Storage of CO_2 in Multi-phase Systems Containing Brine and Hydrocarbons

Project Number: FE-1122-19-FY19

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LA-UR-20-27284

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Capture Front End Engineering Design Studies and CarbonSafe
2020 Integrated Review Webinar

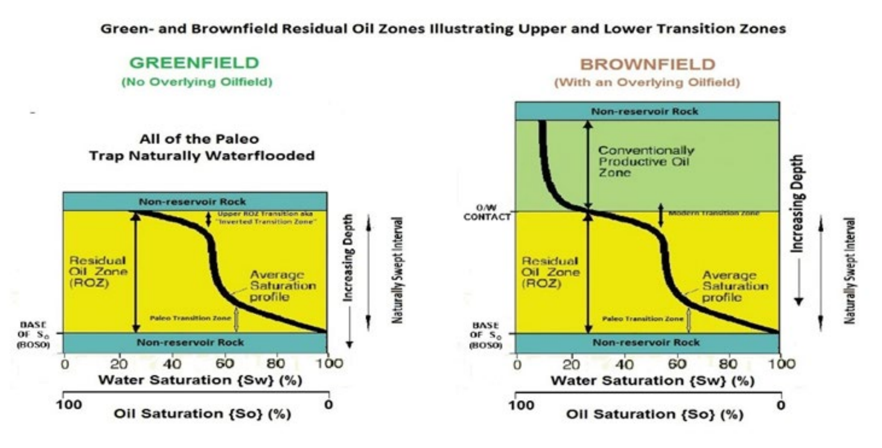
August-17-19 2020

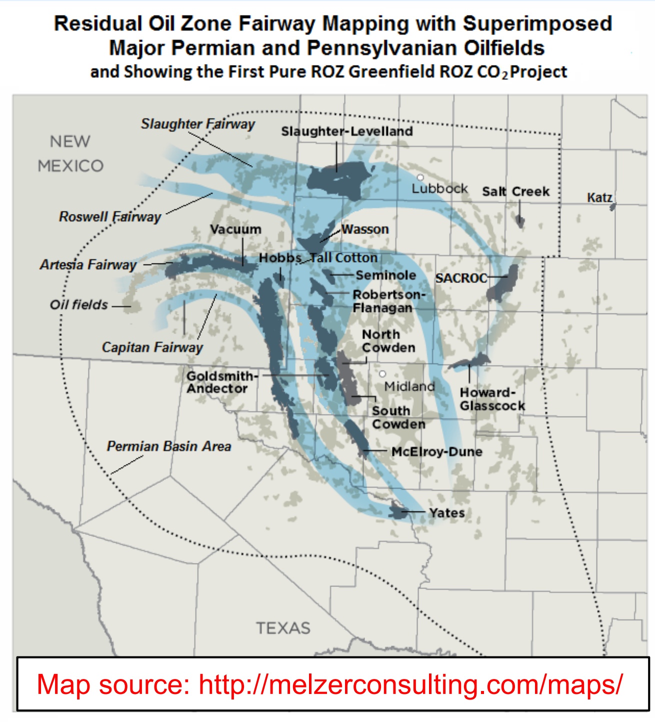
Program Overview

- Funding: DOE $850K over 3 years
- Overall Project Performance Dates: 10/2017 – 9/2020
- Project Participants:
  - Rajesh Pawar (LANL) - PI
  - Bailian Chen (LANL) – Co-Investigator
  - Bill Carey (LANL) – Co-Investigator

CO_2 Storage in Residual Oil Zones

- Residual Oil Zones (ROZs) are defined as those zones where oil is swept over geologic time period (natural flush) and exists at residual saturation
  - Brownfield: ROZ underlies a Main Pay Zone (MPZ).
  - Greenfield: no Main Pay Zone above ROZ.
- ROZs are being commercially produced using CO_2-EOR
- ROZs are potential CO_2 storage option





Greenfield ROZs are unique

- Unconventional CO_2 storage
- Saline-aquifer like: CO_2 storage and associated credits benefit
- Oil-reservoir like: Oil recovery and associated financial benefit
- Limited pre-existing wells: reduced potential for wellbore leakage
- <u>Challenge:</u> Large uncertainties in the parameters and mechanisms related to CO_2 storage in ROZ

Project Objectives

- Develop quantitative, empirical relationships that can be used to assess CO_2 storage efficiencies & oil recovery potential in greenfield ROZs
- Explore strategies for optimal management of CO_2 storage in greenfield ROZs
- Improve fundamental understanding of CO_2 injection induced multi-phase fluid processes in ROZs

- Technical Approach: Combination of numerical modeling and laboratory experiments

Technical Status

- Pre-FY20
  - Developed empirical models for estimating storage capacity, oil recovery, and CO_2 fate:
    - Demonstrated applicability using Permian basin field data (Chen & Pawar, *Energy*, 2019) and Illinois basin data
  - Identified key uncertain characteristics
  - Investigated the effect of geologic/operational parameters: permeability heterogeneity, well completions, injection rates, well patterns
  - Assessed optimal management of ROZ under various scenarios (Chen & Pawar, *JPSE*, 2019)
- FY20
  - Explored optimal management of ROZ
  - Initiated experimental work to investigate multi-phase flow mechanisms

Technical Progress

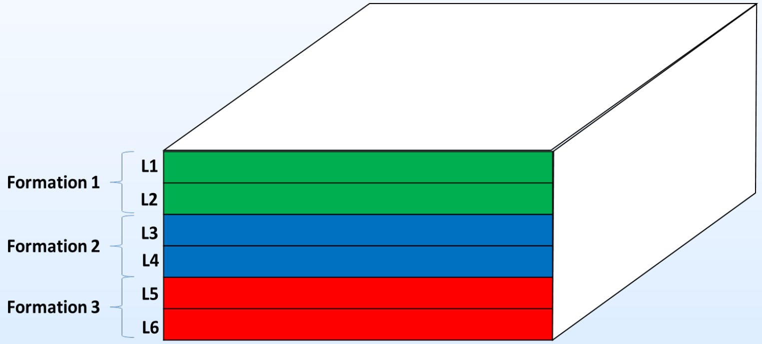
Optimal Management of ROZ

- Objective: Explore optimal reservoir management strategies to maximize different objectives
  - Compare maximization of NPV, CO_2 storage, and oil recovery
    - NPV based on combined revenue from CO_2 credits plus oil recovery minus cost of injected CO_2 and disposing produced water
  - Optimization variables: injection/production well open fraction and well controls (producer BHP & CO_2 injection rate)
  - Investigate impact of reservoir heterogeneity

Reservoir Description

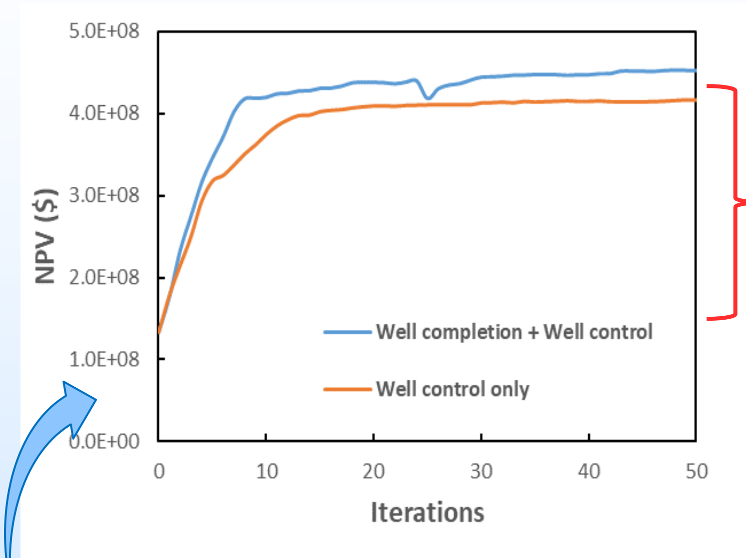
- 6 reservoir layers with different permeability:
  - Top two layers: 100 mD
  - Middle two layers: 10 mD
  - Bottom two layers: 50 mD

Model 1: Horizontally homogeneous, vertically heterogeneous



- Single five-spot well pattern: 4 injectors + 1 producer
- 10 years reservoir lifetime
- Compositional reservoir simulations using Eclipse, E300
- Optimization algorithm: Stochastic Simplex Approximate Gradient (StoSAG), B. Chen PhD dissertation
- Total number of optimization variables:
  - Joint optimization: 5*20+5*6=130 ("5": # of wells, "6": # of layers)
  - Well control only optimization: 5*20=100 ("20": control steps)

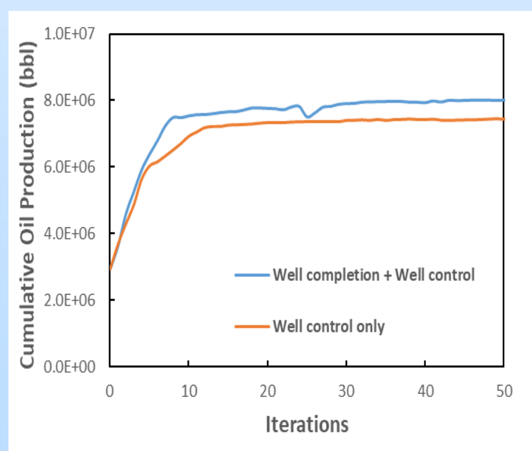
Maximization of NPV



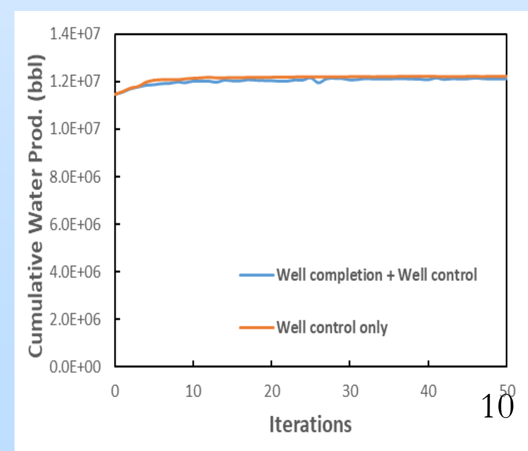
- Optimization strategies significantly improved NPV
- The higher NPV obtained from joint optimization is due to a combination of higher CO_2 storage and higher oil production

CO_2 storage

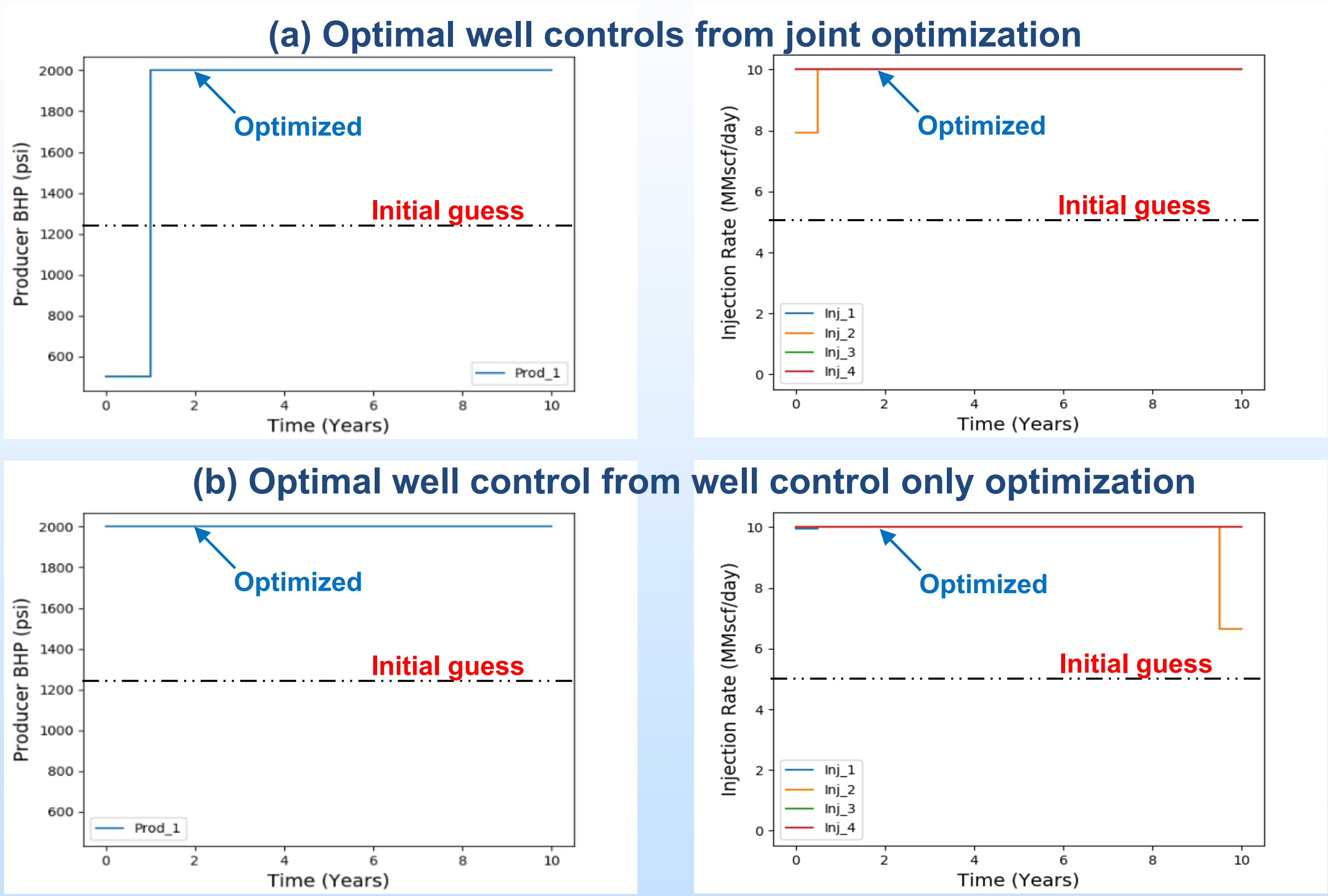
Oil production



Water production

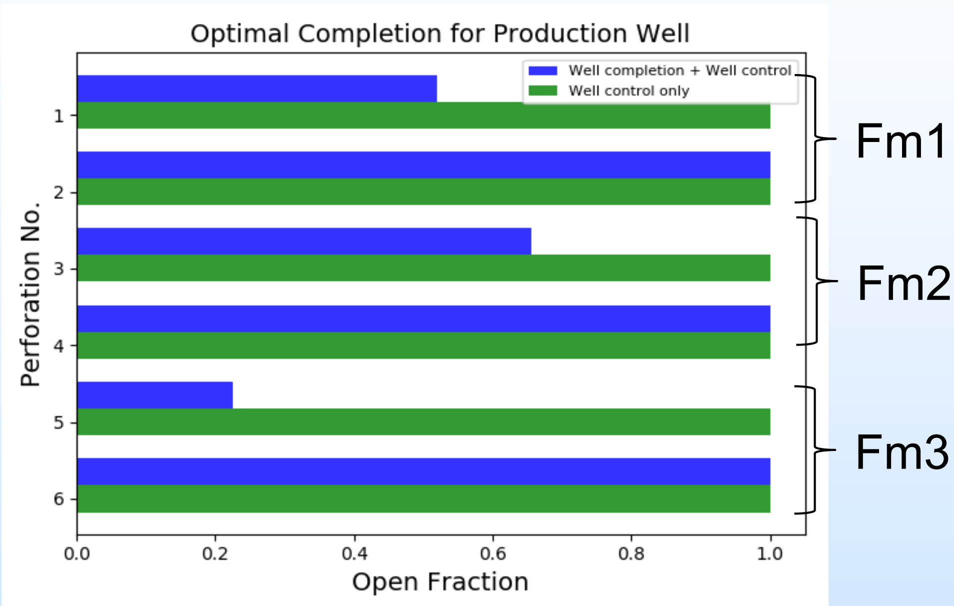


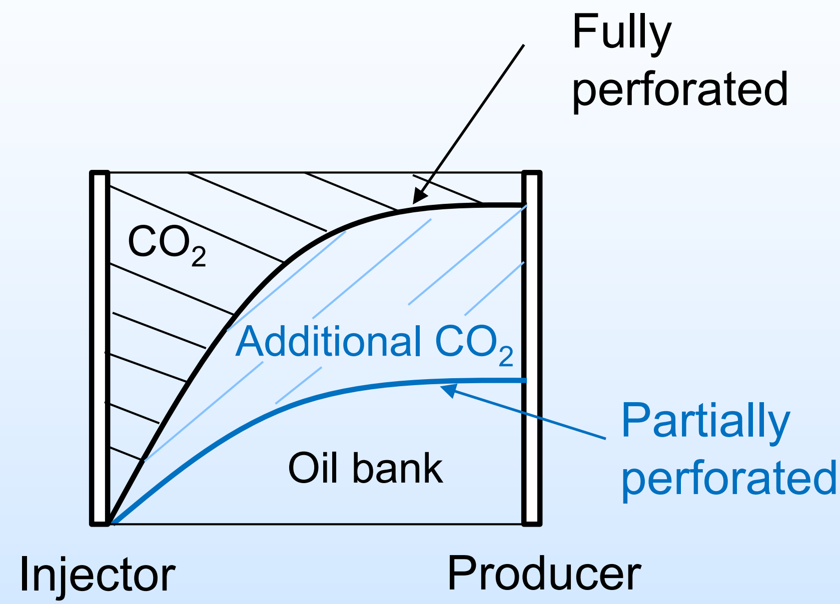
Optimal Well Controls



- Producers operate at the highest BHP (expect for the first year under joint opt.) to avoid large amount of CO_2 breakthrough at early stage
- Injectors operate at the highest (or close to highest) rate to inject as much amount of CO_2 as possible

Optimal Well Completions



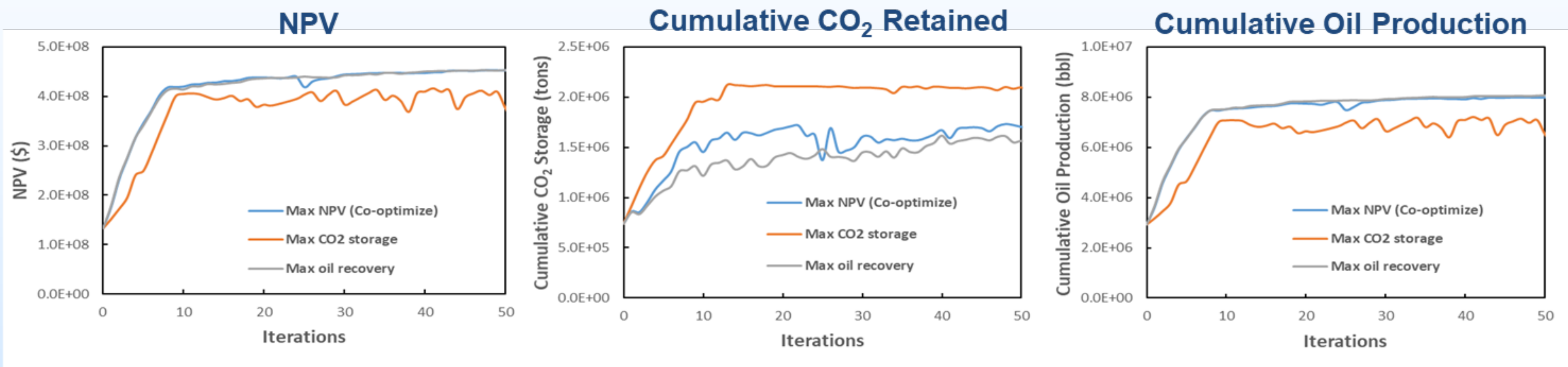


(Note open fraction for well control only opt. is a constant “=1”)

- Optimal completions for injectors is entire well length open
- Only top layers (i.e., L1, L3 and L5) of each formation are partially open under joint optimization
- Partially perforated producer at the top layers of each formation leads to less amount of CO_2 breakthrough and more oil being displaced from each formation due to larger vertical oil sweep efficiency

Comparing Different Optimization Objectives

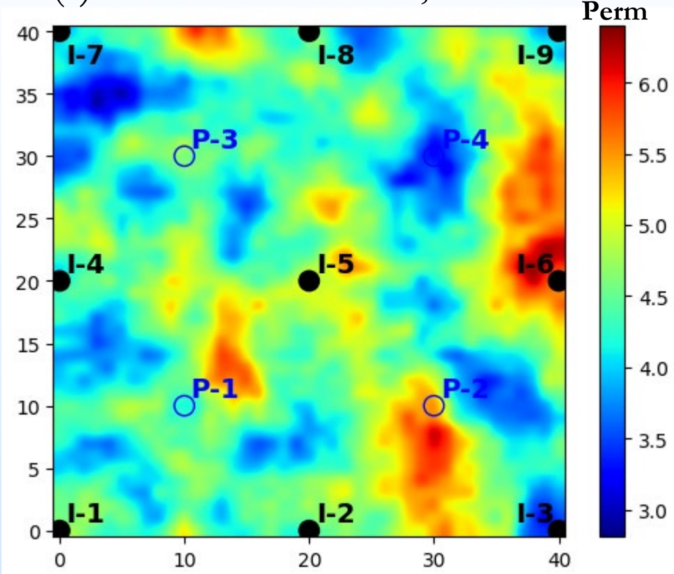
Optimize NPV v/s Maximize CO_2 storage v/s Maximize oil recovery



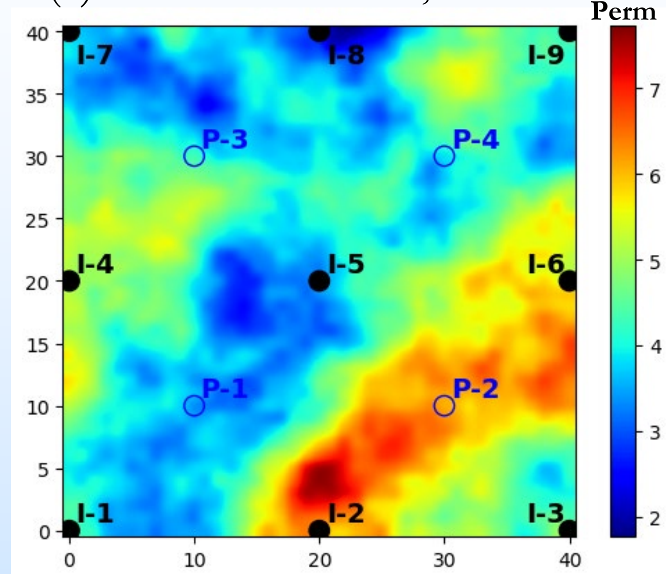
- Both, maximization of NPV and maximization of oil recovery objectives result in higher NPV than maximization of CO_2 storage objective
- Maximization of CO_2 storage objective results in ~30% higher storage

Impact of Reservoir Heterogeneity

(a) **Model 2**: mean 4.6, std: 0.6



(b) **Model 3**: mean 4.6, std: 1

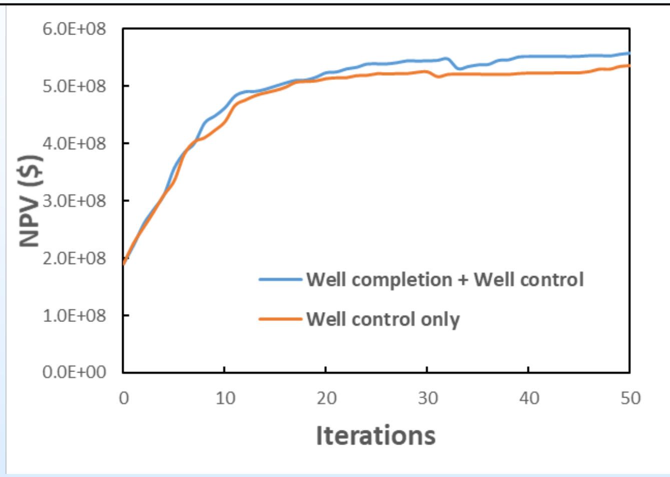


Increasing horizontal permeability heterogeneity

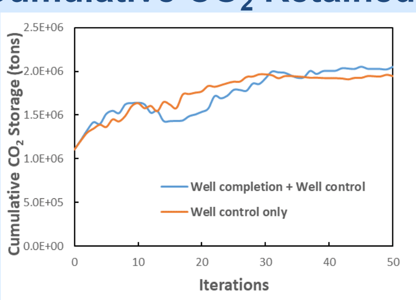
- Permeability heterogeneity:
  - ➢ Top two layers: as shown above for each model
  - ➢ Middle two layers: equal to the perm. field of layer 1 multiplied by 0.5
  - ➢ Bottom two layers: equal to the perm. field of layer 1 multiplied by 2.0
- Four five-spot well patterns

Impact of Reservoir Heterogeneity

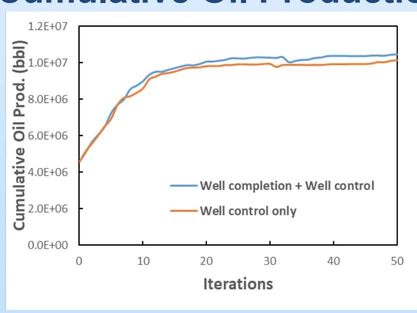
Model 2



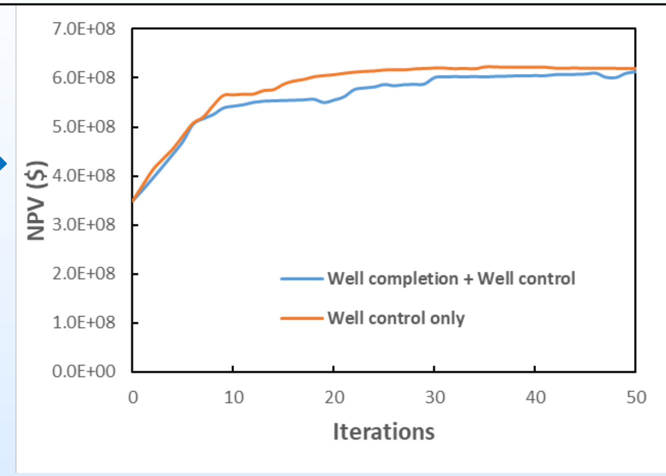
Cumulative CO_2 Retained



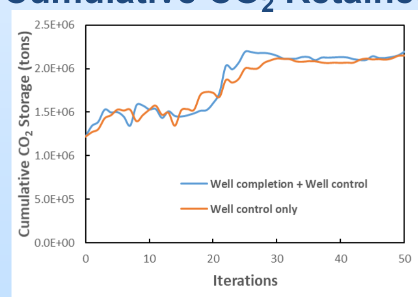
Cumulative Oil Production



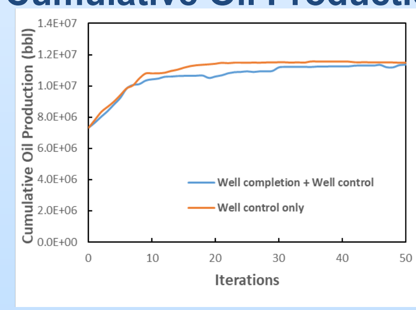
Model 3



Cumulative CO_2 Retained



Cumulative Oil Production



- Increase in reservoir heterogeneity affects the net benefit from joint optimization: NPV increase incremental to minimal
- Horizontal heterogeneity impact greater than vertical heterogeneity

Characterize multi-phase fluid flow in ROZs

- Approach: Simulate CO_2 injection in a residual oil zone using core-flooding experiments at saturations, pressures and temperatures typical to residual oil zone containing fields

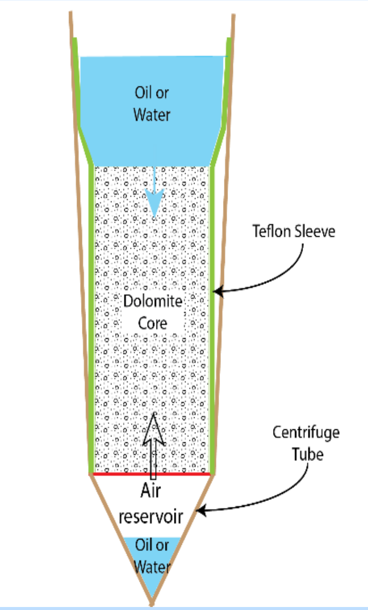
- Challenge: How to create residual oil saturation conditions in laboratory?

Experimental Approach

- Step 1: Basic characterization
  - ➢ Specimens: Dolomite (nearly 100% dolomite with minor calcite)
  - ➢ Porosity: 17%
  - ➢ Wettability: Weakly water wet
- Step 2: Create residual oil specimens
  - ➢ Use decane as oil: 3 phase system: (air, brine, oil)
  - ➢ Centrifuge methodology
  - ➢ Coreflood methodology
- Step 3: Coreflood experiments
  - ➢ Supercritical CO_2 conditions

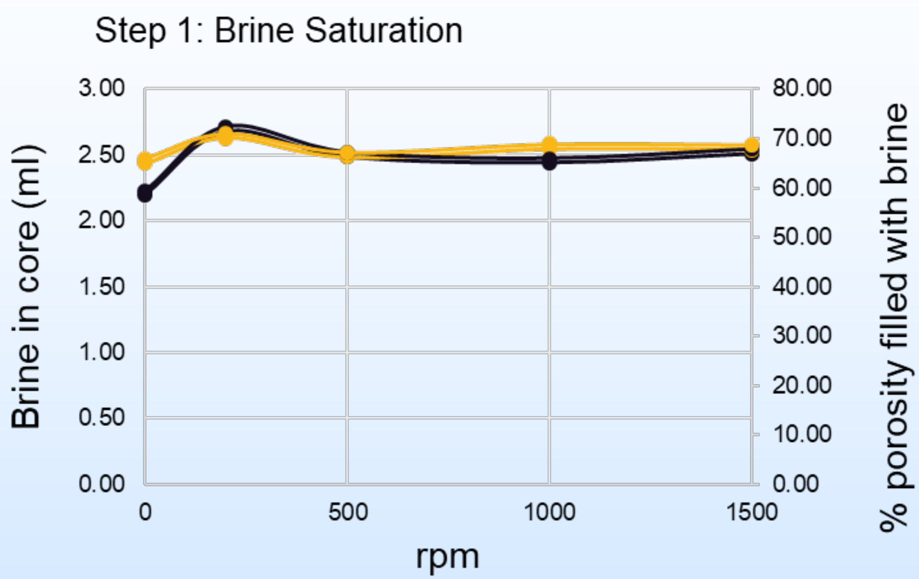
Initial state

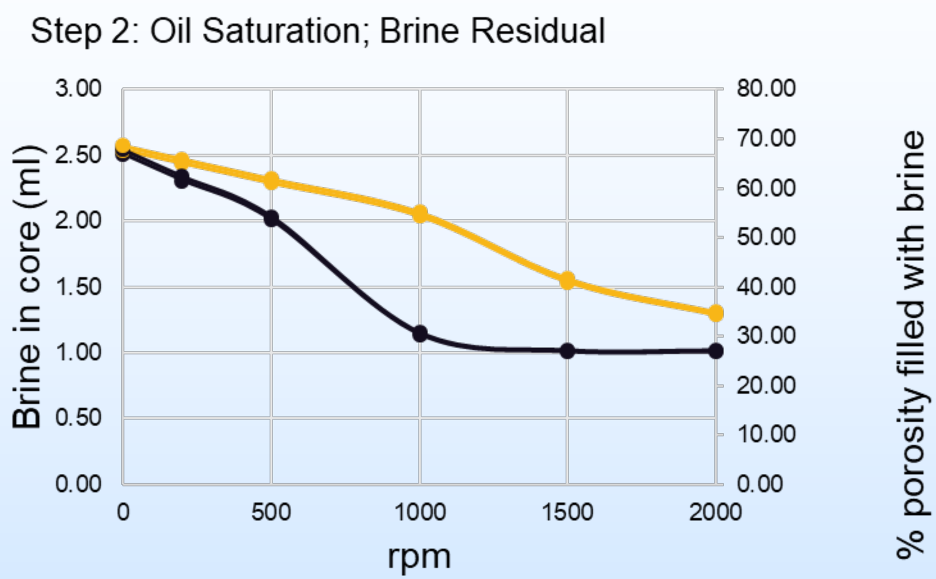
After 5 min

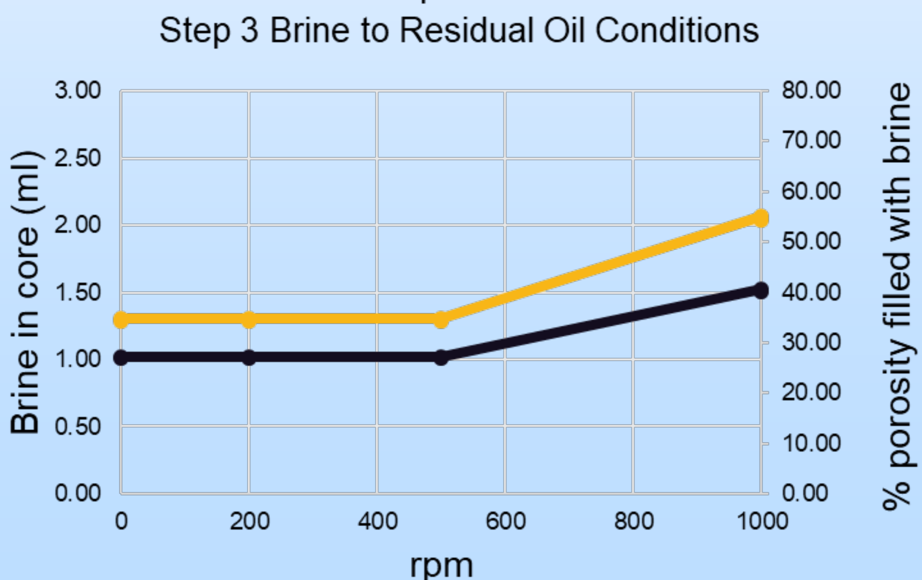


Establishing Residual Oil Conditions

(on two specimens as function of centrifuge speed or rpm)







- Brine spontaneously displaces air
- Decane does not spontaneously displace brine but requires significant pressure drive
- Brine does not spontaneously displace oil but requires significant pressure drive

Establishing Residual Oil Conditions: Redesign of experiments

Water saturate

Oil saturate
Water residual

Water saturate
Oil residual

Original Design

This design was flawed. In the centrifuge, as water/oil was driven down into the core, air percolated up both from the core and from the reservoir below the core. The result was incomplete saturation. This approach might work if there was sufficient water on top to completely displace all of the air below.

New Protocol Step1

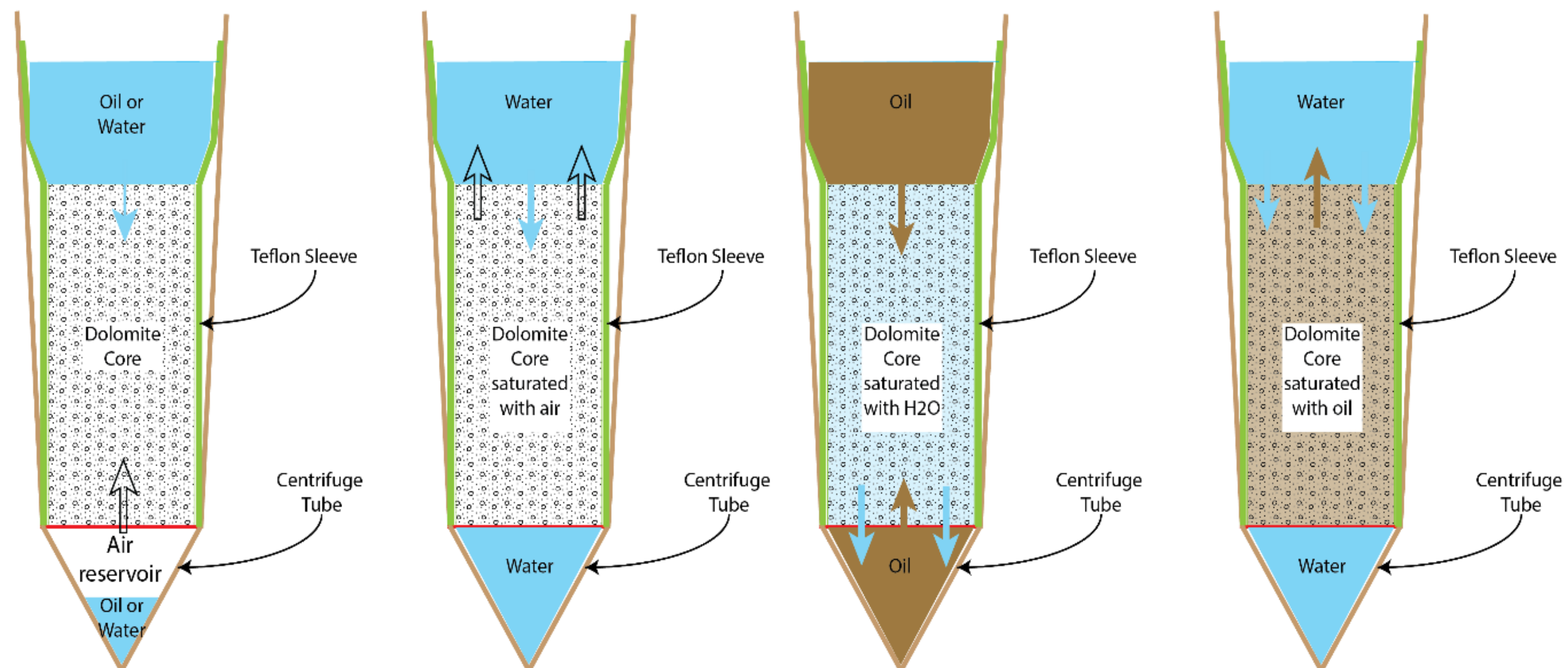
Water completely fills reservoir. Centrifuge displaces water down; air flows up; end result is no air in the core.

New Protocol Step 2

In the centrifuge, oil is driven down from the top and up from bottom by buoyancy. The water flows into the bottom reservoir under both centrifuge and buoyancy.

New Protocol Step 3

In the centrifuge, water is driven down from the top by the centrifuge and buoyancy. The oil has no place to go except up due to buoyancy.



Summary

Project Summary: Lessons Learned

- In spite of increased commercial CO_2-EOR operations in ROZs, critical understanding of CO_2 storage & oil production mechanisms as well as long-term CO_2 fate and risks needs to be further developed
  - Lack of appropriate data
  - Large uncertainty
- Need to develop and test laboratory experimental procedures to simulate ROZ in-situ conditions
- Focused field-specific studies needed to improve predictions & predictive capabilities

Project Summary

- Key Findings (FY20):
  - Optimal reservoir management strategies can significantly improve CO_2 storage and utilization in ROZs
  - Reservoir heterogeneity can affect effectiveness of optimal reservoir management strategies

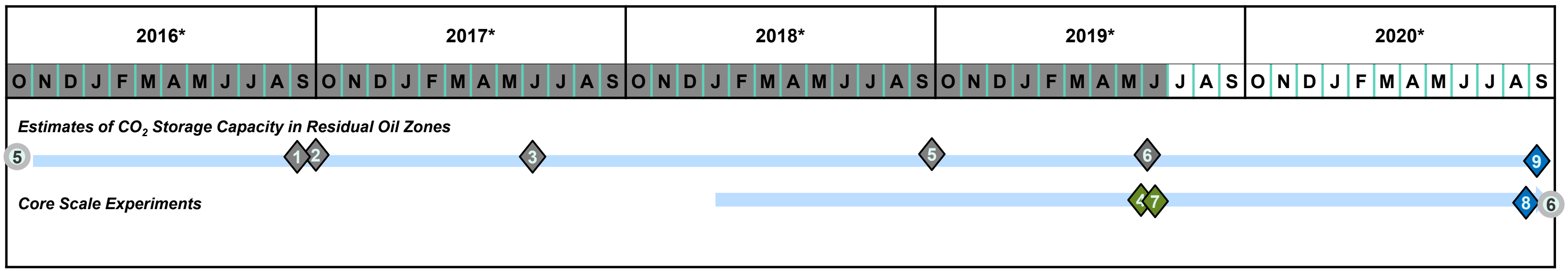
- Next Steps:
  - Test optimal reservoir management strategies with field data
  - Complete experimental characterization with coreflood

Thank You!

Organization Chart

- Rajesh Pawar, PI
- Bailian Chen, Post-doc
- George Guthrie, LANL Program Manager

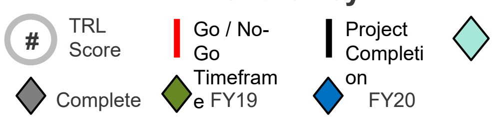
Gantt Chart



Milestones

1. Preliminary estimates of CO_2 storage potential in representative ROZs across US with associated uncertainties.
2. Empirical model to estimate CO_2 storage and utilization potential in ROZs.
3. Re-assessment of ROZ potential in conjunction with CO_2 storage.
4. Strategy to explore uncertain parameters in ROZ fields through core scale experiments.
5. Empirical models for applications to estimate CO_2 storage capacity, long-term fate and oil recovery potential from ROZs including identification of potentially impactful uncertain parameters.
6. Application of empirical models to fields with ROZs.
7. Initial Experiments.
8. Update empirical models based on experimental results.
9. Application of updated empirical models to ROZ fields through synergistic collaborations. Public dissemination of empirical models to CCUS stakeholders.

Chart Key



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