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Energy & Environmental Research Center (EERC)

CO_2 ENHANCED OIL RECOVERY IMPROVEMENT IN CONVENTIONAL FIELDS USING RICH GAS

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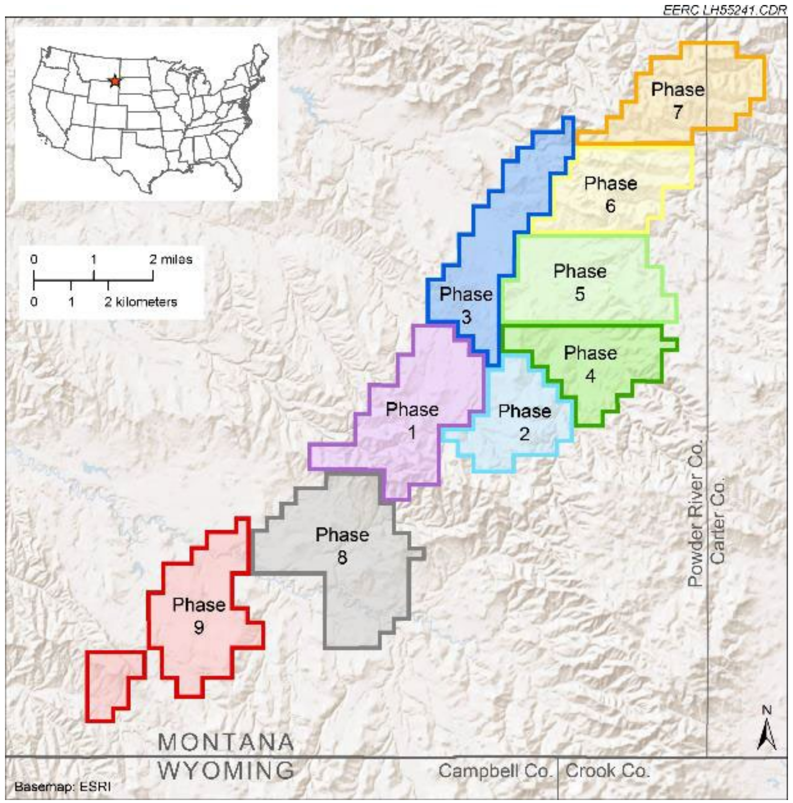
CO_2 BLENDED WITH RICH GAS

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.*



Bell Creek Oil Field

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.

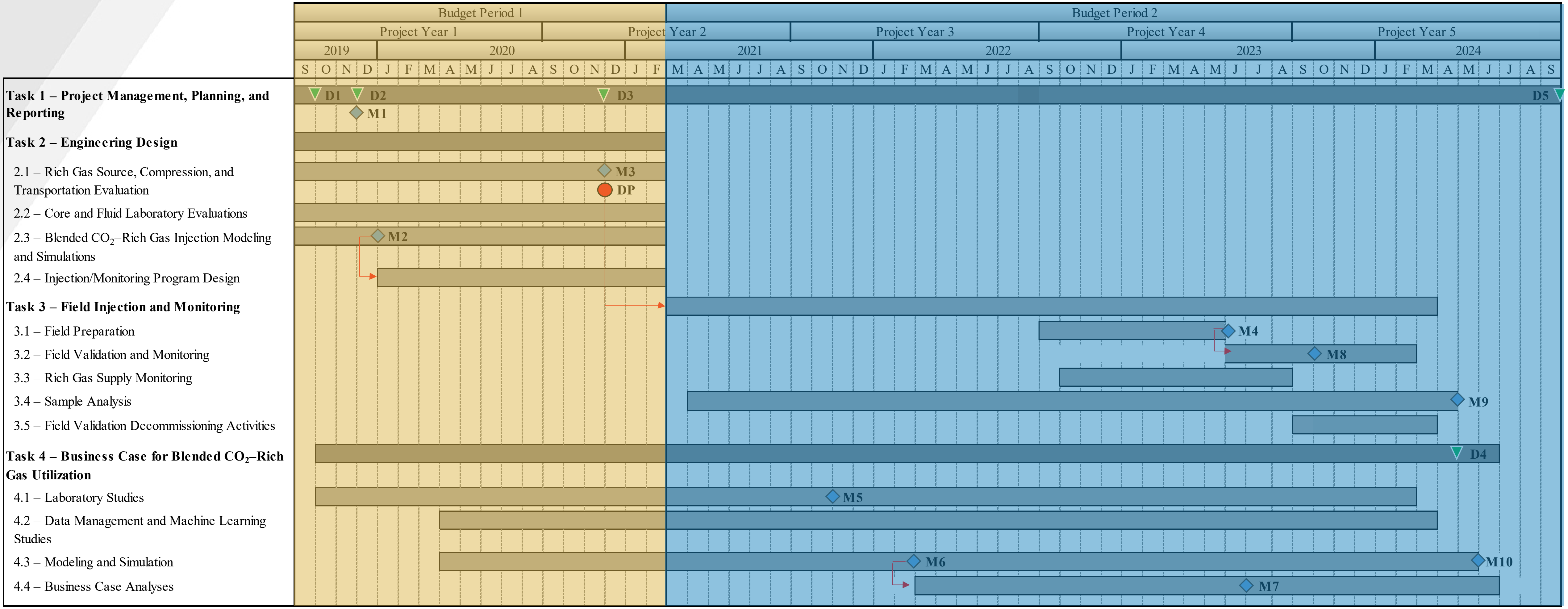
FUNDING AND PROJECT PERFORMANCE DATES

- 5-year period of performance (10/2019 – 9-2024)
- Project Budget $9,973,881
  - DOE -- $7,973,881
  - CMG/SLB -- $2,000,000 – In-Kind Cost Share

	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	–
SLB	–	$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.*

CO_2 BLENDED WITH RICH GAS TIMELINE



Key for Deliverables (D)	Key for Milestones (M)		
D1 – Updated Project Management Plan	M1 – Kickoff Meeting Held	M7 – First Field Business Case Developed	Summary Task
D2 – Data Management Plan	M2 – Injection Site Verified	M8 – Blended CO_2–Rich Gas Injection Completed	Activity Bar
D3 – Workforce Readiness Plan	M3 – Rich Gas Source Secured	M9 – Validation Test Fluid Sample Analyses Completed	Deliverable (D)
D4 – Laboratory Studies of Blended CO_2–Rich Gas EOR	M4 – Field Preparation Completed	M10 – Modeling and Simulation Completed	Milestone (M)
D5 – Data Submitted to NETL EDX	M5 – All Core Samples Obtained		Decision Point (DP)
	M6 – Initial Geostatic Models Completed		Critical Path

TB 9/15/22

BUDGET PERIOD 1 PROGRESS OVERVIEW

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

- Worked with Trimeric Corporation 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.

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
- MW shifting

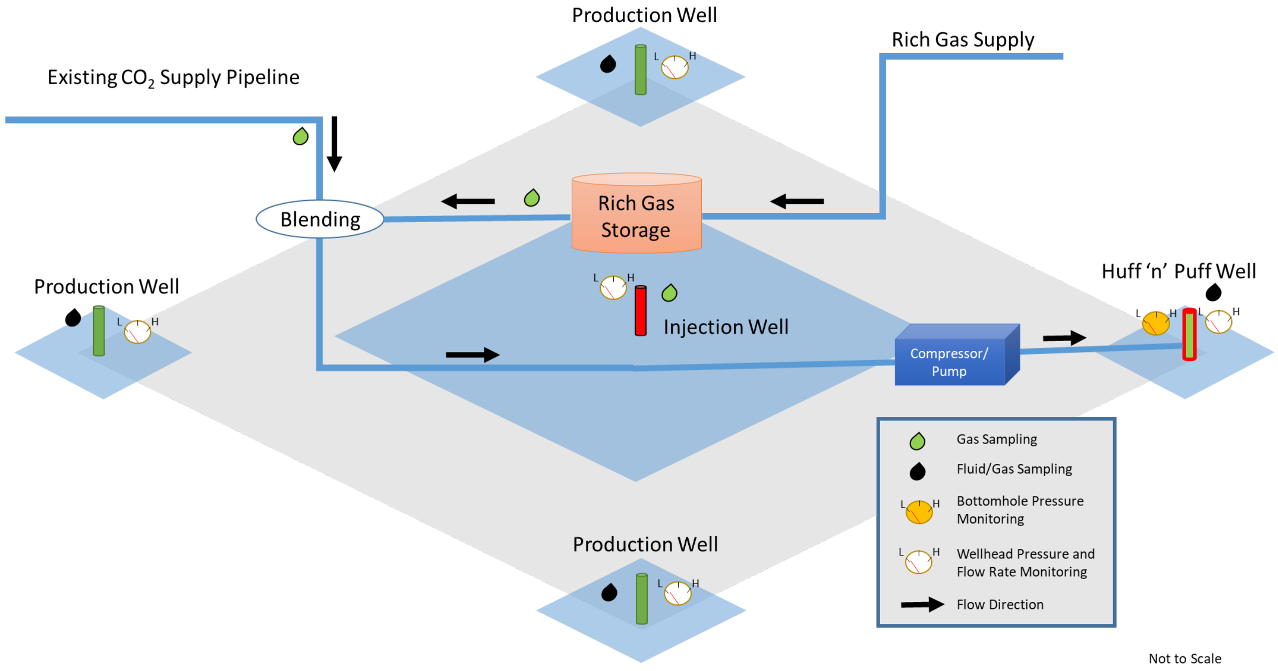
Business Case Evaluation for Other Potential Target Fields

- 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:

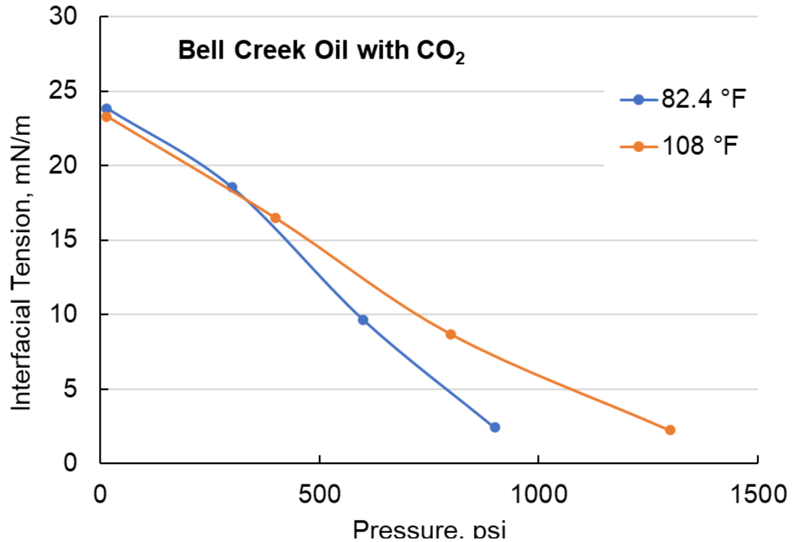
- Two storage vessels
- Pump system
  - Booster pump
  - Primary pump
- Metering
  - Rich gas: Coriolis meter
  - CO_2 stream: existing meter inside the building
- Connections inside the building to the 03-04 line
- All equipment to be located within the footprint of the test site

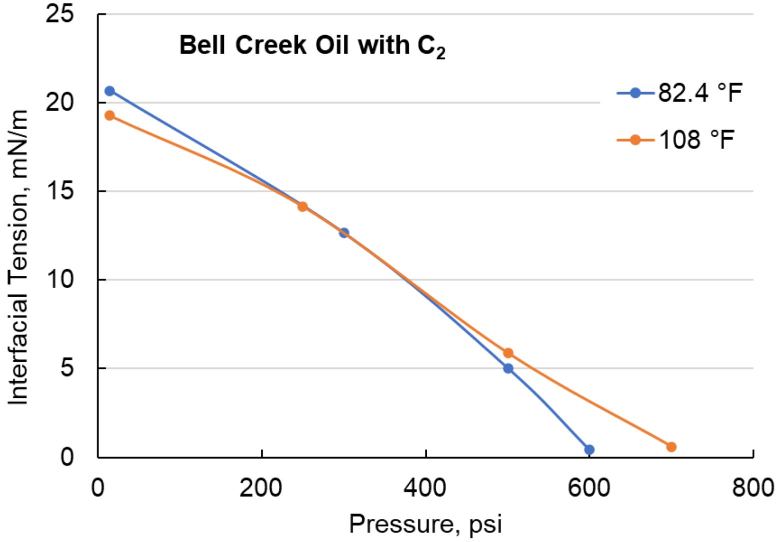
BENEFITS OF SITING EQUIPMENT AT THE TEST SITE

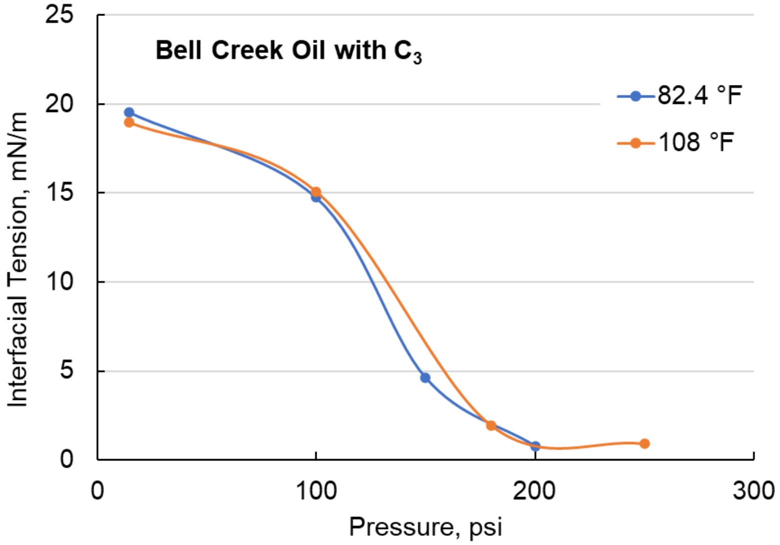
- Installation of equipment at the test site allows for project monitoring through Denbury's telemetry system.
- The monitoring system will be utilized to provide:
  – Daily monitoring of oil, water, and gas production while accommodating the routine testing of other wells within the test site.
- Routine sampling of oil, water, and gas streams during production cycles.
- Utilities are already in place with adequate capacity available for additional loads, minimizing cost of installation.

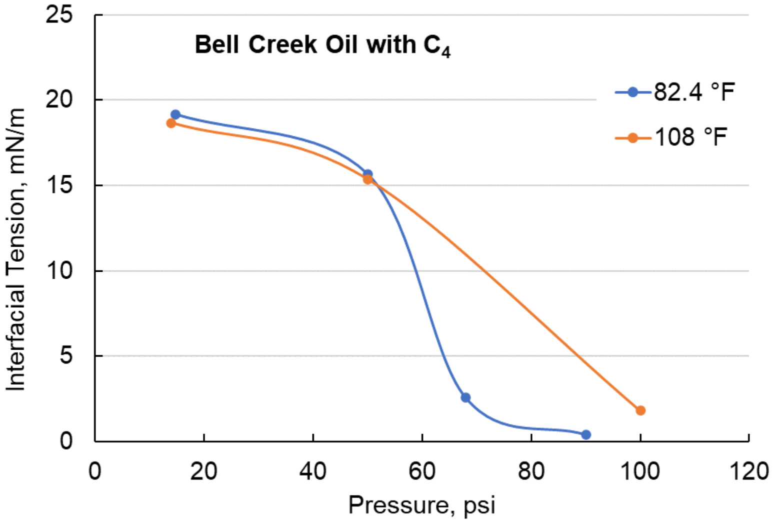
INTERFACIAL TENSION FOR PURE GASES (4.1)

- Lowering the interfacial tension helps in mobilizing residual oil and thus enhancing oil recovery from reservoirs;
- The specific interfacial tension between oil and gas can vary depending on factors such as the composition of the oil and gas, pressure, and temperature;
- The ability to reduce IFT: $C_4 > C_3 > C_2 > CO_2$.

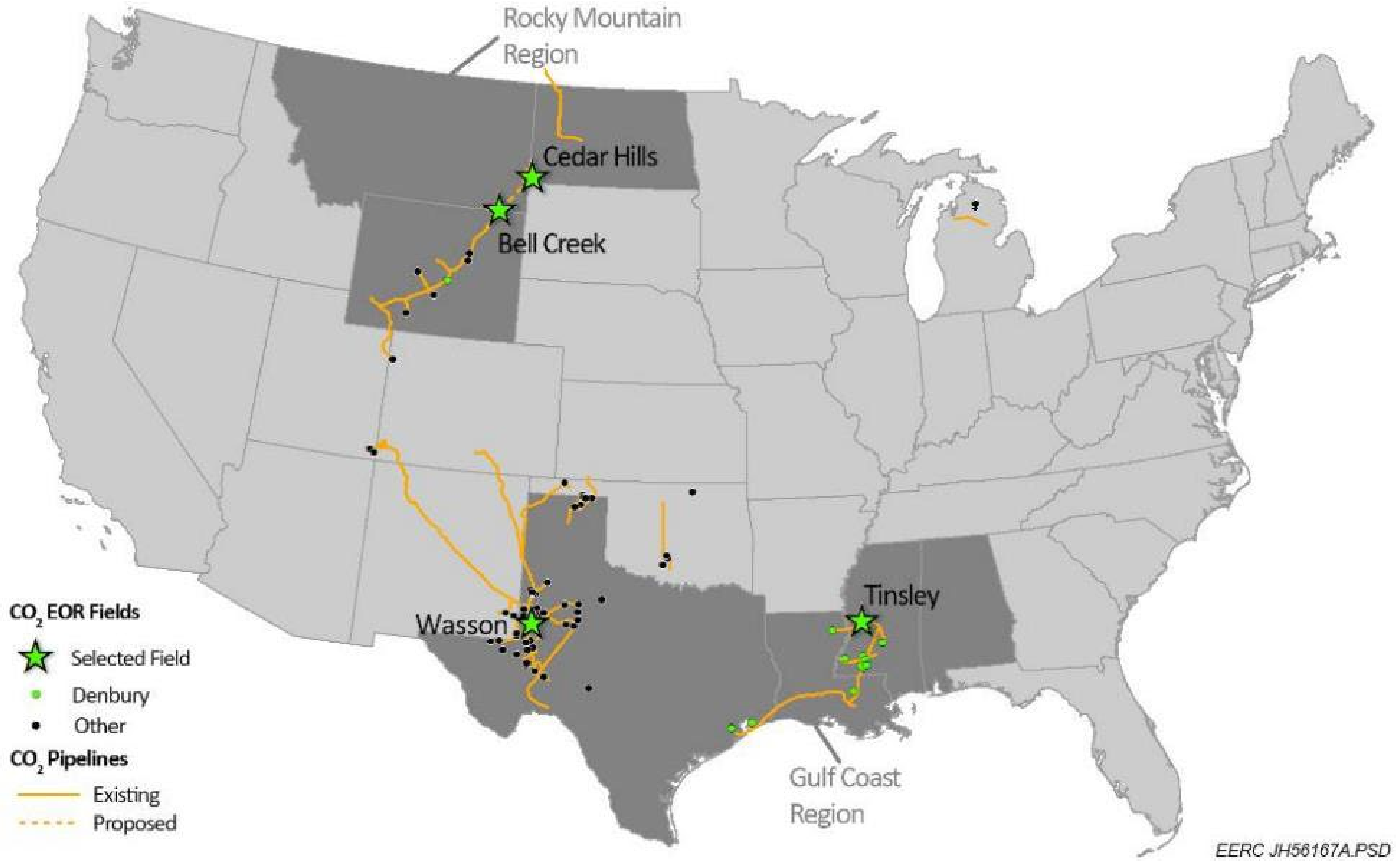








BUSINESS CASE SCENARIOS



4.2 – DATA MANAGEMENT AND MACHINE LEARNING STUDIES

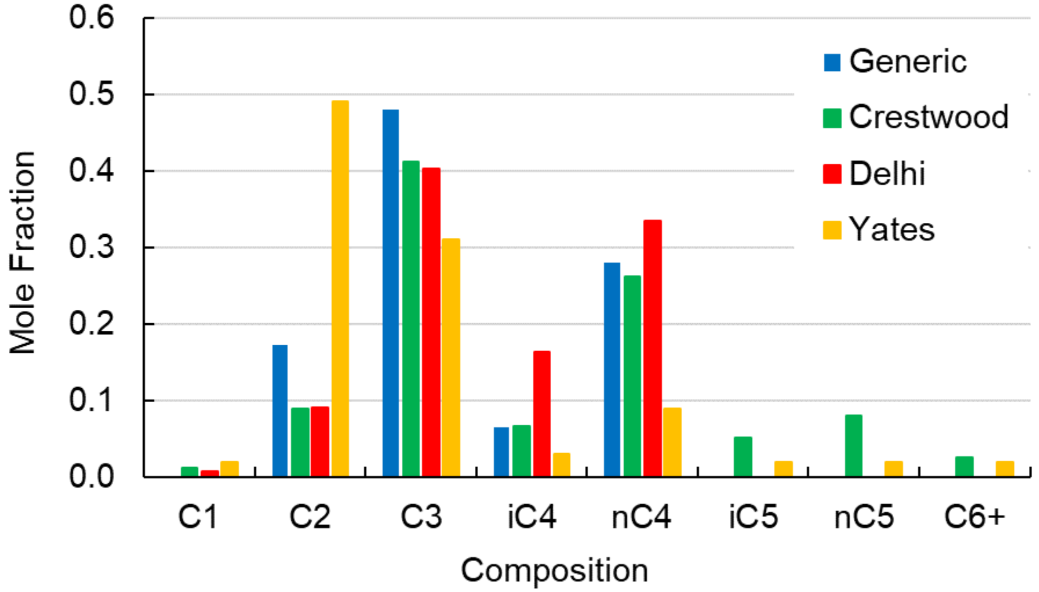
- Multiple variables are involved in the operational design process including:
  - rich gas type,
  - rich gas concentration,
  - huff 'n' puff timing and duration,
  - rich gas injection timing and duration
- The Box-Behnken experimental design method was employed in this study to optimize the EOR design.
  - 54 EOR cases were designed for each field.

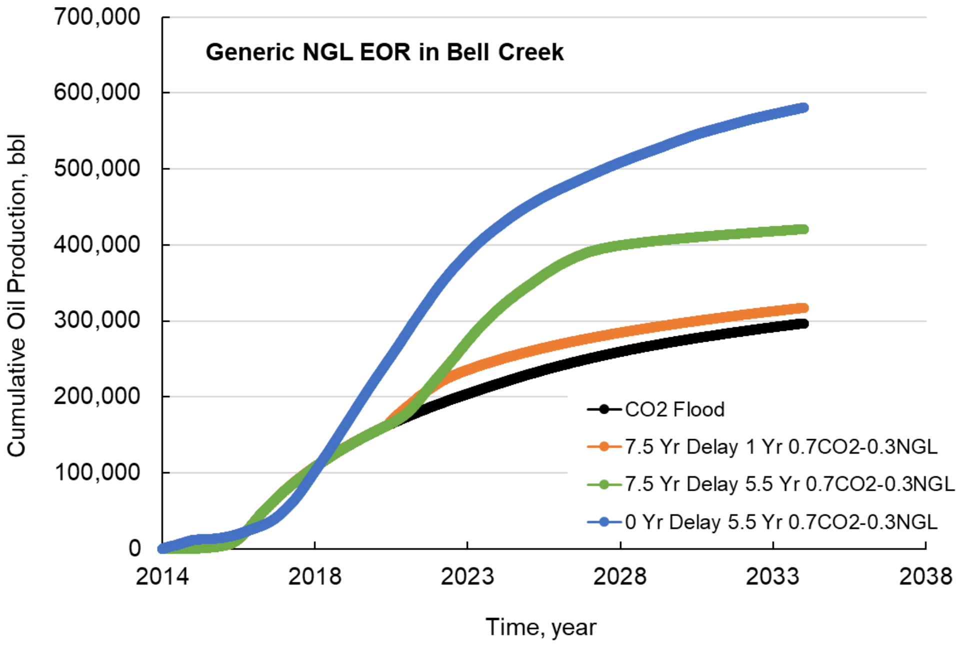
Field	Delay, year		Injection Time, year		CO_2 Fraction		HnP Time, year		NGL Type	
	Min	Max	Min	Max	Min	Max	Min	Max	A	B
Bell Creek	0	15	1	10	0.7	0.9	0	2	Generic	Crestwood
Tinsley	0	15	1	10	0.6	0.9	0	2	Generic	Delhi
Wasson	0	15	1	10	0.5	0.75	0	2	Generic	Yates
Cedar Hills	TBD									

4.3 – BUSINESS CASE MODELING AND SIMULATION

- Four NGLs: Generic, Crestwood, Delhi, and Yates, were selected to improve CO_2 EOR performance in the target fields;
- C2-C4 are the main components in these NGLs;
- Simulation results showed that a higher concentration of NGL and NGL injection timing play key roles in EOR performance.

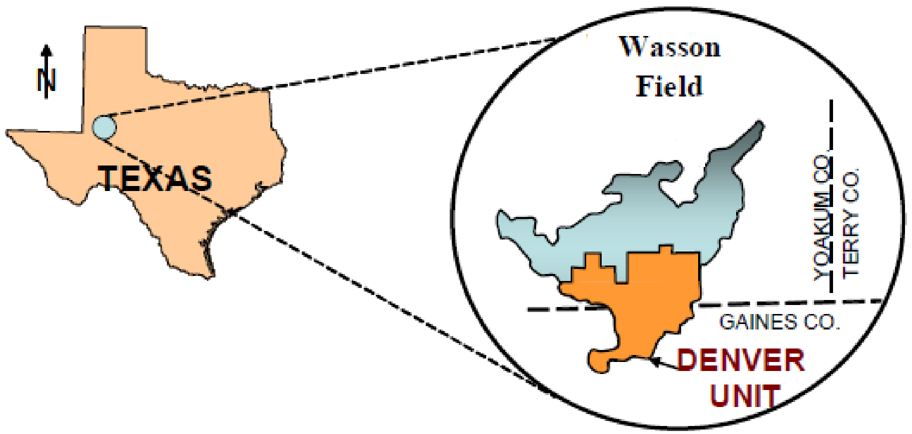
Field	NGL Type	
	A	B
Bell Creek	Generic	Crestwood
Tinsley	Generic	Delhi
Wasson	Generic	Yates





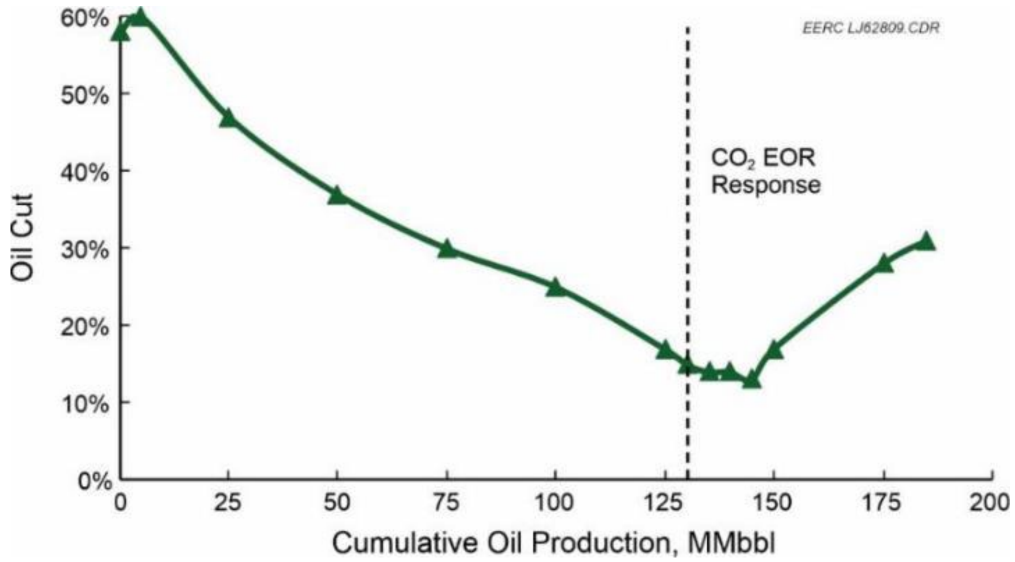
4.3 – BUSINESS CASE MODELING AND SIMULATION

- 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).

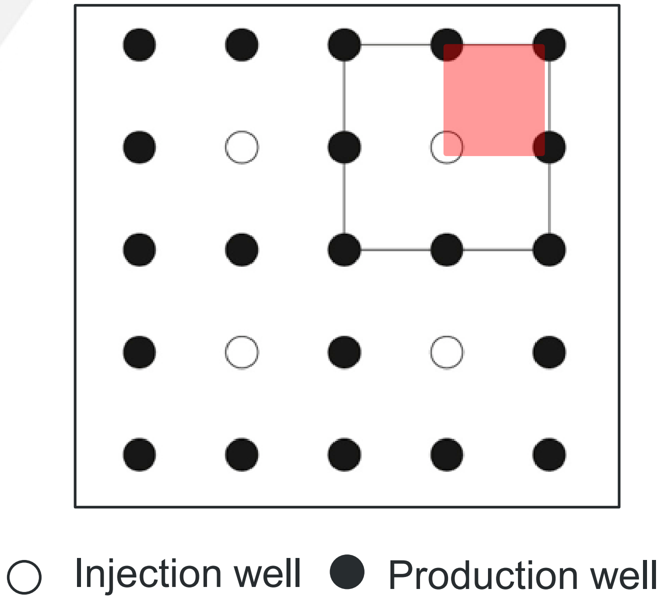
Garcia Quijada, M., 2006, Optimization of a CO_2 flood design Wesson Field, West Texas: Master's Thesis, Texas A&M University.



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

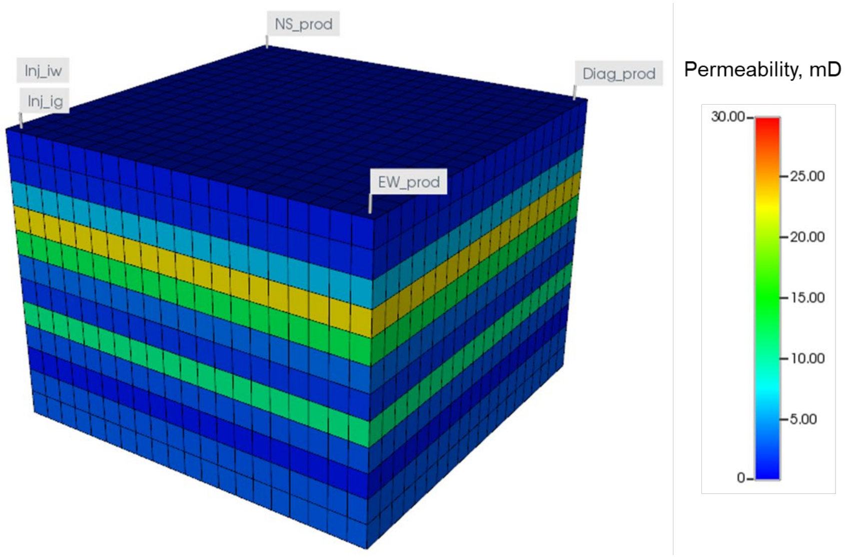
4.3 – BUSINESS CASE MODELING AND SIMULATION

- 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

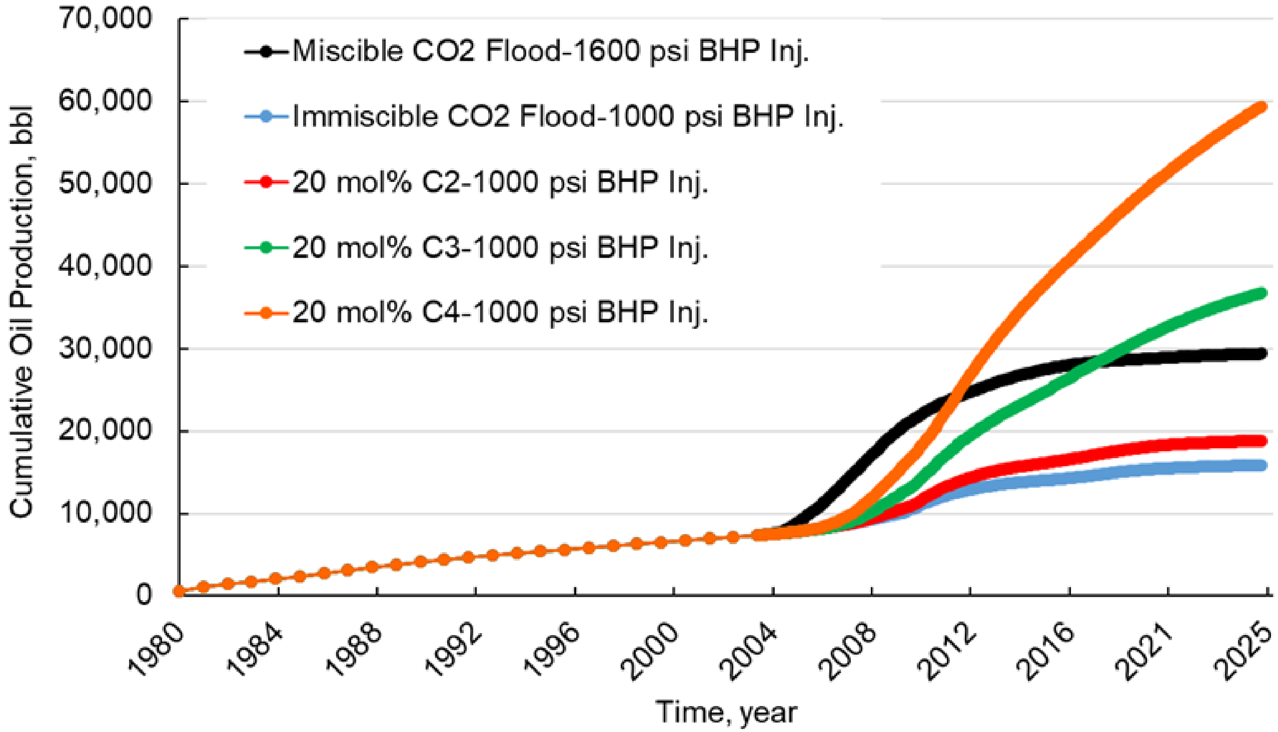


Schematic of the Simulation Model.

4.3 – BUSINESS CASE MODELING AND SIMULATION

- 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.

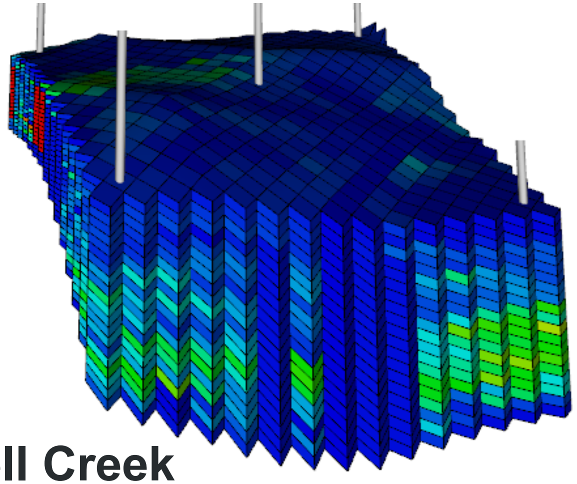
- A fivefold (52,012 vs. 8515 bbl) increase in incremental oil could be achieved by using the CO_2–butane mixture as an EOR injectate compared to that of an immiscible CO_2 flood.
- The long-term EOR performance of 1000-psi injection with propane or butane added to the injection gas could outperform that of a 1600-psi CO_2 flood.



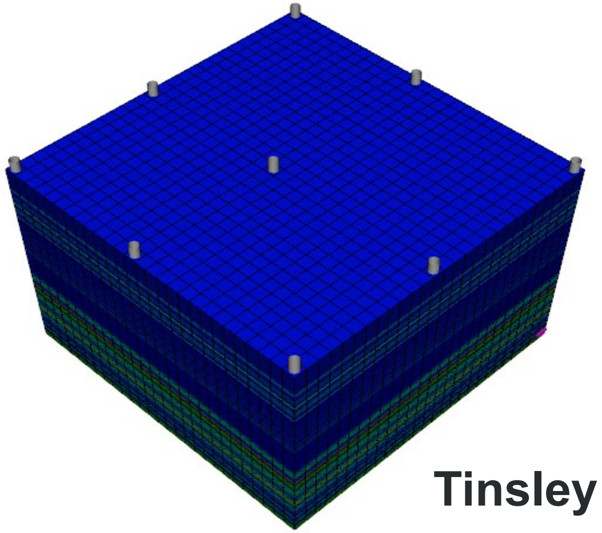
4.3 – BUSINESS CASE MODELING AND SIMULATION

- Four pattern-scale simulation models were developed to investigate the CO_2 EOR improvement performance of the selected oilfields;
- The models have unique reservoir properties and well settings that cover EOR under different scenarios.

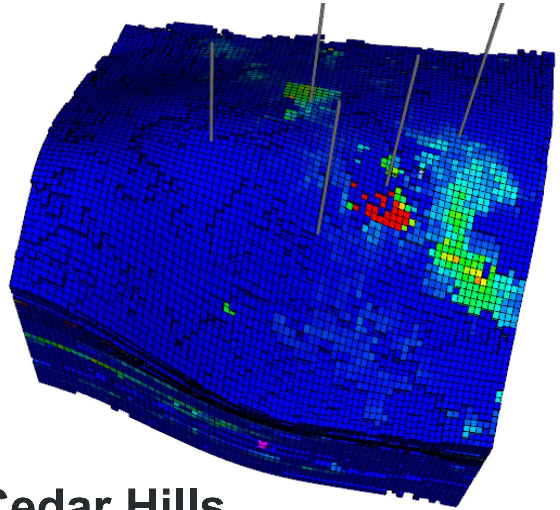
Field	Pattern	Injector No.	Producer No.
Bell Creek	Five-spot	1	4
Cedar Hills	Irregular	2	3
Tinsley	Inverted nine-spot	1	8
Wasson	Inverted nine-spot	1	8



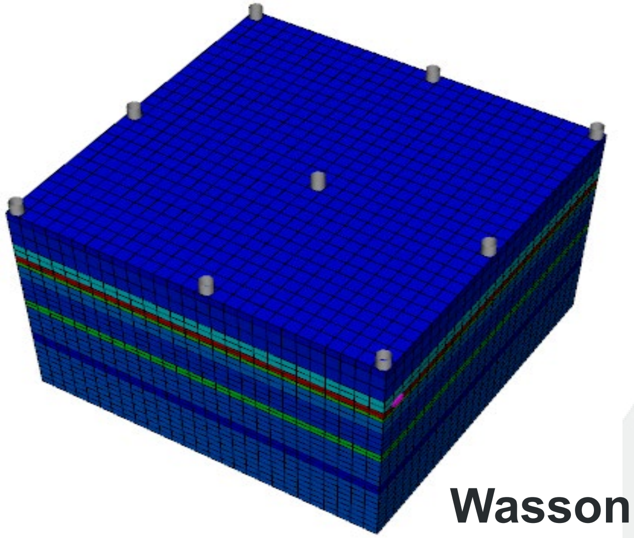
Bell Creek



Tinsley



Cedar Hills

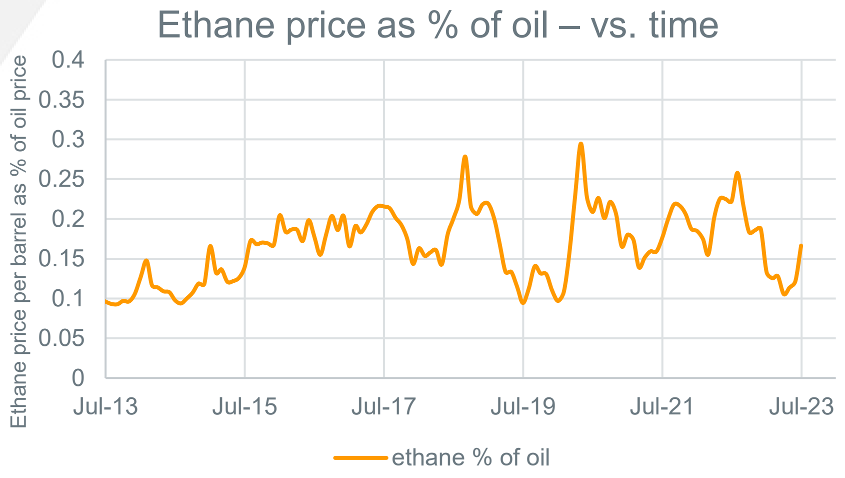


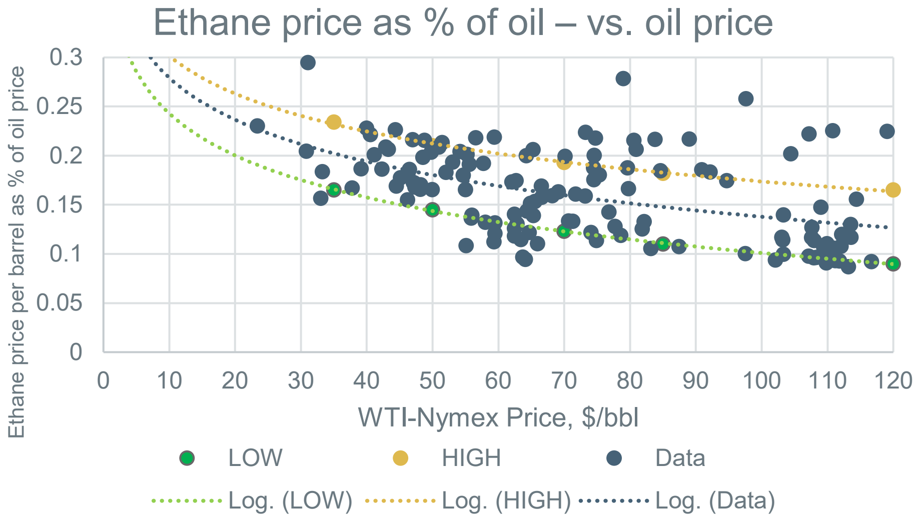
Wasson

BUSINESS CASE ECONOMIC ASSUMPTIONS

- Economics are incremental to a base case in which pure CO_2 is injected (status quo)
- NGL prices have partial dependence on oil prices
- Field development would be done in a manner where rich gas could be recycled and reinjected
- Richness of reinjected gas would be maintained by adding appropriate amount of fresh NGL
- No other changes would be made to injection facilities or to WAG schemes
- Change in CO_2 purchases due to inclusion of NGL was accounted for at rate of $25/tonne

NGL PRICES AND CRUDE OIL PRICES

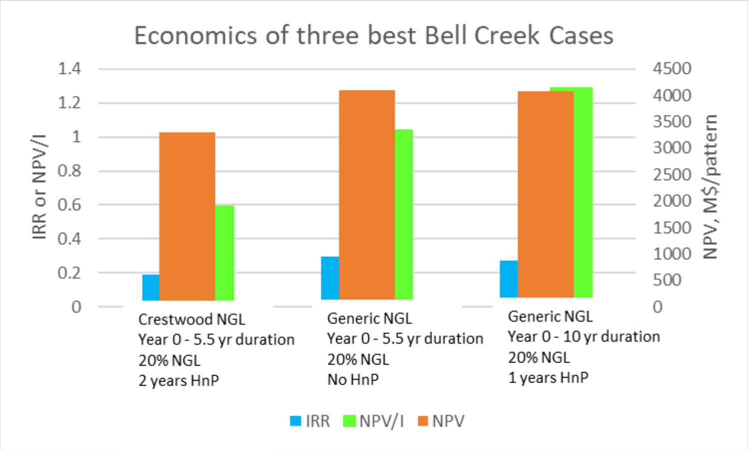


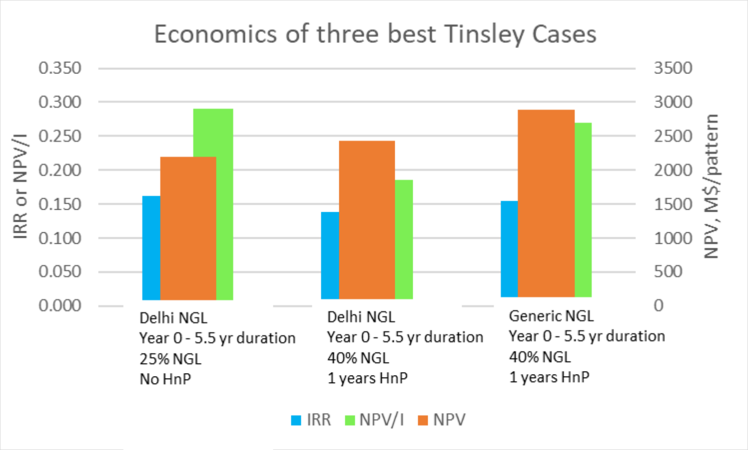


- Relationship between crude oil prices and NGL prices was modeled
- Price trends for each NGL component were analyzed (ethane shown here as an example)
- Ratio of NGL price to oil price decreases as oil price increases
- High, low and mid curves established for ratio NGL price to oil price ratio
- Weighted-average composite price was calculated based on composition and applying relevant location differentials

4.4 – BUSINESS CASE ANALYSIS

- 27 cases to be run for 2 NGL mixtures across four fields
- Economic analysis results:
  - ♦ Many cases had positive incremental economic return when rich gas injection is initiated early
  - ♦ Better economics are attained at Bell Creek compared to Tinsley
  - ♦ Generic (leaner) NGL usage resulted in better Present Value Ratio (NPV/I)





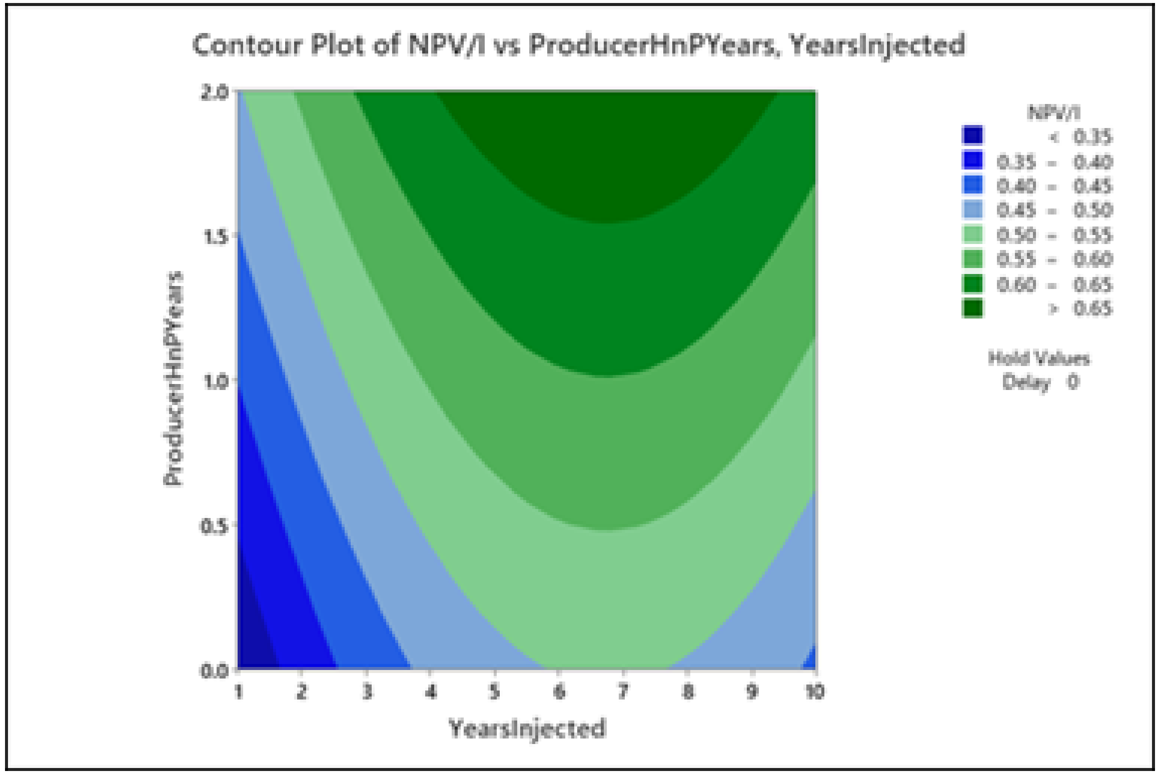
Bell Creek CASE MATRIX	Delay	NGL Frac*	Rich Gas duration	HnP duration
Case 1	7.5	0.3	1	1
Case 2	0	0.2	1	1
Case 3	7.5	0.2	1	0
Case 4	7.5	0.2	1	2
Case 5	15	0.2	1	1
Case 6	7.5	0.1	1	1
Case 7	0	0.3	5.5	1
Case 8	7.5	0.3	5.5	0
Case 9	7.5	0.3	5.5	2
Case 10	15	0.3	5.5	1
Case 11	0	0.2	5.5	0
Case 12	0	0.2	5.5	2
Case 13	7.5	0.2	5.5	1
Case 14	7.5	0.2	5.5	1
Case 15	7.5	0.2	5.5	1
Case 16	15	0.2	5.5	0
Case 17	15	0.2	5.5	2
Case 18	0	0.1	5.5	1
Case 19	7.5	0.1	5.5	0
Case 20	7.5	0.1	5.5	2
Case 21	15	0.1	5.5	1
Case 22	7.5	0.3	10	1
Case 23	0	0.2	10	1
Case 24	7.5	0.2	10	0
Case 25	7.5	0.2	10	2
Case 26	15	0.2	10	1
Case 27	7.5	0.1	10	1

***Tinsley evaluated NGL fractions of 10%, 25% and 40%, otherwise the case matrix is identical**

OPTIMIZATION USING RESPONSE SURFACE ANALYSIS

- Response surface methodology applied to
  - Major economic indicators
    - ♦ Rate of Return
    - ♦ Net Present Value
    - ♦ Present Value Ratio (NPV/I)
  - Incremental Oil Recovery

- In this example NPV/I is maximized by a rich gas injection duration of 6.7 years



PLANS FOR FUTURE TESTING/DEVELOPMENT/ COMMERCIALIZATION

- The pilot test is on hold due to contract negotiations between EERC and ExxonMobil
- Equipment acquisition and site development are expected to begin during Q1 2025
- Results of the pilot test will further inform business case scenarios.
- 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.

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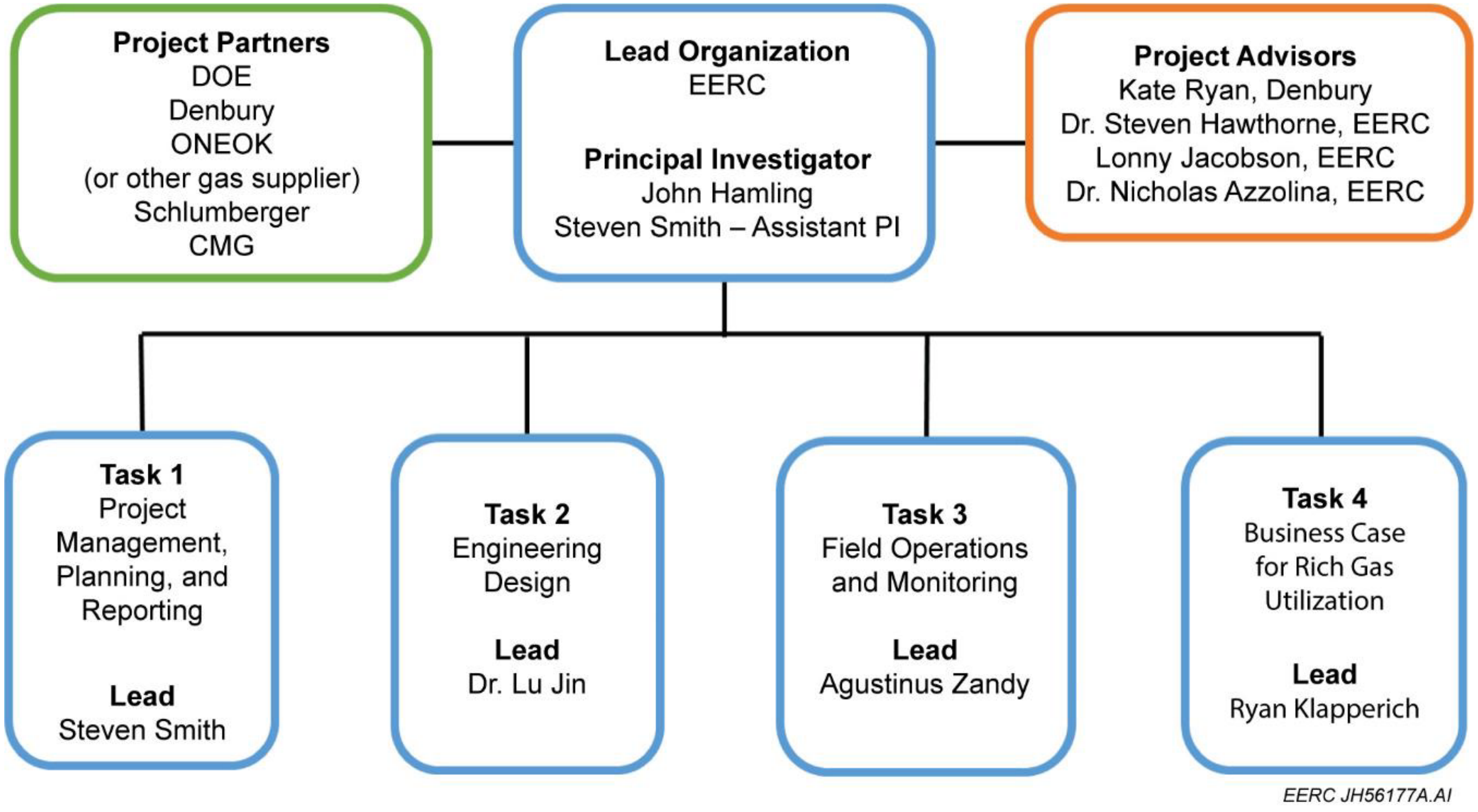
ORGANIZATION CHART



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