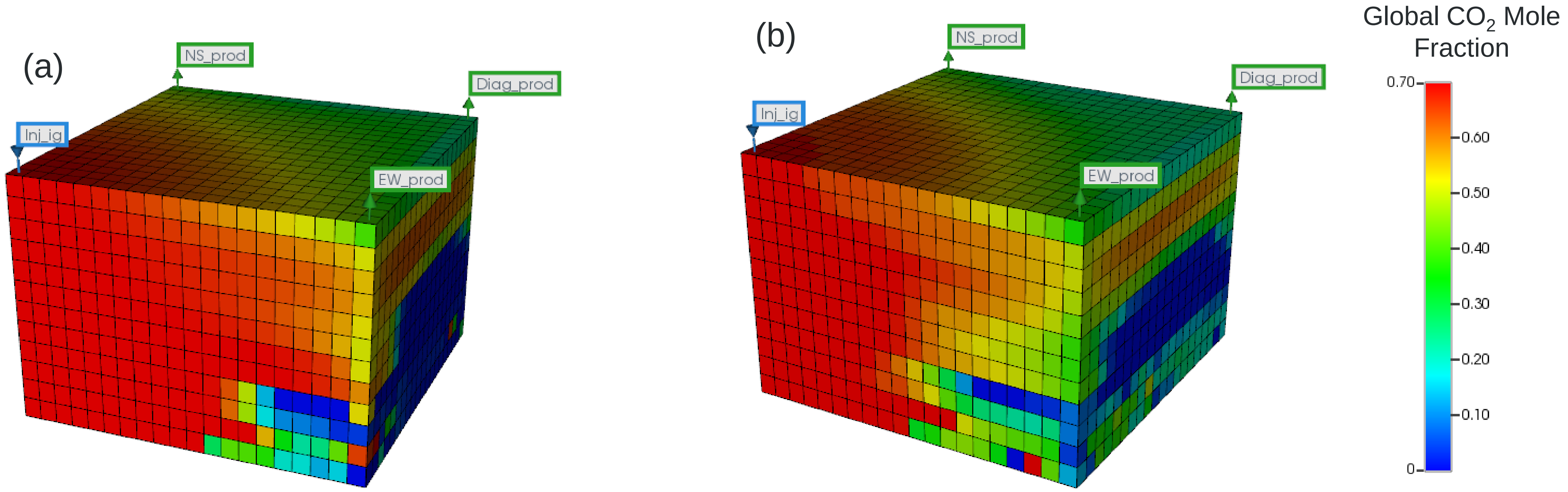
SIMULATION RESULTS – CO_2–RICH GAS EOR COMPARISON

- Rich gas components (C2, C3, and C4) were added to the CO_2 injection gas stream to reduce the MMP and achieve better EOR results.
- The simulation results indicated that adding propane or butane to the injection gas stream could improve the EOR performance significantly even at 1000-psi bottomhole injection pressure.
- A fivefold (52,012 vs. 8515 bbl) increase in incremental oil could be achieved by using the CO_2–butane mixture as an EOR injectate compared to that of an immiscible CO_2 flood.
- The long-term EOR performance of 1000-psi injection with propane or butane added to the injection gas could outperform that of a 1600-psi CO_2 flood.



SIMULATION RESULTS – CO_2 STORAGE COMPARISON (T4)

- The sweep efficiency of the gas flood was greatly improved by adding butane to the injection gas stream.
- More CO_2 could be stored in the reservoir—5248 vs. 7854 tonnes of CO_2 in scenarios (a) and (b), respectively. The results indicate that by adding 20 mol% butane to the injection gas stream, CO_2 storage could increase by 50% in 20 years of EOR operation in this 23-acre unit.



(a) Immiscible CO_2 Flood with 1000-psi BHP.

(b) CO_2–C4 Flood with 20 mol% Butane in the Injection Gas, 1000-psi BHP.

BUSINESS CASE ANALYSIS – PLANNED WORK (T4)

- Geologic uncertainty scenario cases will be created for each of the four fields (e.g., p10, p50, p90); ~2000 iterations per field.
- This information will be used to identify numerical simulation uncertainty.
  - Development scenarios for comparison with both site-specific and generic NGL composition for each field
    - ♦ CO_2 flooding base case
    - ♦ Full life/continuous injection with pure NGL stream
    - ♦ Full life/continuous injection with CO_2 enriched with NGLs
    - ♦ Initial CO_2 injection followed by injection of NGL-enriched CO_2
    - ♦ HnP using NGL-enriched CO_2 at initial flood response
    - ♦ HnP using NGL-enriched CO_2 at mature flood stage
    - ♦ HnP using pure CO_2
    - ♦ HnP using pure NGL
- Economic evaluation of each business case spanning a range of crude oil and NGL prices.

PLANS FOR FUTURE TESTING/DEVELOPMENT/ COMMERCIALIZATION

- The pilot test during BP2 will provide a unique U.S. data set on rich gas EOR, paving the way for larger-scale tests and deployment.
- Positive pilot test results would support the development of infrastructure and a market for stranded rich gas.
- Results would be applicable to develop business cases for other potential target fields.
- Because of the ability to leverage existing oilfield infrastructure, commercial implementation of rich gas EOR could occur quickly.

Bethany A. Kurz
Director of Analytical Solutions
bkurz@undeerc.org
701.777.5050

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

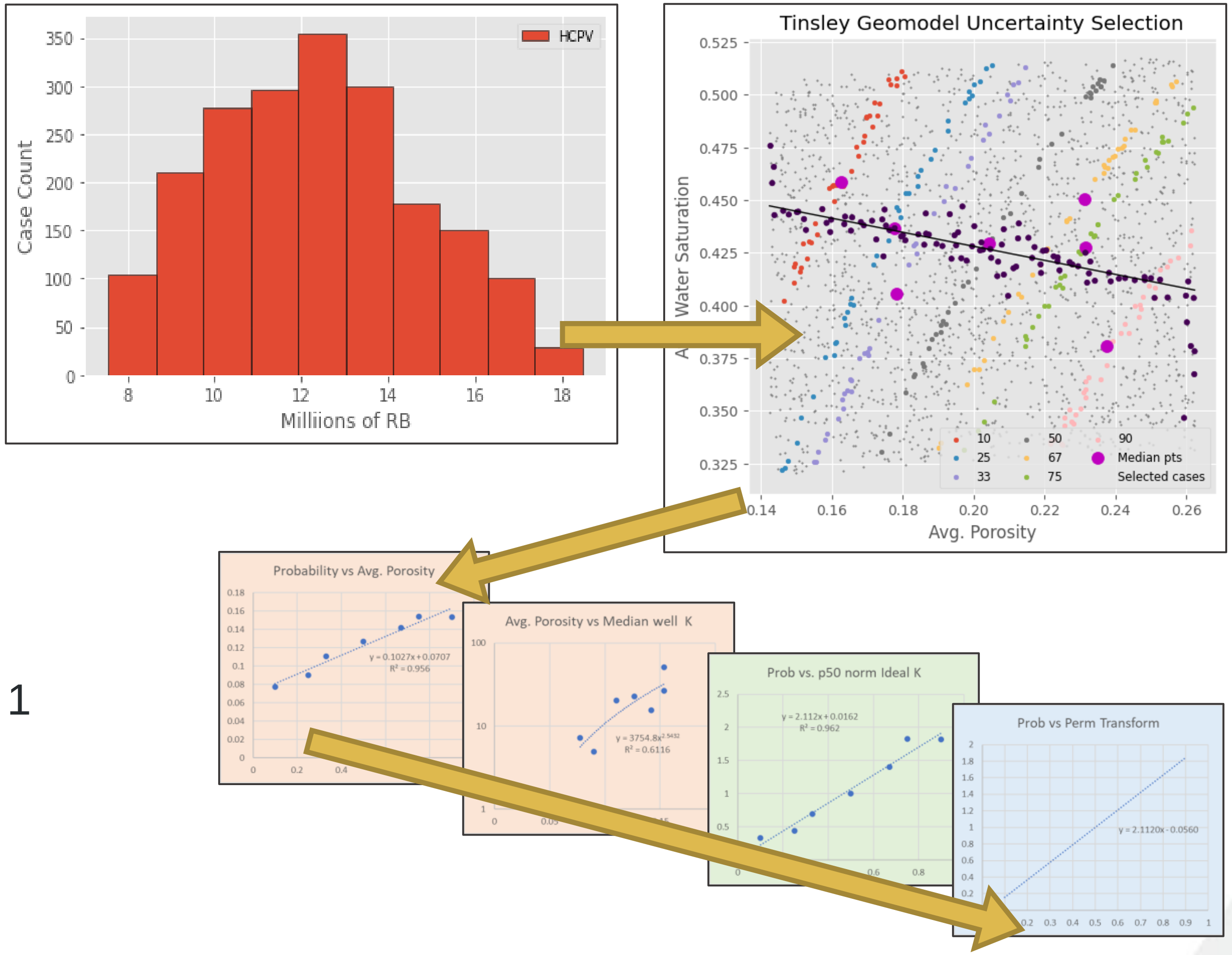
www.undeerc.org
701.777.5000 (phone)
701.777.5181 (fax)

THANK YOU

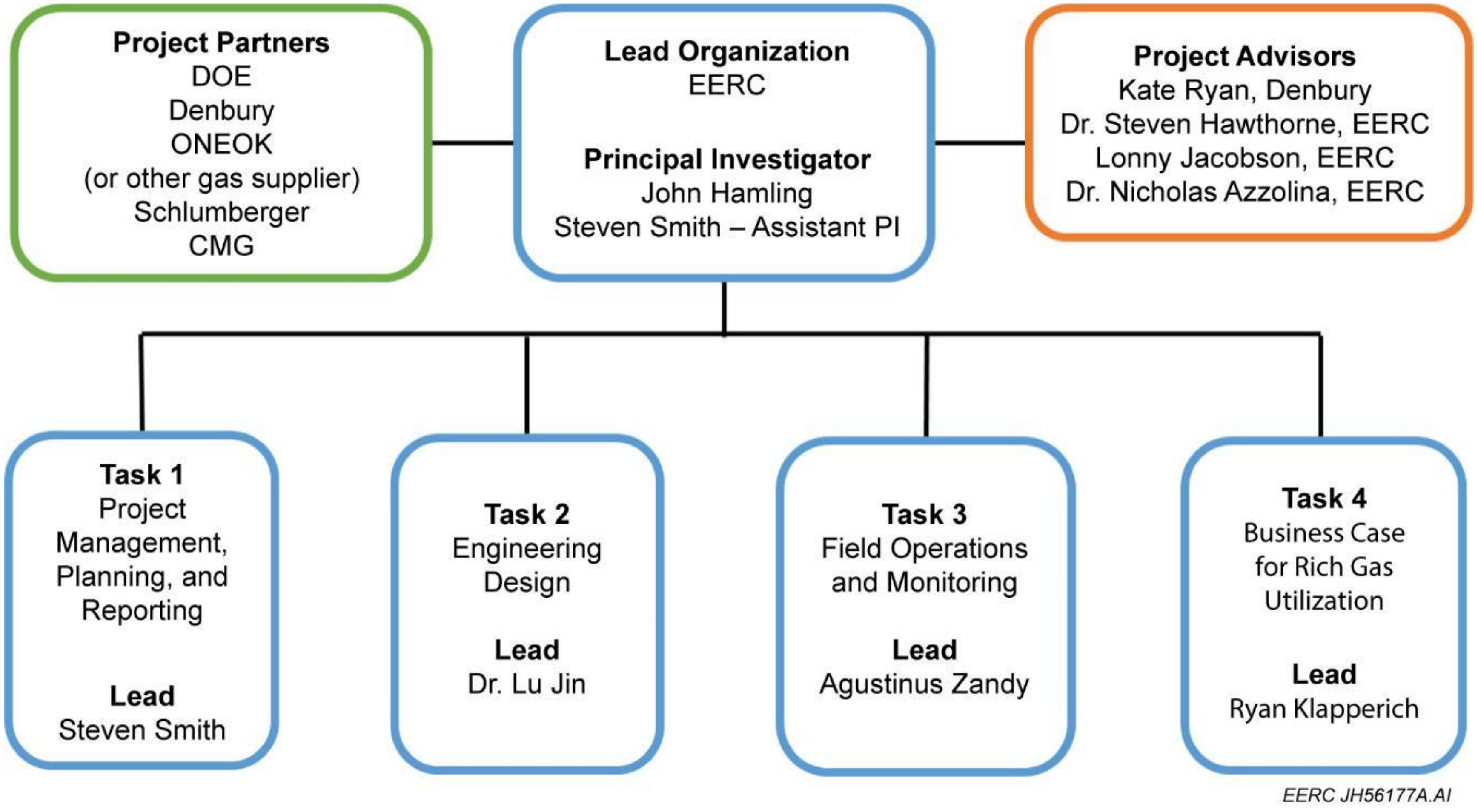
Critical Challenges. Practical Solutions.

GEOMODEL UNCERTAINTY PROCESS (T4)

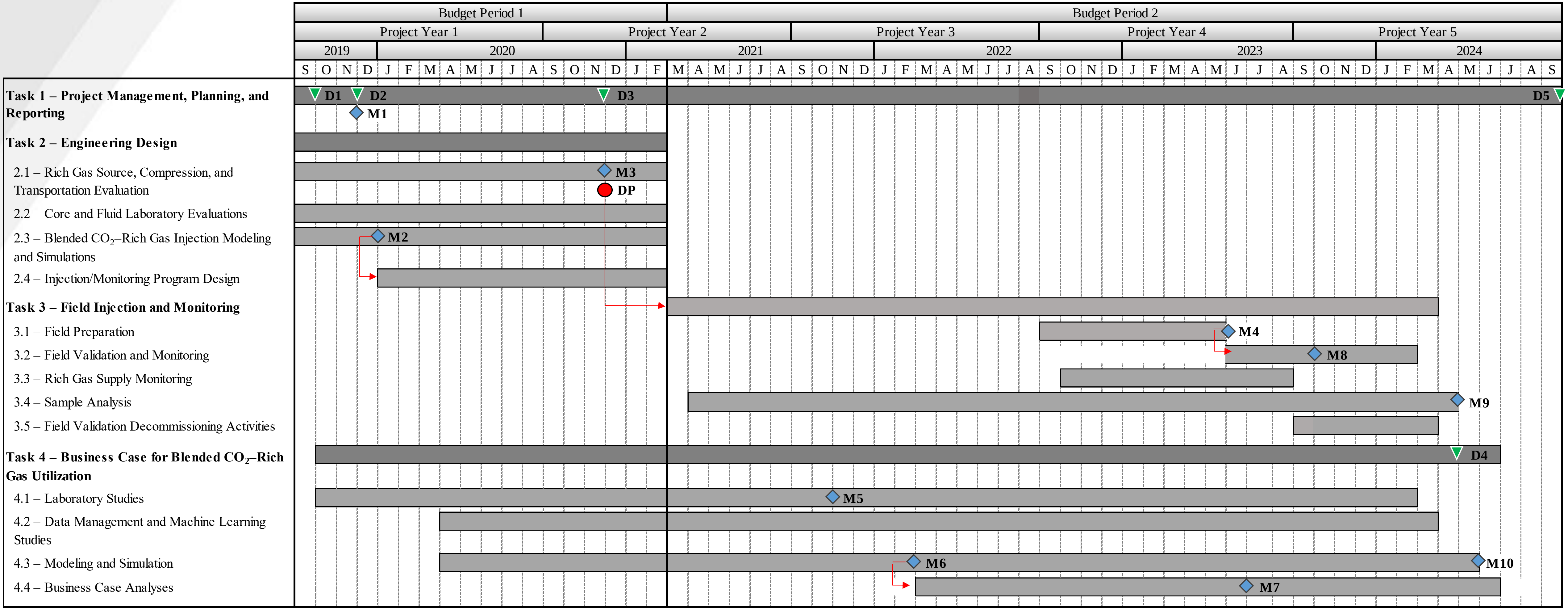
- Geomodel uncertainty analysis
  - 2000 iterations per field
  - Φ and Sw uncertainty for 9-spot pattern
- Uncertainty case selection
  - HCPV probability functions for all iterations
    - ♦ Plotted by Avg. Φ vs. Avg. S_w
  - Representative p1 to p99 identified
  - After Belobraydic and Kaufman (2014)
- Permeability uncertainty transform
  - Scale permeability to case probability
    - ♦ $K_{Pcase} = K * f(pCase)$
    - ♦ $f(pCase) = m* pCase + b$; where $f(p50) = 1$
- Deliver cases for numerical simulation
  - $p10(\Phi,S_w,K)$, $p50(\Phi,S_w,K)$, $p90(\Phi,S_w,K)$



ORGANIZATION CHART



CO_2 BLENDED WITH RICH GAS TIMELINE



Key for Deliverables (D)

D1 – Updated Project Management Plan
D2 – Data Management Plan
D3 – Workforce Readiness Plan
D4 – Laboratory Studies of Blended CO_2–Rich Gas EOR
D5 – Data Submitted to NETL EDX

Key for Milestones (M)

M1 – Kickoff Meeting Held
M2 – Injection Site Verified
M3 – Rich Gas Source Secured
M4 – Field Preparation Completed
M5 – All Core Samples Obtained
M6 – Initial Geostatic Models Completed
M7 – First Field Business Case Developed
M8 – Blended CO_2–Rich Gas Injection Completed
M9 – Validation Test Fluid Sample Analyses Completed
M10 – Modeling and Simulation Completed

Summary Task
Activity Bar
Deliverable (D)
Milestone (M)
Decision Point (DP)
Critical Path

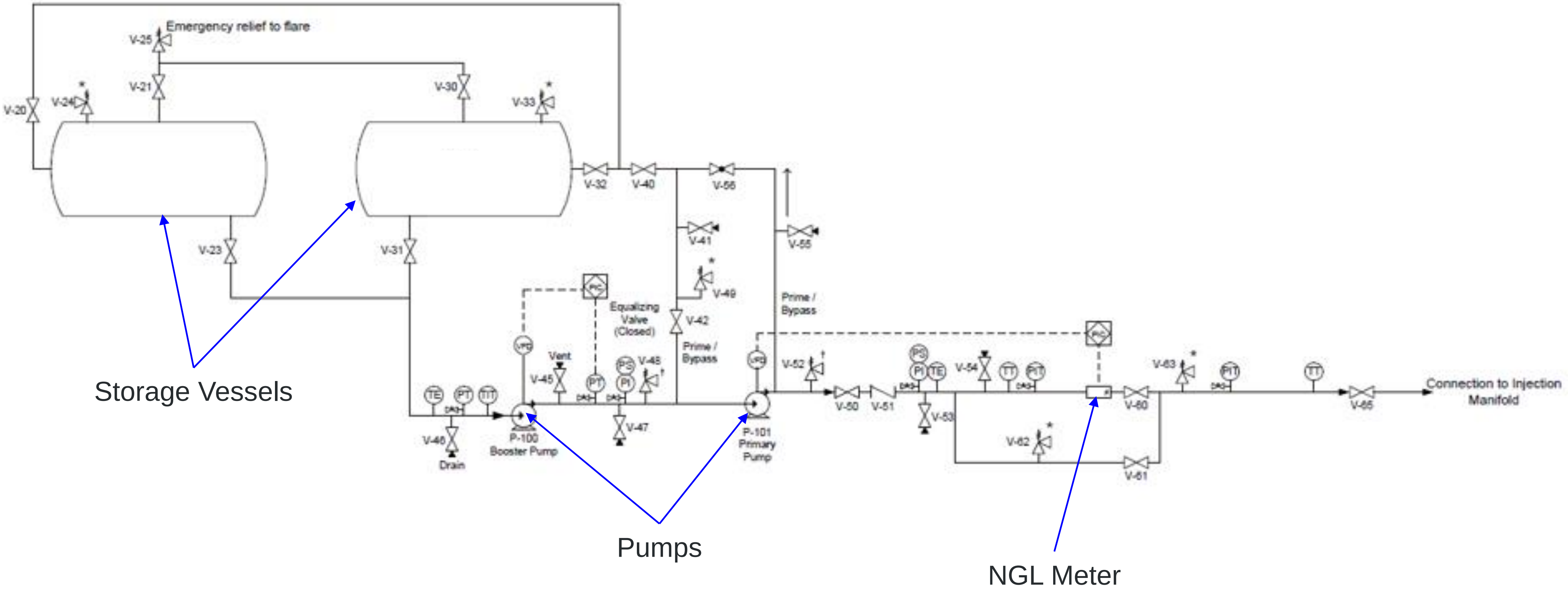
TB 9/15/22

OIL COLLECTION PROCESS

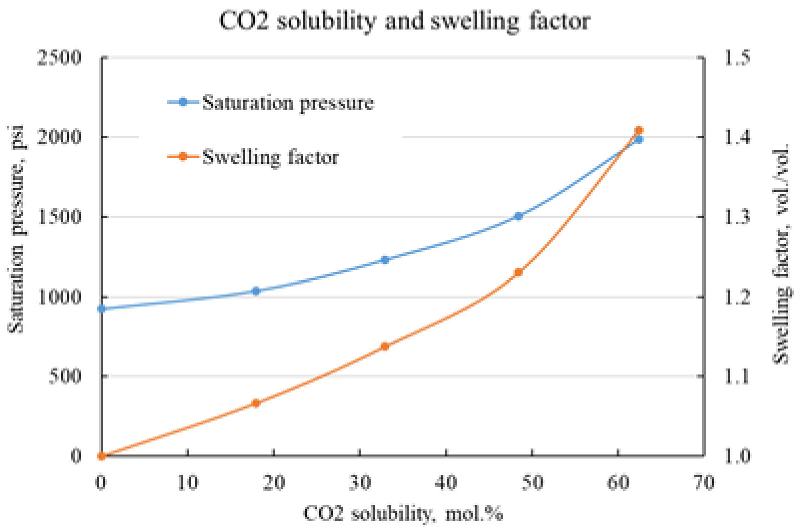
CO_2-Flooded Oil –
Easy to Flow

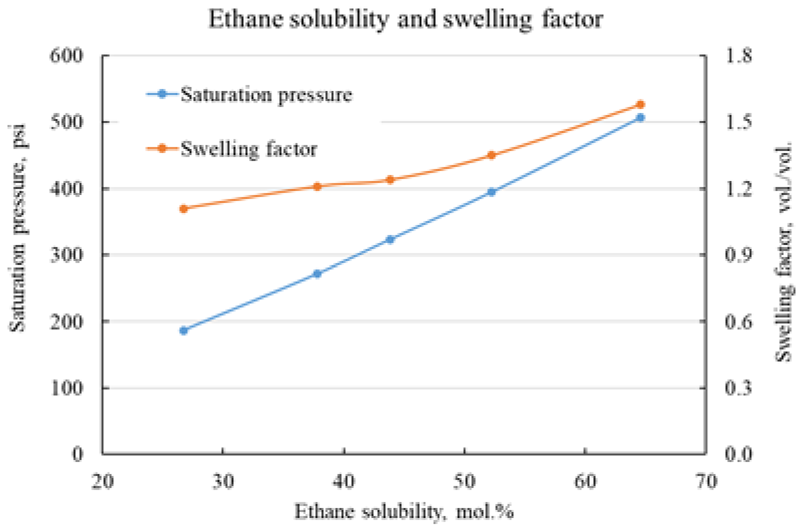
C3-Flooded Oil –
Sticky, Viscous, And Foamy

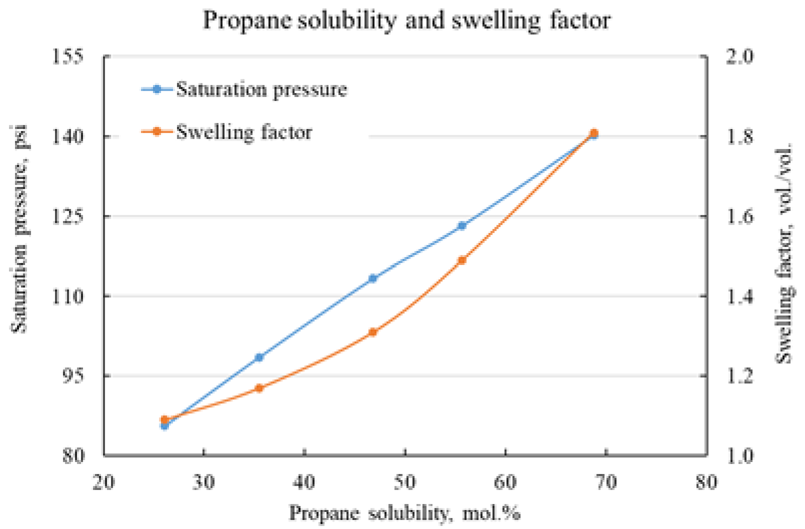
EXAMPLE OF PROCESS AND INSTRUMENTATION DRAWING

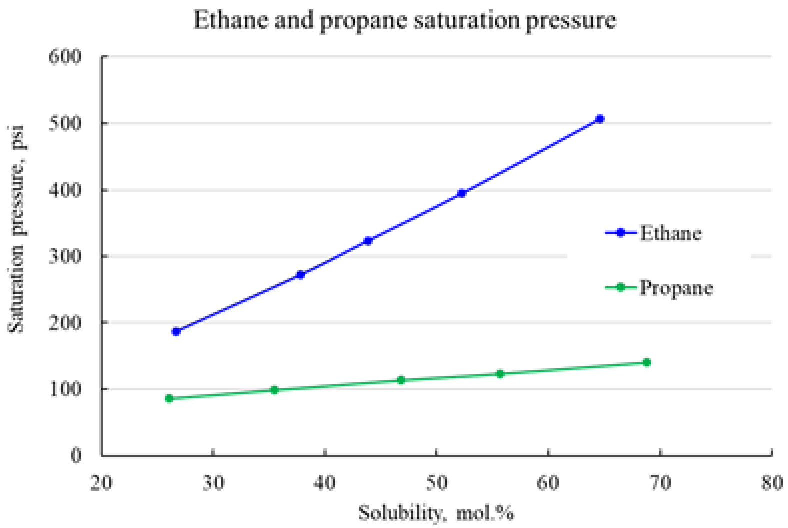


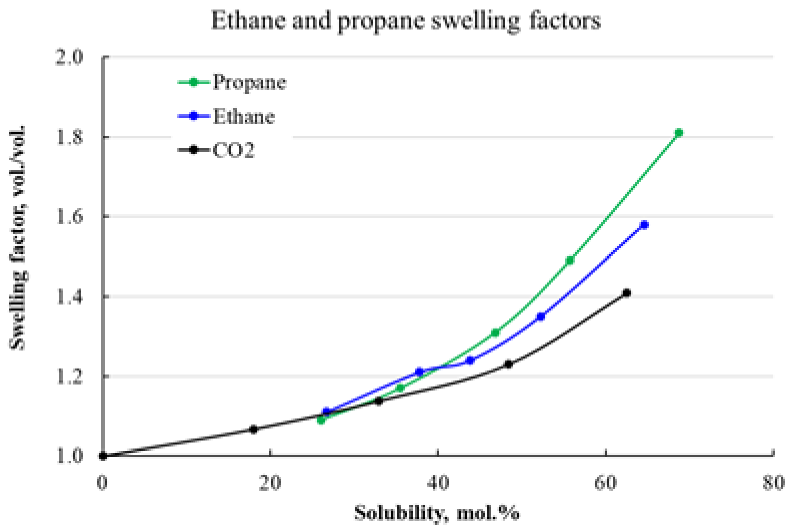
SWELLING AND SOLUBILITY DATA











EERC® | UND® UNIVERSITY OF NORTH DAKOTA®

Critical Challenges. Practical Solutions.