Relative Permeability for Offshore HPHT Reservoirs

NETL Offshore FWP – Task 7

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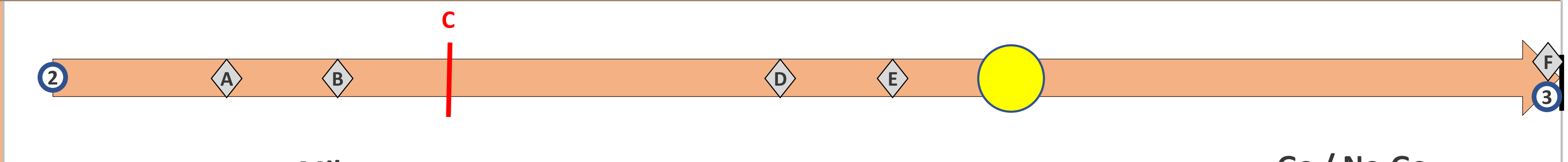
Project Description and Objectives

- Relative permeability (k_r) is the description of **multiphase transport through porous media** that is most widely accepted and utilized to scale relationships up to the field scale through simulations.
- Previous research at NETL has shown a **dependence of k_r on the flow rates and porous media structure** that is poorly captured in most descriptions of this process.
- ~3-year project to (2019-2022)
    1. ~~Determine if this poor literature description is true for offshore environments.~~
    2. Collect data on the generation of relevant k_r curves for describing fluid flow in these environments: e.g. carbon storage and wellbore.
    3. Distribute this collected data, methodology and resultant curves via easily accessible platform.

Project Timeline Update

Due to budget constrictions, 3.5-year project

Research Activities	2019			2020				2021				2022		
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Subtask 7.1 – Relative Permeability for Offshore EOR														



Milestones

7.A – ~~Complete gas/oil and water/oil k_r curves developed for a minimum of two flow rates through two different representative offshore cores. Eight k_r curves total. (Sept '19)~~

7.B - ~~Complete literature review of available and most used k_r curves for EOR simulations in offshore environments. Will include fluids, flow rate, methods that have been used to derive these curves, and curve types. Required for following Go/No-Go decision point. (Dec '19)~~

~~**7.D** - Perform a minimum of 4 additional gas/oil and water/oil tests to determine variations in the k_r curves based of different representative offshore environments. (Dec '20)~~

~~**7.E** – Develop beta tool, populate and make available for industry review. Anticipating ~1/2 of tests completed and seek feedback from industry to direct work towards the highest priority missing data. (March '21)~~

7.F – Publish offshore EOR k_r tool. Fully functioning tool that offshore planners can access and utilize to reduce the uncertainty in their reservoir simulations of Offshore projects. (Sept '22)

Go / No-Go

7.C – March '20 Go/No-Go Decision

No-Go: If existing k_r curves for water/oil and gas/oil flows in the literature, and within industrial knowledge, accurately describes the results obtained with the unsteady state methodology the project will be halted.

Go: If the unsteady state methodology shows that existing data is lacking in accuracy.

Impact

Key Accomplishments/Deliverables	Value Delivered
• Building upon techniques and tools developed in the FE Coal/Carbon Storage FWP, to directly measure variations in water/oil and gas/oil k_r curves within cores representative of offshore environments at subsurface temperature and pressure.	• The product of this work is to deliver a database with measurements of relative permeability, residual saturation, and wettability for offshore storage and resource extraction simulations, and accessible tools for reservoir modelers to access this data and reduce uncertainty in their estimates.

Chart Key

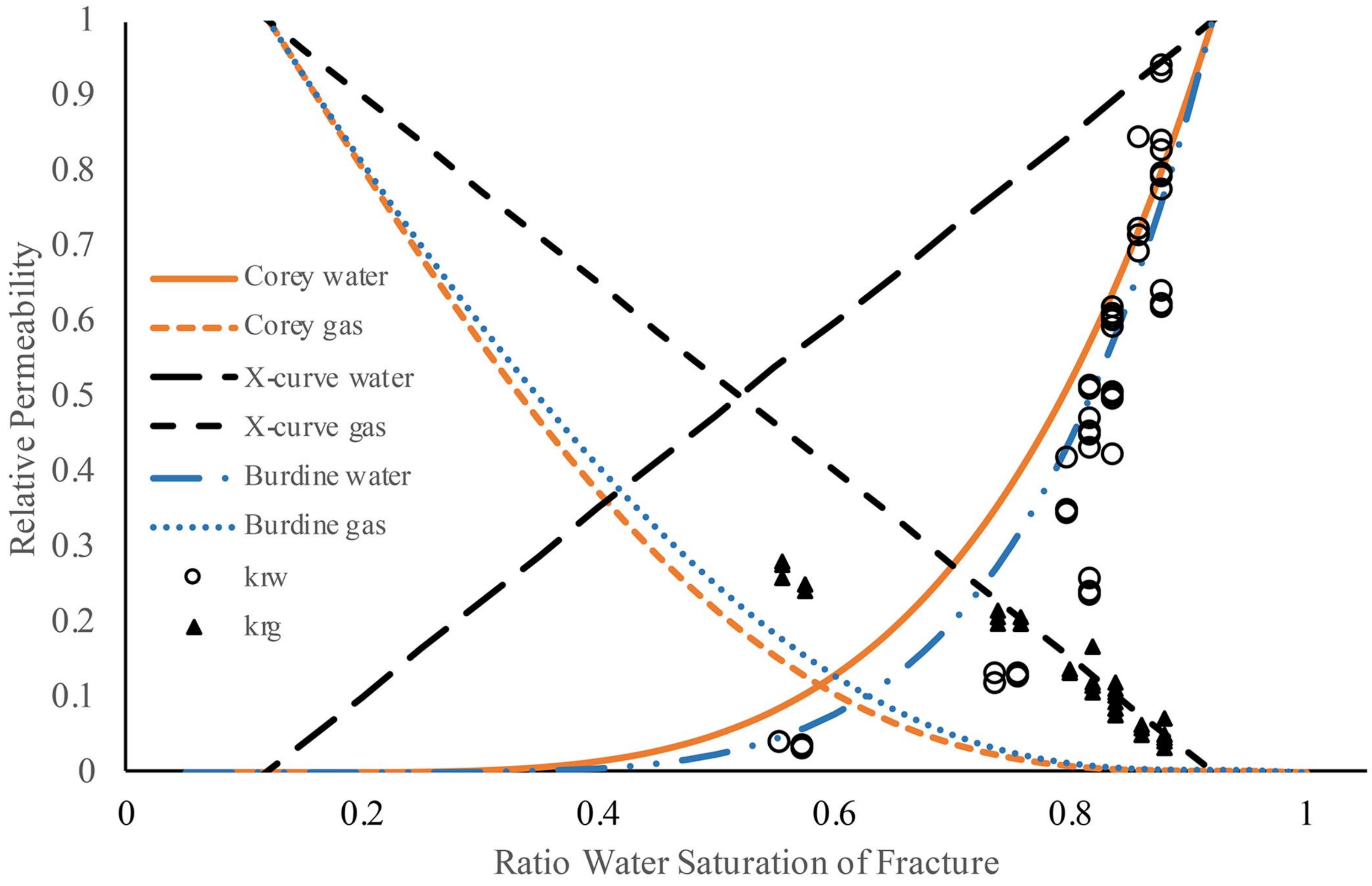
\# TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

So What is Relative Permeability?

- Relative permeability (**k_r**) is the ratio of effective permeability of a fluid with saturation less than 100% to absolute permeability

$$k_{rx} = {k_x(sat)}/{k}$$

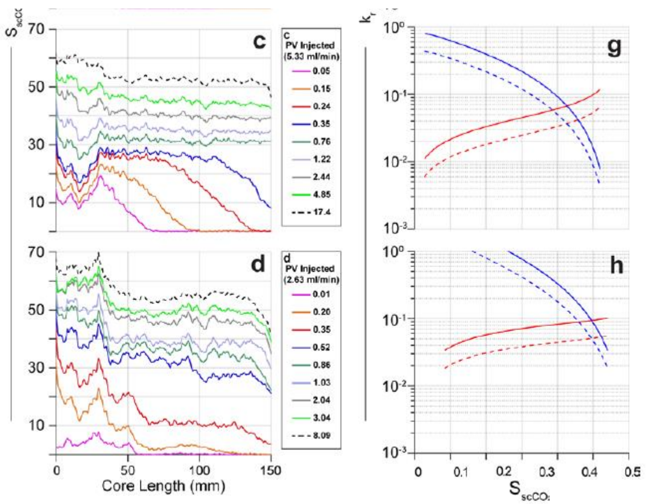
- Numerous models
- Experimental data
  - Unsteady vs steady state
  - Relevance to field operations
  - Fits to models



Rod, K. et al (2019) Relative permeability for water and gas through fractures in cement, PLoS One 14(1): e0210741. https://doi.org/10.1371/journal.pone.0210741

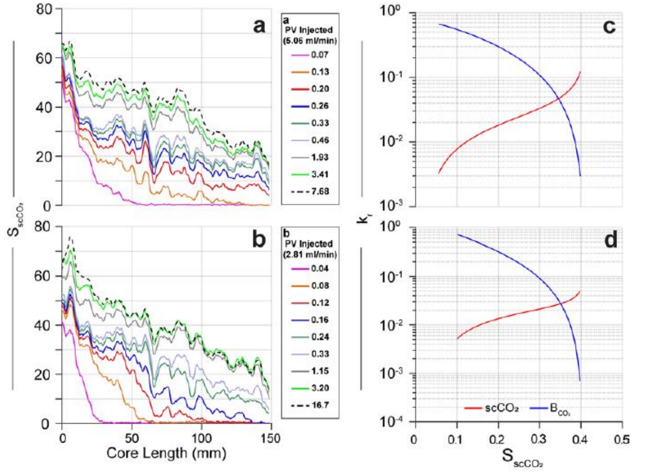
Recap Literature Review

- **Few studies** of high permeability cores at subsea conditions using oil
  - Some decent sand pack studies
  - Very few core studies published from offshore wells
- **Data** from experiments **not** readily **available**
  - Ability to compare techniques and apply different curve fits difficult
- Steady state methods predominant
  - Injection of two fluids simultaneously



Supplemental Figure 3: Saturation and k_r curves for Edwards Yellow. **(a-d)** Saturation curves for flow e
ml/min (a), 10.73 ml/min (b), 5.33 ml/min (c), and 2.63 ml/min (d). **(e-h)** Representative k_r curves for flow
ml/min (e), 10.73 ml/min (f), 5.33 ml/min (g), and 2.63 ml/min (h). Dashed lines in f-h indicate original, u
solid lines represent k_r curves after correction.

Low permeability (24 mD)
Edwards Yellow



High permeability (760 mD)
White Rim

Supplemental Figure 11: Saturation and k_r curves for White Rim. **(a-b)** Saturation curves for flow experiments at 5.06 ml/min (a) and 2.81 ml/min (b). **(c-d)** Representative k_r curves for flow experiments at 5.06 ml/min (c) and 2.81 ml/min (d).

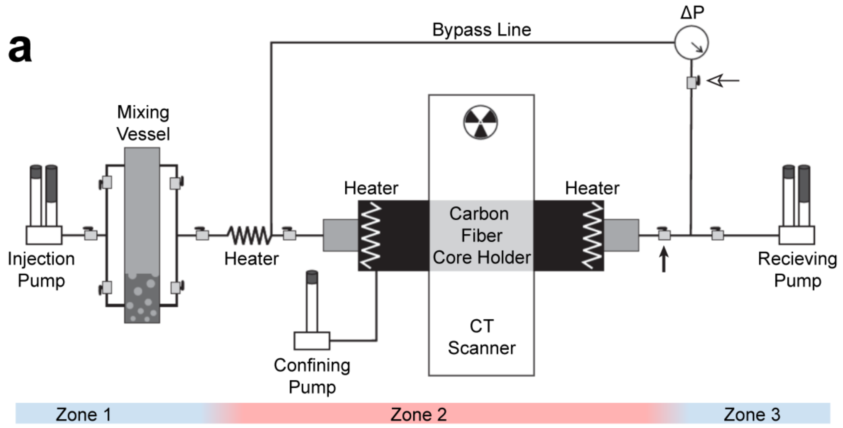
With the few specific studies examining k_r from offshore EOR out there, go/no-go review was passed

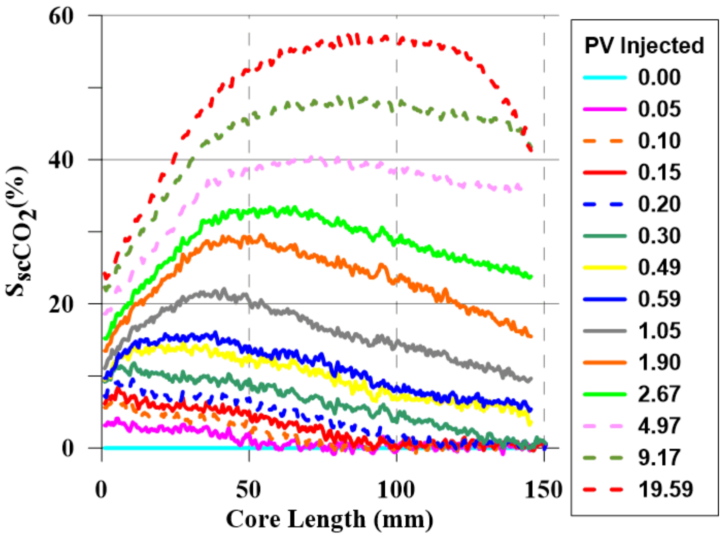
Experimental Process

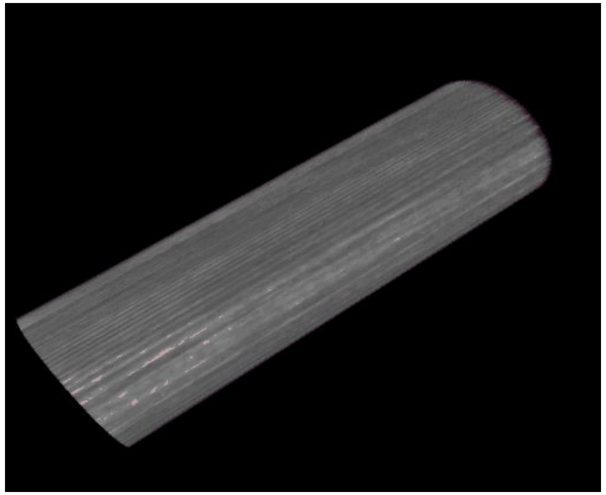
- Controlled injection of one fluid (N_2, H_2O, or CO_2) at elevated temperature and pressure conditions into core initially saturated with oil

  Unsteady state method

- Computed tomography used to determine saturation over time and differential pressure measured







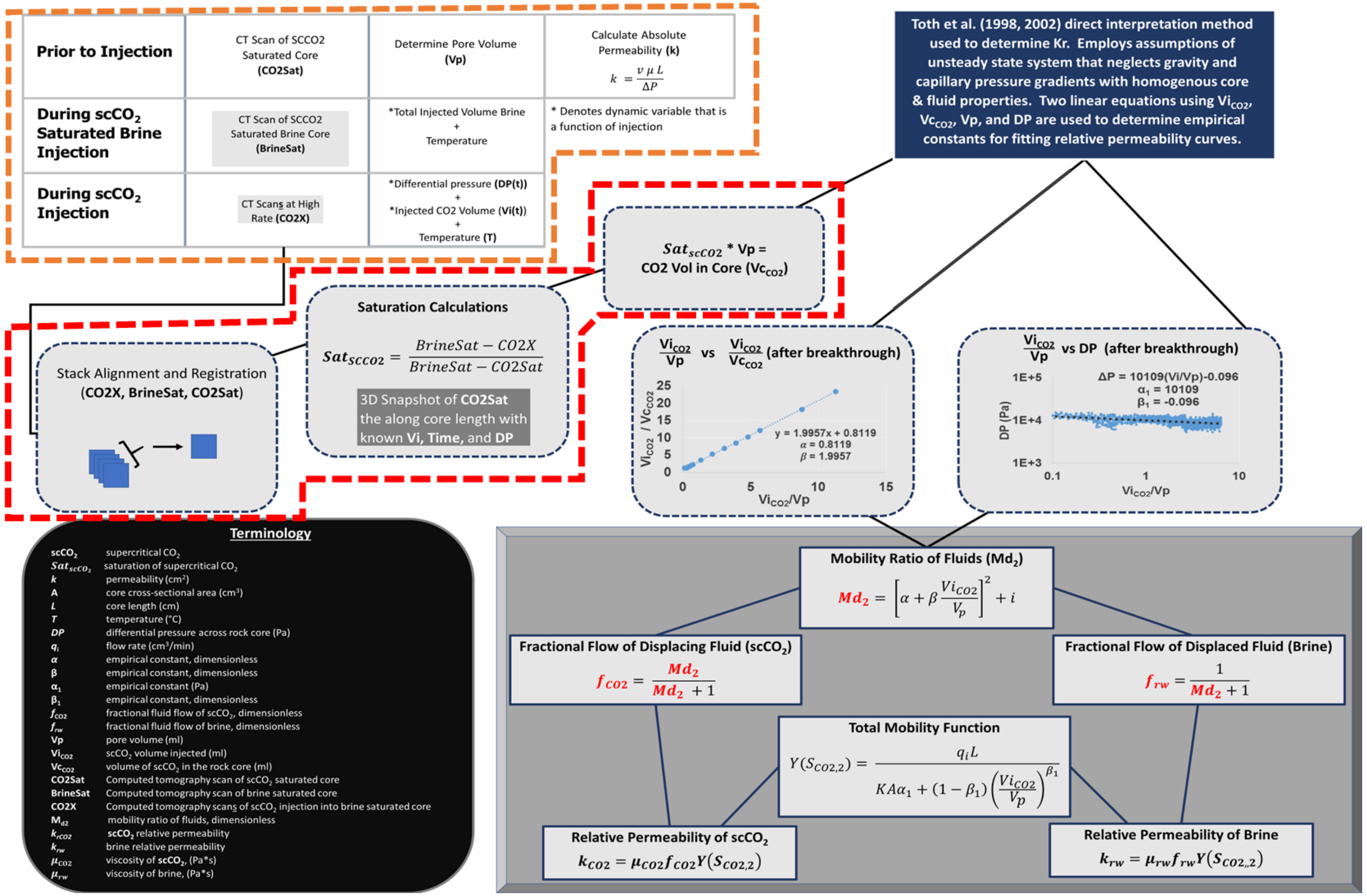
Moore et al. (2021) Rapid determination of supercritical CO2 and brine relative permeability using an unsteady-state flow method. Adv. In Water Res., 153.

Calculation Method

Toth et al. (2002) Convenient formulae for determination of relative permeability from unsteady-state fluid displacements in core plugs. *J Petrol Sci & Eng*, *36*(1–2), 33–44.

Moore et al. (2021) Rapid determination of supercritical CO2 and brine relative permeability using an unsteady-state flow method. Adv. In Water Res., 153.

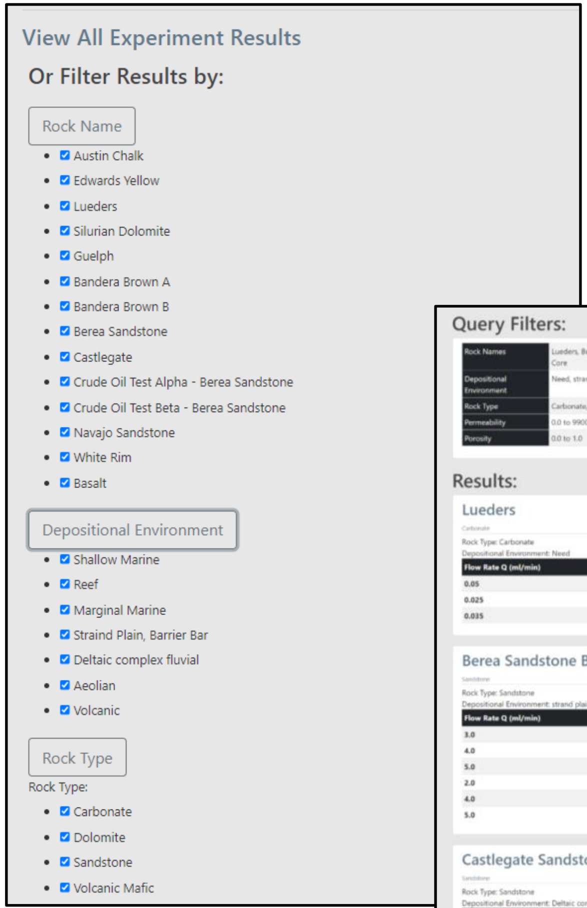
- Collect raw data
  - Pre, setup and during flood
- Calculate saturation of fluids from CT scanning via image processing
- Calculate mobility ratios of the fluids from the Toth et al (2002) method
- From the mobility ratios, plot the k_r(saturation)

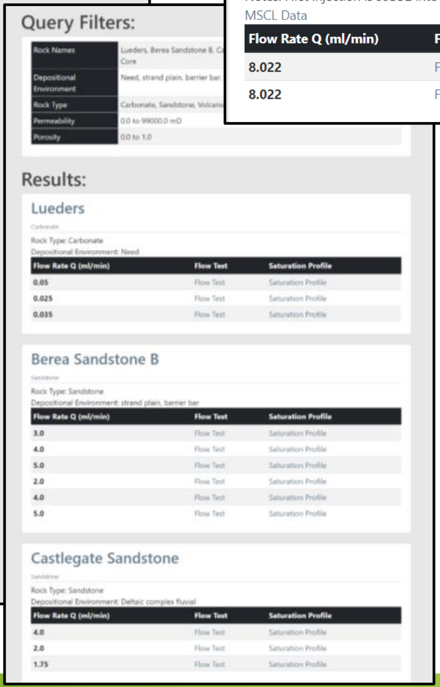


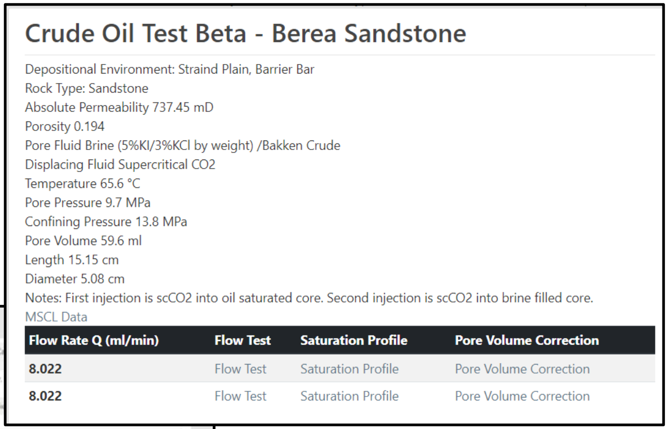
Distribution Platform

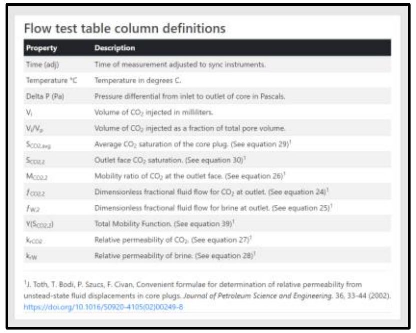
CO_2-Brine Relative Permeability Accessible database

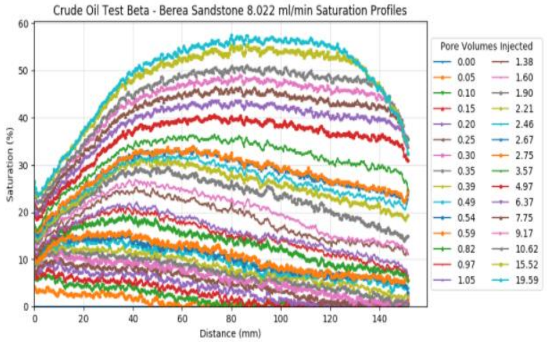
- https://edx.netl.doe.gov/hosting/co2bra

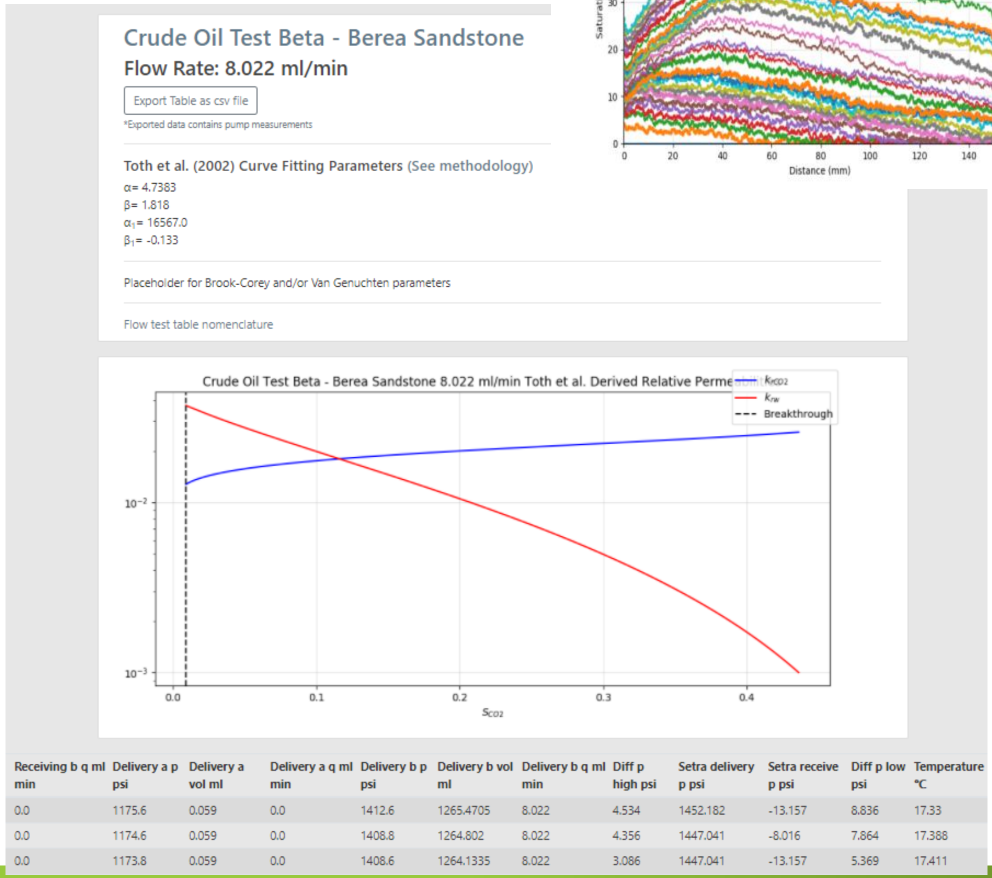




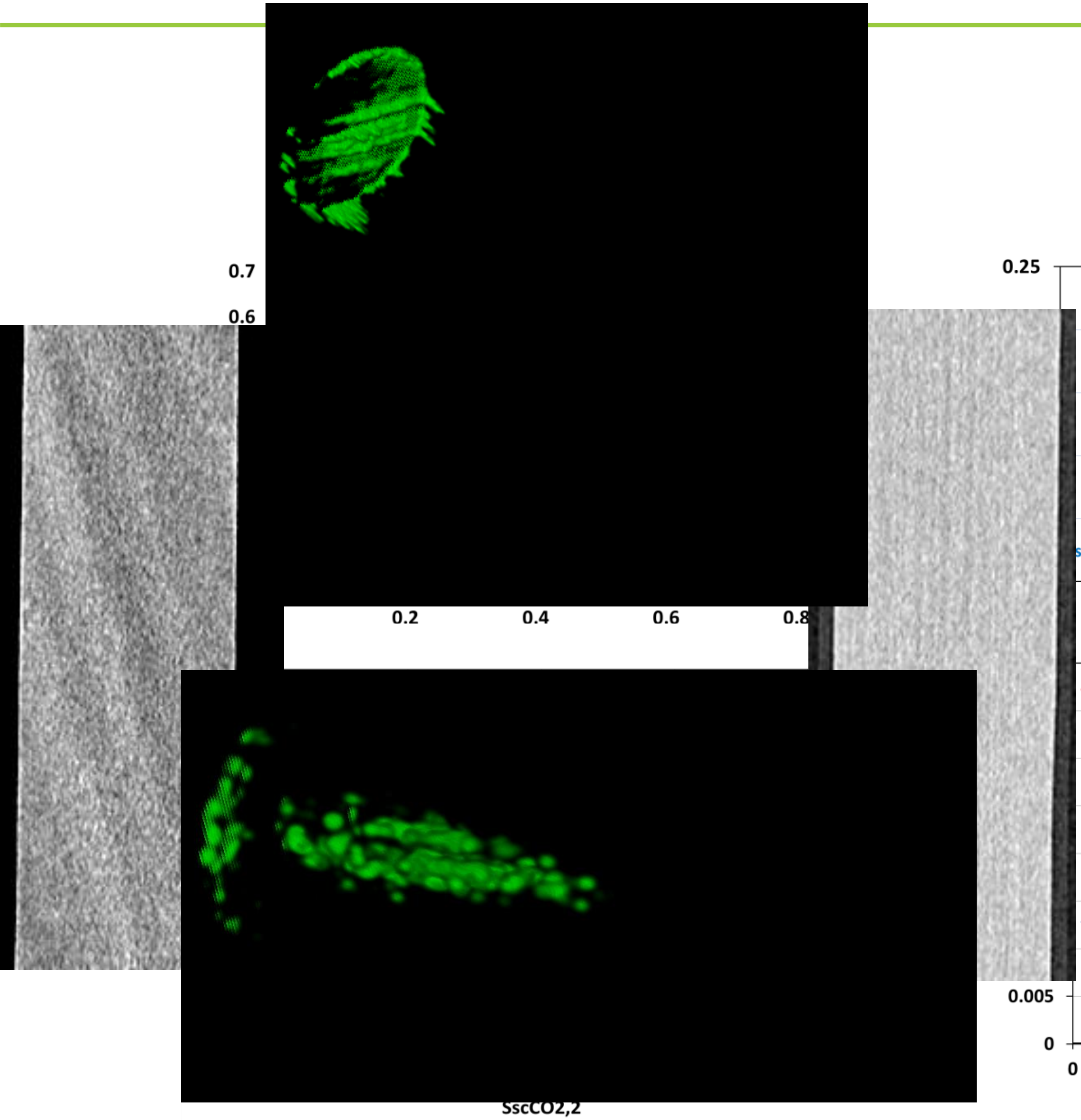




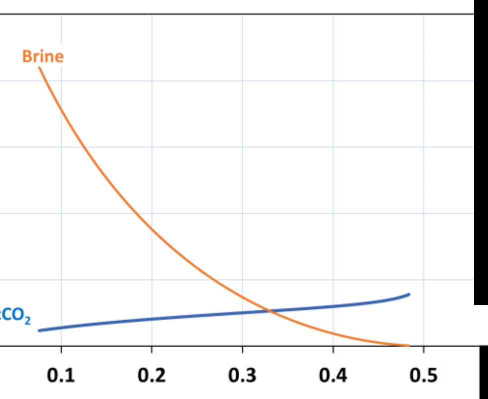


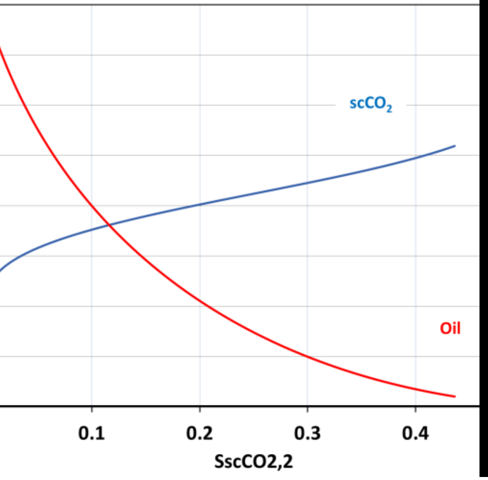


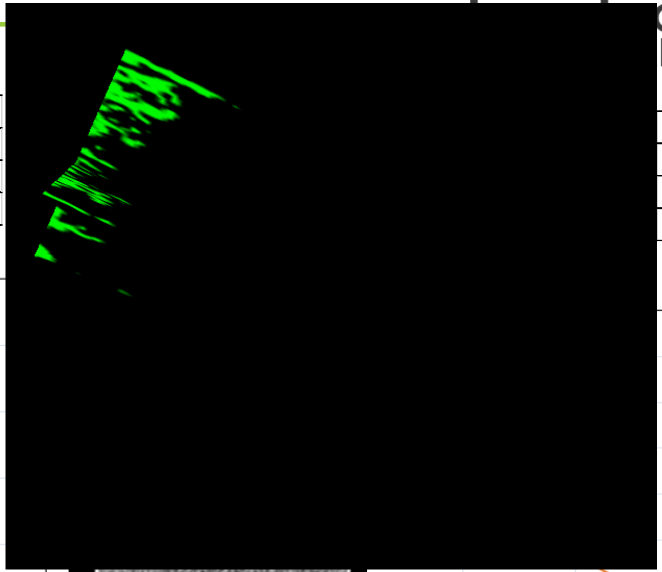
Initial Data



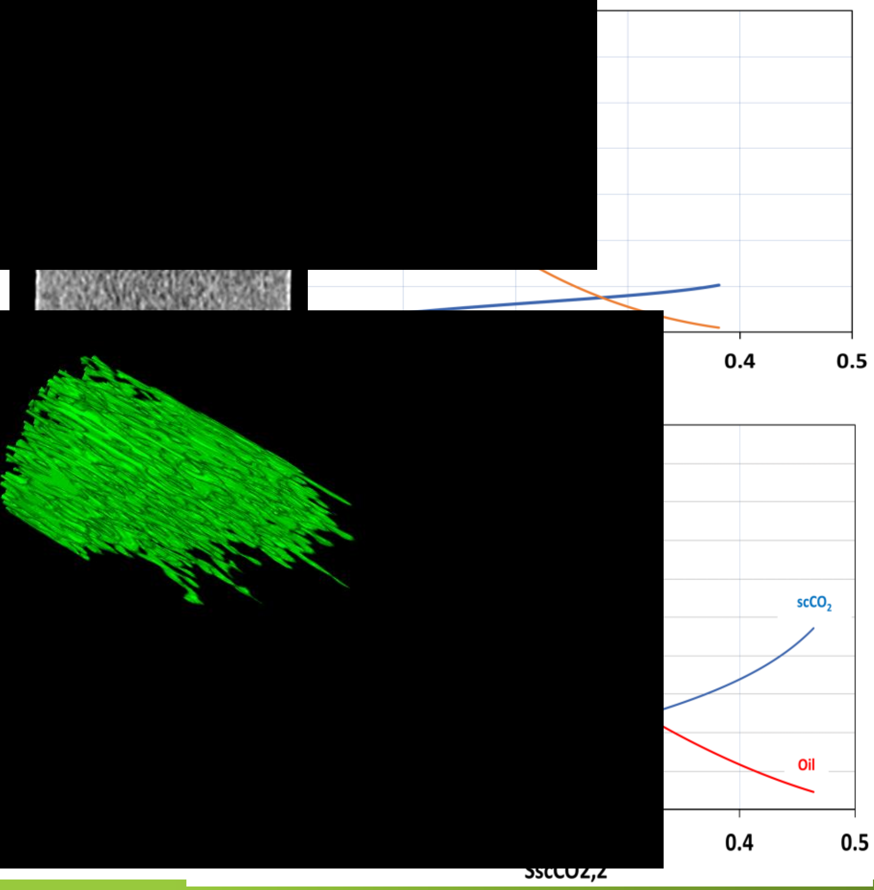
Rock name	Berea Sandstone
Absolute Permeability (k, mD)	737.45
Porosity (Ø)	0.19
Pore Volume	59.6







	Bandera Brown Sandstone
	261.33
	0.26
	74.6



Project Updates

NATIONAL ENERGY TECHNOLOGY LABORATORY

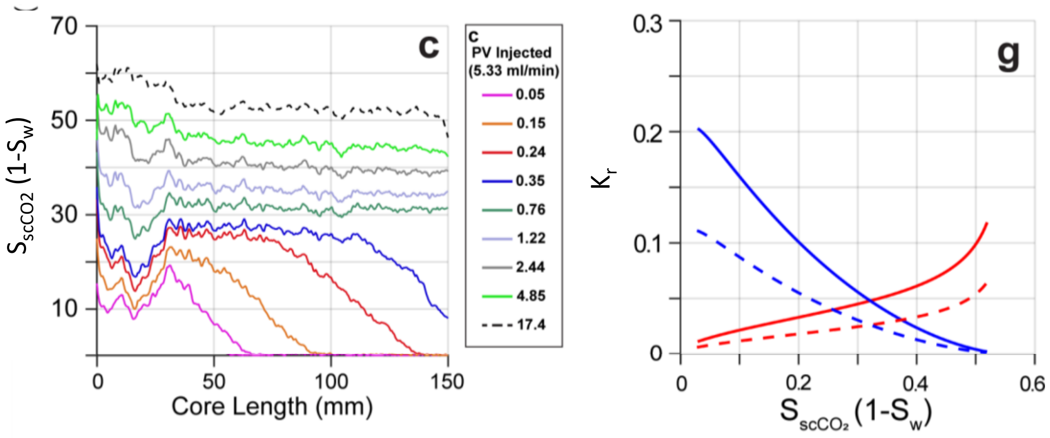
Data collection underway

- There was a slow down on these floods earlier last year due to COVID but we have recovered
  - Currently have completed 6 experiments, with 3 viable results
  - Working on completing #7
  - 3 of the cores were not fully analyzed due to equipment failures resulting in lost tests
- Use of previously refined unsteady state methodology for CO_2/brine k_r curve measurements still working well
  - Oil contamination of system, and resulting cleaning, results in slightly longer experiment times. We now have a fully developed methodology for QA/QC of equipment to mitigate this issue.
  - Oil attenuation is harder to differentiate from CO_2 than brine. We have had to modify our image analysis protocol

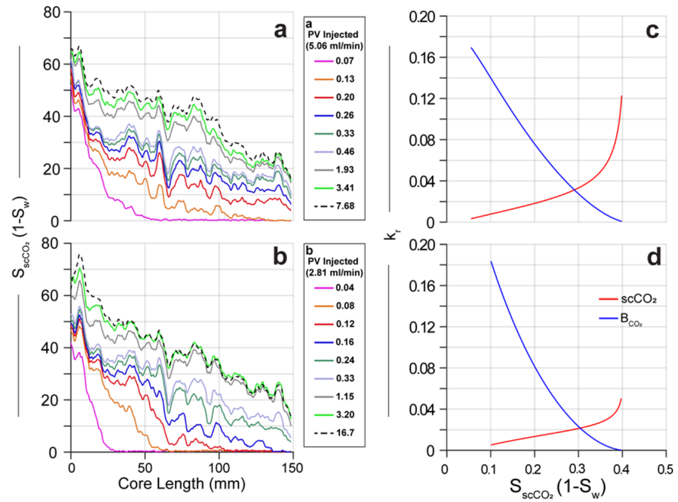
Project Next Steps

Continue measurements

- Close attention to the impact of high permeability/high connectivity porous structures



Low permeability (24 mD) Edwards Yellow



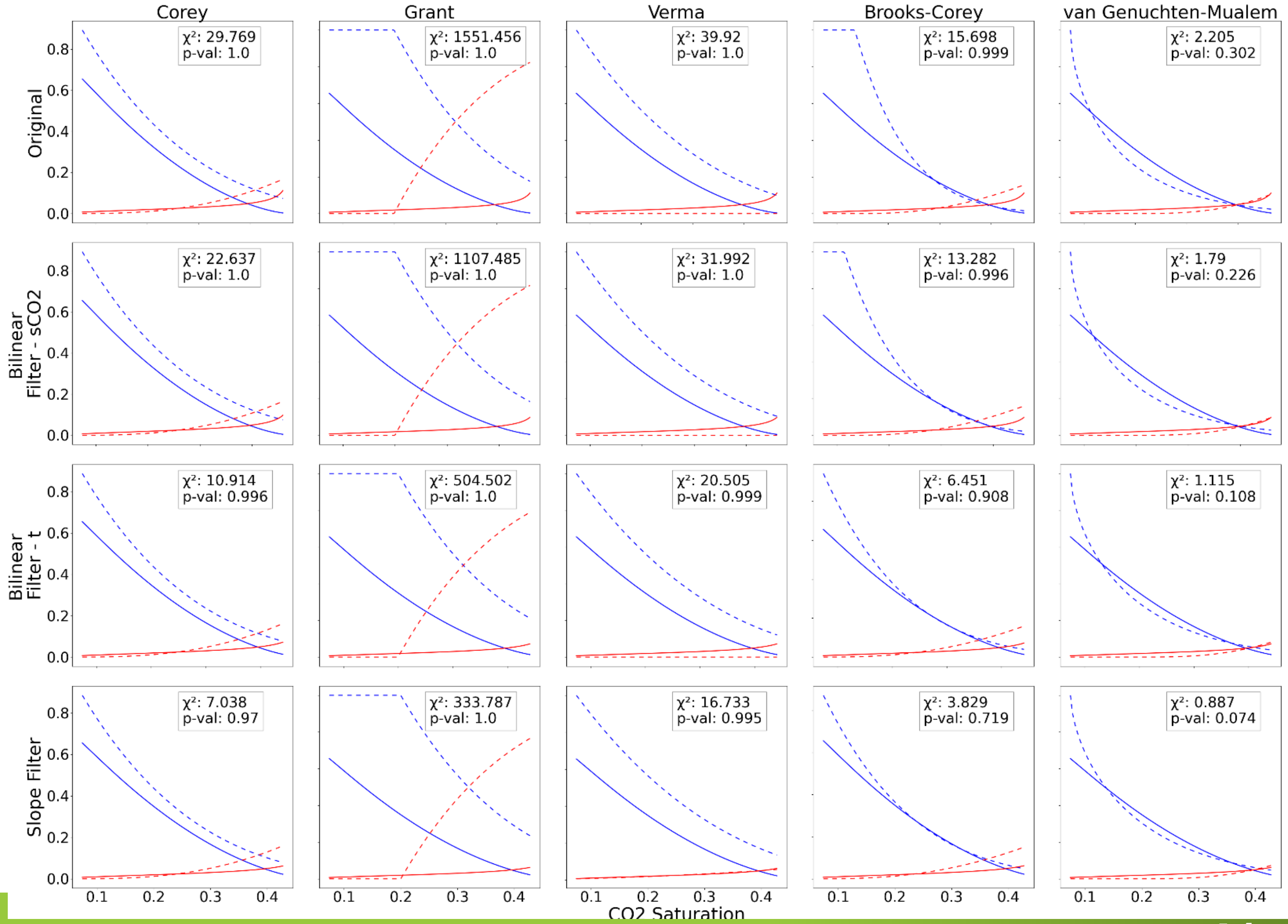
High permeability (760 mD) White Rim

Technology-to-Market Path

- Continue adding data to the CO2BRA platform in 2021/2022
- Added value via data that can be used to model fluid behavior in offshore environment for applications in carbon storage, wellbore-reservoir flow issues (blowout) and EOR.

Project Next Steps

- **Leverage ML and SMART to improve curve fits**
  - Enhanced data filters
  - Multiple curve parameter simultaneous fits
- **These improvements have led to research questions about appropriate k_r curve behavior after high pore volume injection, versus primary drainage behavior**



Concluding Remarks

- At the conclusion of this project, we will have an open platform with fluid relative permeability curves, data used to collect those curves, and explanations of the process. These curves will be generated for conditions relevant to the Offshore environment, with the benefits of:
  - Providing additional improved modeling parameters for
    - CO_2 storage in petroleum plays
    - Wellbore blowout and near wellbore flow
  - Providing open access to relative permeability data for oil/water/CO_2 systems
- The next 3 quarters will primarily be in finishing the data collection/analysis phase, with some preparation of the open online platform.
  - **Strong push to obtain offshore cores. Currently have discussions ongoing with government agencies, academia and industry.**

Thank you

Big thanks to Dustin Crandall, Kelly Rose, Paul Holcomb, Scott Workman, Jeong Choi, Seth King and all the others who have made this work possible.

Thank you for your interest today!

Bibliography

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