Relative Permeability for Offshore HPHT Reservoirs

2022 Resource Sustainability Annual Project Review Meeting — Pittsburgh, PA — October 25-27, 2022

Project Overview

- Project Staff:

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3 ½ year long project with a focus on generating relative permeability data under realistic offshore HPHT conditions.

- Wrapping up this fall. Experiments complete, analyses of results almost complete, to be uploaded to online open portal this fall.

Builds on research completed under the Carbon Storage program to examine relative permeability of $scCO_2$ in various onshore reservoirs

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

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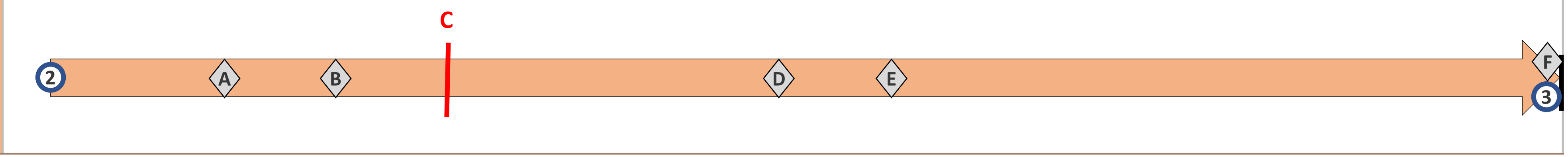
3.5-year project

Research Activities	2019 ($100k)			2020 ($155k)				2021 ($160k)				2022 ($47k)		
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Task 7 – Relative Permeability for Offshore HPHT Reservoirs														



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~~ Nov '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

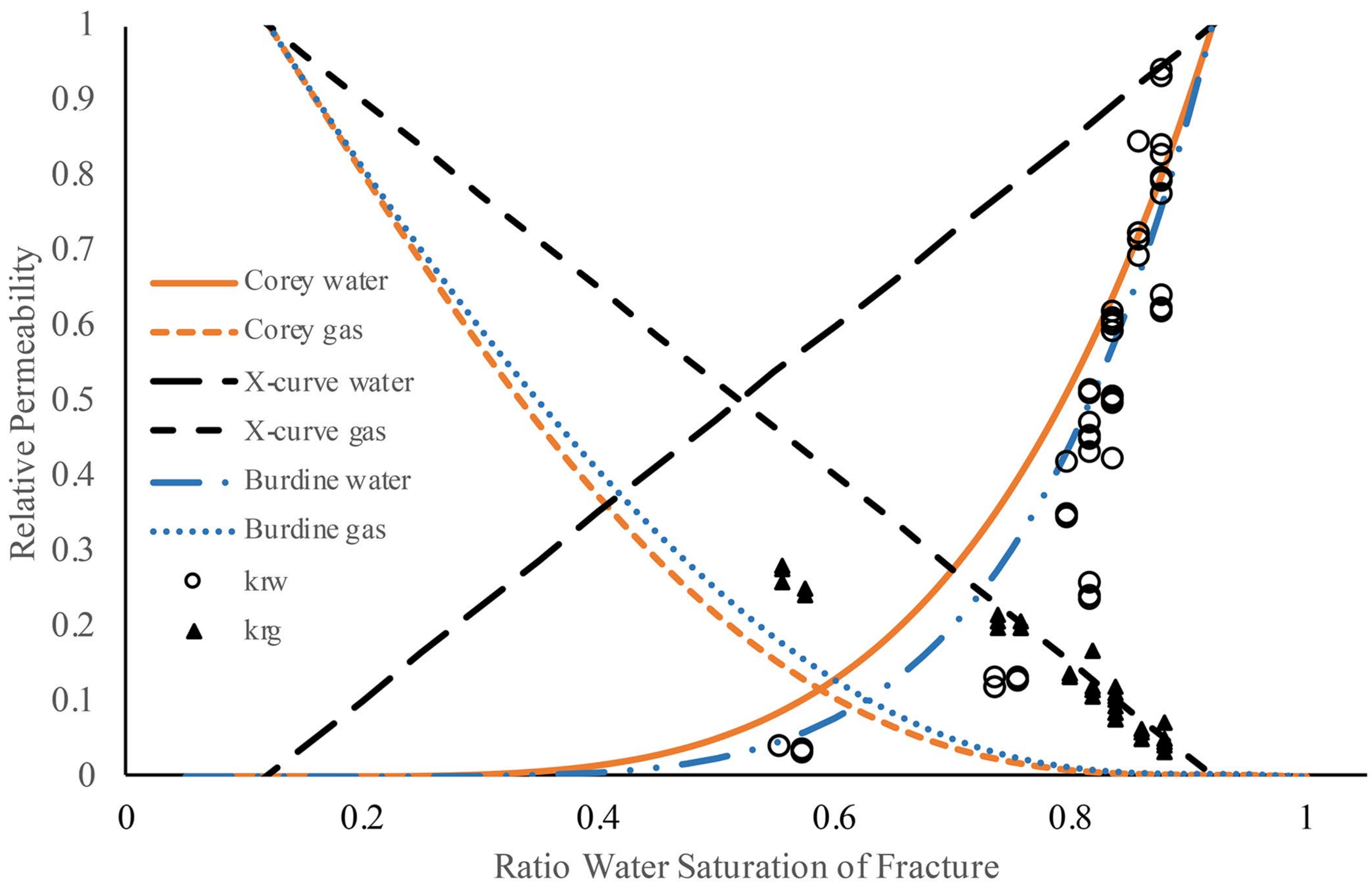
TRL Score | Go / No-Go Timeframe | Project Completion | Milestone

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

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

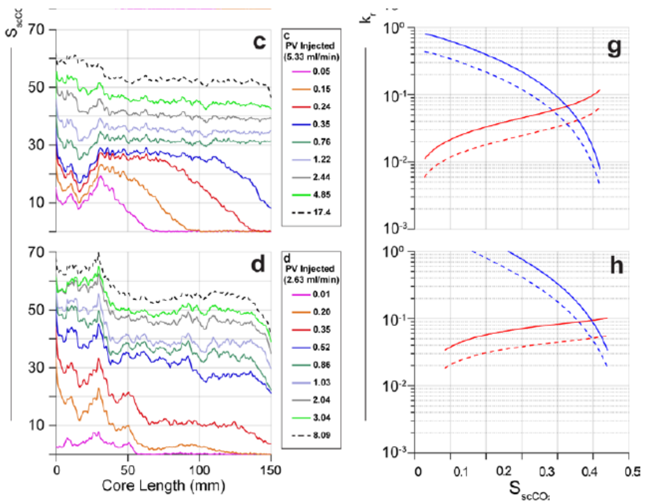
- Numerous models
- Experimental data
    - Unsteady vs steady state
    - Relevance to field operations
    - Fits to models



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

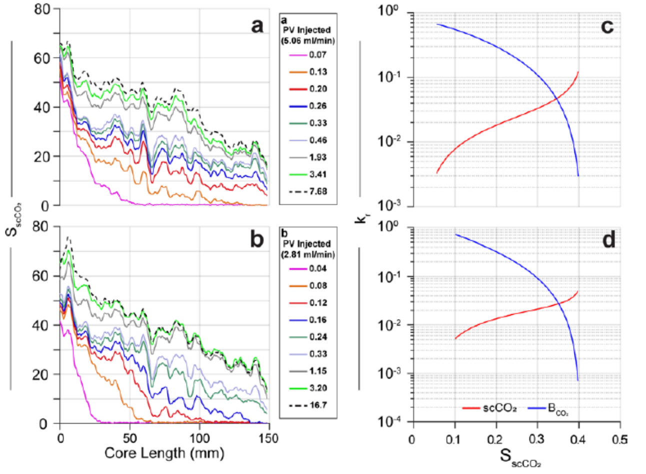
- **Few studies** of high permeability cores at subsea conditions using oil
    - Some decent sand pack studies
    - Very few core studies published from offshore wells
- **Data** from experiments **not** readily **available**
    - Ability to compare techniques and apply different curve fits difficult
- 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 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).

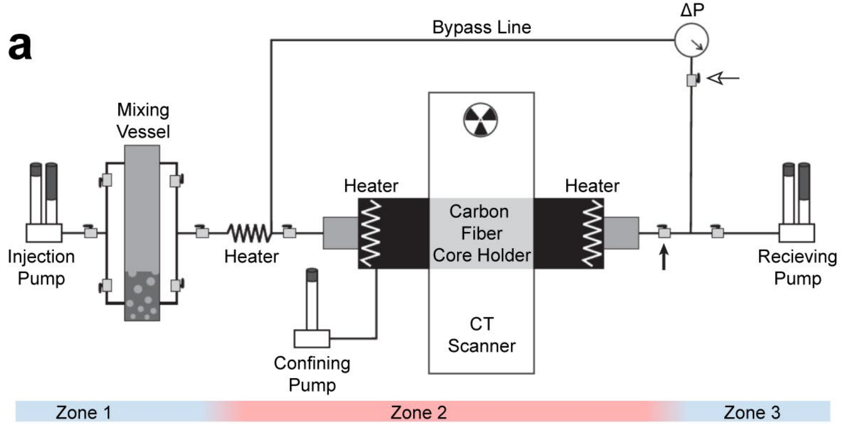
With the few specific studies examining k_r from offshore flows, go/no-go review was passed

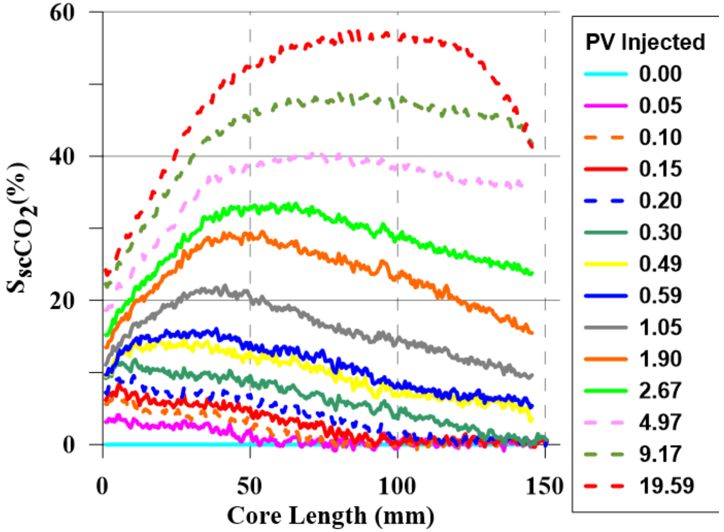
Experimental Process

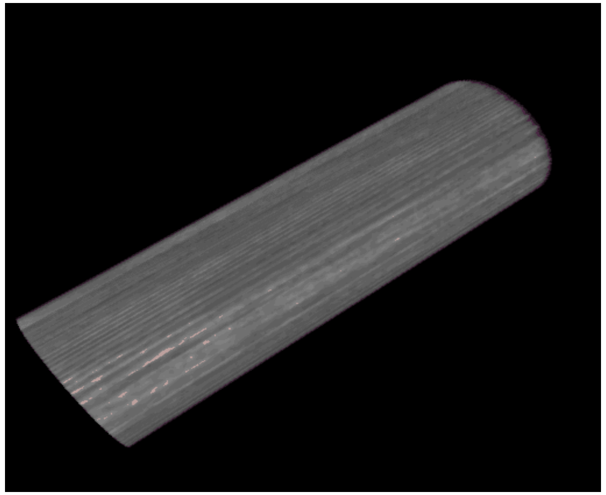
- Controlled injection of one fluid (N_2, H_2O, or CO_2) at elevated temperature and pressure conditions into core initially saturated with oil

  Unsteady state method

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





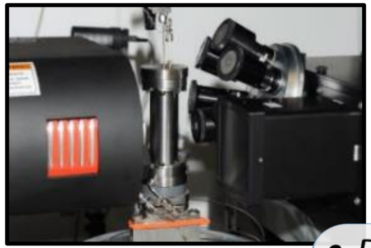


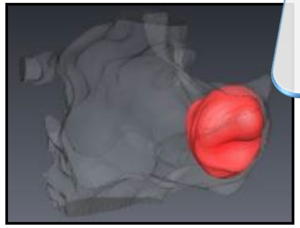
Moore et al. (2021) Rapid determination of supercritical CO_2 and brine relative permeability using an unsteady-state flow method. Adv. In Water Res., 153.

NETL's Multi-Scale CT and Core Flow Facility

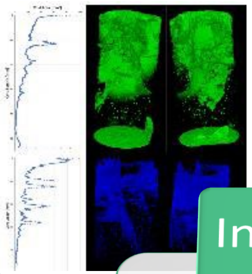
Unique Capabilities: Four computed tomography scanners with 3D resolution from microns to millimeters, all with ancillary core flow capabilities. Able to performed controlled multiphase flow in cores from 0.25" to 2" in diameter at conditions up to 10,000 psi and 200 ˚C. Full time technical staff to assist with rock preparation, experimentation design, setup, execution, and analysis. Plus, controlled flow systems for long term tests, and GeoTek multi-sensor core logger.

Opportunities: Direct examination of rocks from carbon storage sites under *in-situ* conditions with supercritical CO_2. Stressing of samples to understand mechanical behaviors. Examination of relationships between rock properties, geochemical alteration, and permeability (or structural properties). Scanning to complement other experiments, or to digitally and non-destructively preserve core from relevant locations.



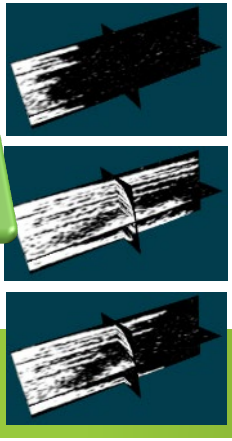


Micro-CT
- *Pore Scale*
- *Small Samples*
- *Dynamic Flooding*



Industrial CT
- Pore & Core scale
- 1" Diameter plus Samples
- Highest Pressures

Medical CT
- Core Scale
- Large Samples
- Dynamic Flooding



For More Information:
- Equipment/Lab Factsheet (link)
- Core characterization EDX Data Group (link)
- Core characterization YouTube Video (link)
- CO_2 Brine Relative Permeability Accessible Database (link)

Relative Permeability Experiments with NETL's Medical CT Scanner and Core Flow System

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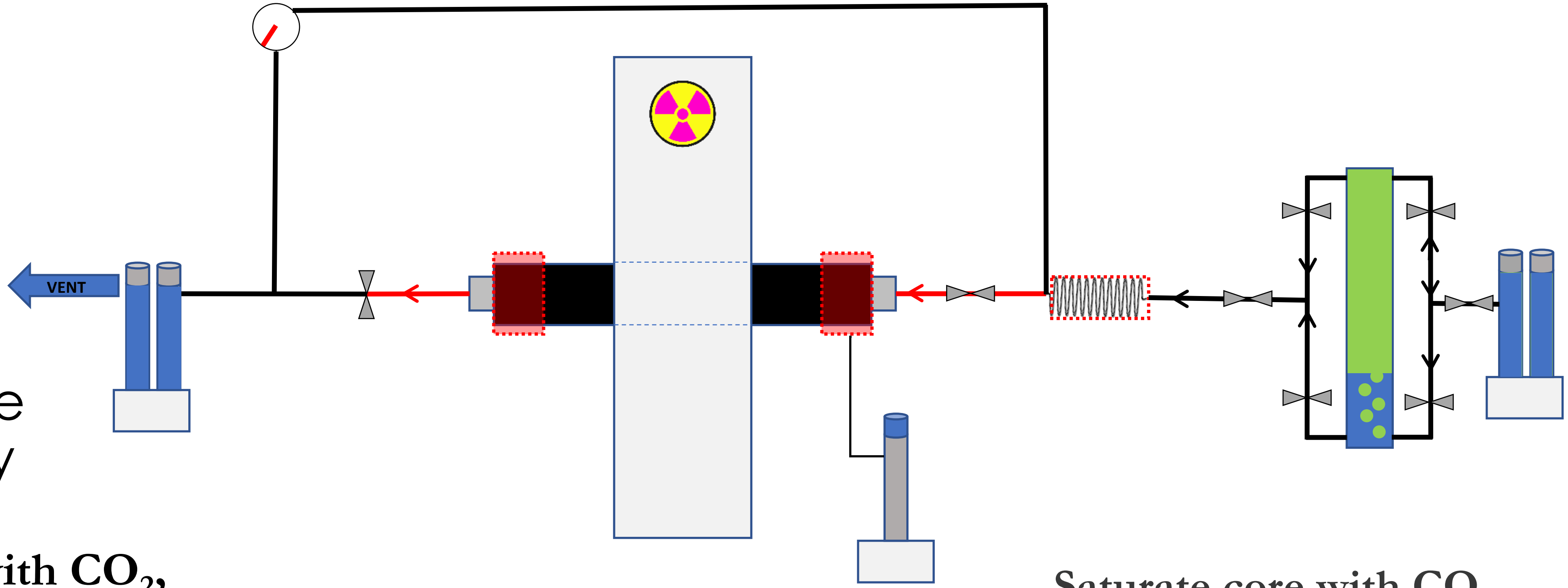


Prior to flow test, measure core porosity

Fill core with CO_2, obtain base scan.

Heat core holder and pressurize pore fluid

Saturate core at T&P

Drain effluent pumps while leaving core at condition

Saturate injection fluid with CO_2 and equilibrate

Circulate CO_2 and fluid in pumps to ensure mixing

Saturate core with CO_2 equilibrated fluid

Obtain brine saturated core scan

Vent effluent pumps and fill injection pumps with CO_2

Prepare to inject brine saturated CO_2

FINALLY, inject equilibrated CO_2 through the core and measure saturations via CT scanning

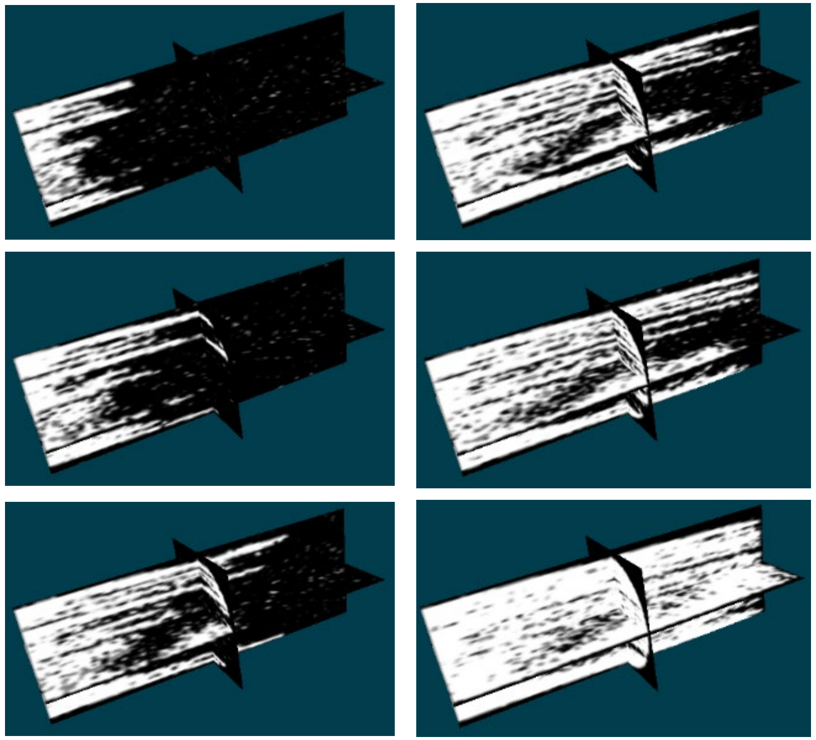
Additional Notes on Experimental Scanning Process

Developed over the past ~decade through trial, error, luck and frustration

- During the initial flow through of the non-wetting fluid, we scan the entire core ~twice a minute (27 seconds for 6-inch-long cores)
  - Use of automated scanning scripts with the Medical CT scanner, 20 in a batch
  - Non-wetting fluid breakthrough to the backside is apparent from greyscale variations in the core
- Once non-wetting fluid breaks through we transition to 5-minute scan intervals for an hour (12 scans)
  - Changes in saturation and pressure drop across the core is much slower at this stage
- We continue with 30-minute interval scans until 5 pore volumes injected, or we run out of pump volume, or we run out of time
  - Do scan automatically over the night as needed. Which was critical for these large porosity samples.
- Results in **40-60 scans** of the rock over the experiment…

Image Processing

- Isolation of core data
  - Remove slices before/after core
  - Crop data from outside of the core (sleeve, coreholder, etc)
  - Save as image stacks
- Register image stacks
  - Fancy way of saying make sure they line up. Heating and core movement can cause slight shifts (less than mm) over the course of the test, and with the 0.25 mm resolution this can cause issues
- Image subtractions to observe change in saturations
  - Report out changes in saturation for each slice
  - Calculate CO_2 saturation in core at each time



$$\boldsymbol{Sat_{scco_2}} = \frac{BrineSat - CO2X}{BrineSat - CO2Sat}$$

Calculation Method

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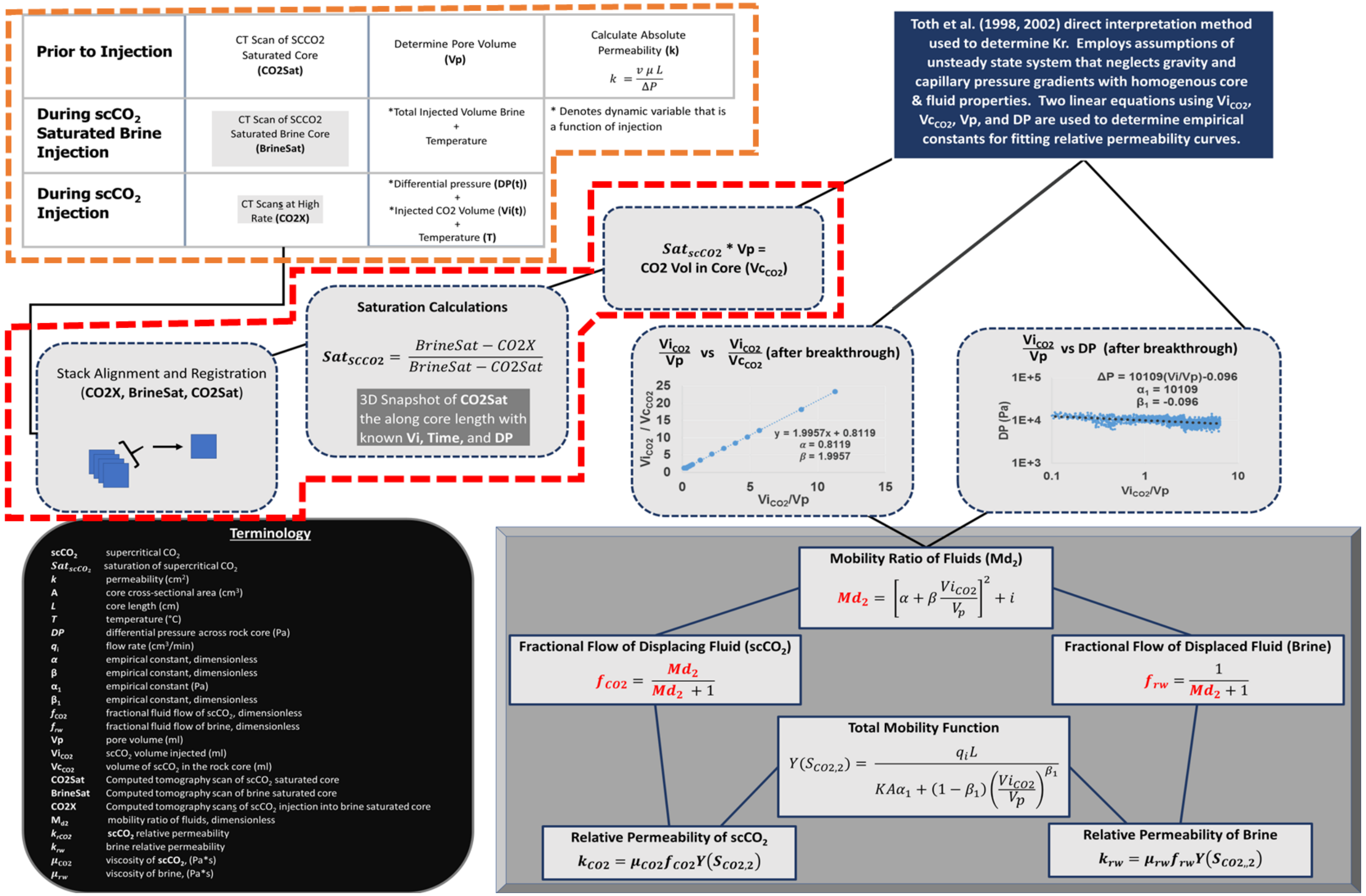
Toth et al. (2002) Convenient formulae for determination of relative permeability from unsteady-state fluid displacements in core plugs. *J Petrol Sci & Eng*, 36(1–2), 33–44.

Moore et al. (2021) Rapid determination of supercritical CO_2 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

View All Experiment Results

Or Filter Results by:

Rock Name

- ☑ Austin Chalk
- ☑ Edwards Yellow
- ☑ Lueders
- ☑ Silurian Dolomite
- ☑ Guelph
- ☑ Bandera Brown A
- ☑ Bandera Brown B
- ☑ Berea Sandstone
- ☑ Castlegate
- ☑ Crude Oil Test Alpha - Berea Sandstone
- ☑ Crude Oil Test Beta - Berea Sandstone
- ☑ Navajo Sandstone
- ☑ White Rim
- ☑ Basalt

Depositional Environment

- ☑ Shallow Marine
- ☑ Reef
- ☑ Marginal Marine
- ☑ Straind Plain, Barrier Bar
- ☑ Deltaic complex fluvial
- ☑ Aeolian
- ☑ Volcanic

Rock Type

Rock Type:

- ☑ Carbonate
- ☑ Dolomite
- ☑ Sandstone
- ☑ Volcanic Mafic

Query Filters:

Rock Names	Lueders, Berea Sandstone B, C... Core
Depositional Environment	Need, strand plain, barrier bar,
Rock Type	Carbonate, Sandstone, Volcani...
Permeability	0.0 to 99000.0 mD
Porosity	0.0 to 1.0

Results:

Lueders

Carbonate

Rock Type: Carbonate
Depositional Environment: Need

Flow Rate Q (ml/min)	Flow Test	Saturation Profile
0.05	Flow Test	Saturation Profile
0.025	Flow Test	Saturation Profile
0.035	Flow Test	Saturation Profile

Berea Sandstone B

Sandstone

Rock Type: Sandstone
Depositional Environment: strand plain, barrier bar

Flow Rate Q (ml/min)	Flow Test	Saturation Profile
3.0	Flow Test	Saturation Profile
4.0	Flow Test	Saturation Profile
5.0	Flow Test	Saturation Profile
2.0	Flow Test	Saturation Profile
4.0	Flow Test	Saturation Profile
5.0	Flow Test	Saturation Profile

Castlegate Sandstone

Sandstone

Rock Type: Sandstone
Depositional Environment: Deltaic complex fluvial

Flow Rate Q (ml/min)	Flow Test	Saturation Profile
4.0	Flow Test	Saturation Profile
2.0	Flow Test	Saturation Profile
1.75	Flow Test	Saturation Profile

Crude Oil Test Beta - Berea Sandstone

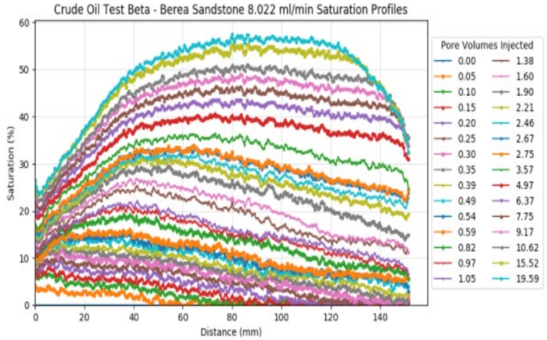
Depositional Environment: Straind Plain, Barrier Bar
Rock Type: Sandstone
Absolute Permeability 737.45 mD
Porosity 0.194
Pore Fluid Brine (5%KI/3%KCl by weight) /Bakken Crude
Displacing Fluid Supercritical CO2
Temperature 65.6 °C
Pore Pressure 9.7 MPa
Confining Pressure 13.8 MPa
Pore Volume 59.6 ml
Length 15.15 cm
Diameter 5.08 cm
Notes: First injection is scCO2 into oil saturated core. Second injection is scCO2 into brine filled core.
MSCL Data

Flow Rate Q (ml/min)	Flow Test	Saturation Profile	Pore Volume Correction
8.022	Flow Test	Saturation Profile	Pore Volume Correction
8.022	Flow Test	Saturation Profile	Pore Volume Correction

Flow test table column definitions

Property	Description
Time (adj)	Time of measurement adjusted to sync instruments.
Temperature °C	Temperature in degrees C.
Delta P (Pa)	Pressure differential from inlet to outlet of core in Pascals.
V_i	Volume of CO_2 injected in milliliters.
V_i/V_p	Volume of CO_2 injected as a fraction of total pore volume.
$S_{CO2,avg}$	Average CO_2 saturation of the core plug. (See equation 29)[1]
$S_{CO2,2}$	Outlet face CO_2 saturation. (See equation 30)[1]
$M_{CO2,2}$	Mobility ratio of CO_2 at the outlet face. (See equation 26)[1]
$f_{CO2,2}$	Dimensionless fractional fluid flow for CO_2 at outlet. (See equation 24)[1]
$f_{W,2}$	Dimensionless fractional fluid flow for brine at outlet. (See equation 25)[1]
$Y(S_{CO2,2})$	Total Mobility Function. (See equation 39)[1]
k_{rCO2}	Relative permeability of CO_2. (See equation 27)[1]
k_{rW}	Relative permeability of brine. (See equation 28)[1]

[1] J. Toth, T. Bodi, P. Szucs, F. Civan, Convenient formulae for determination of relative permeability from unstead-state fluid displacements in core plugs. *Journal of Petroleum Science and Engineering*. 36, 33-44 (2002). https://doi.org/10.1016/S0920-4105(02)00249-8



Crude Oil Test Beta - Berea Sandstone

Flow Rate: 8.022 ml/min

Export Table as csv file

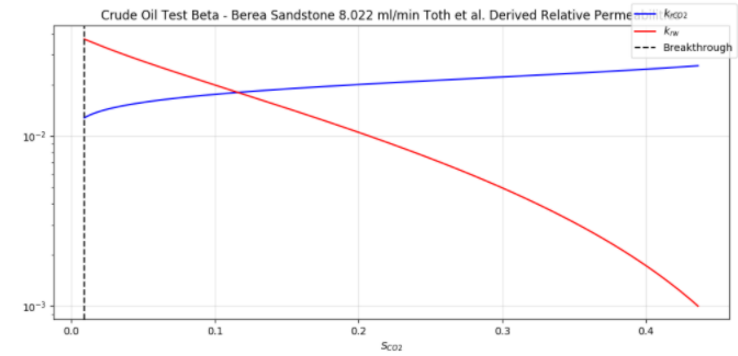
*Exported data contains pump measurements

Toth et al. (2002) Curve Fitting Parameters (See methodology)

α= 4.7383
β= 1.818
α_1= 16567.0
β_1= -0.133

Placeholder for Brook-Corey and/or Van Genuchten parameters

Flow test table nomenclature

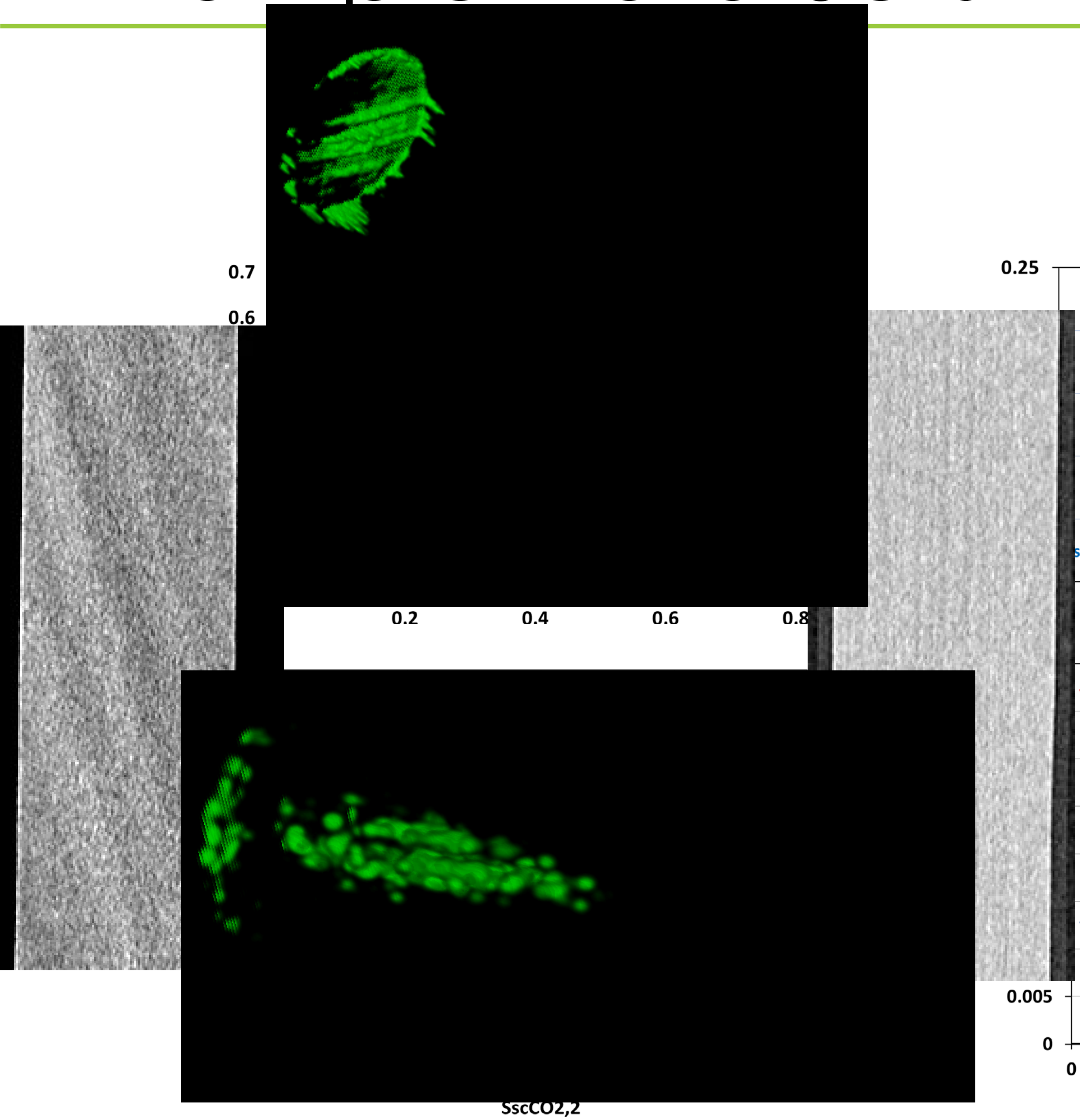


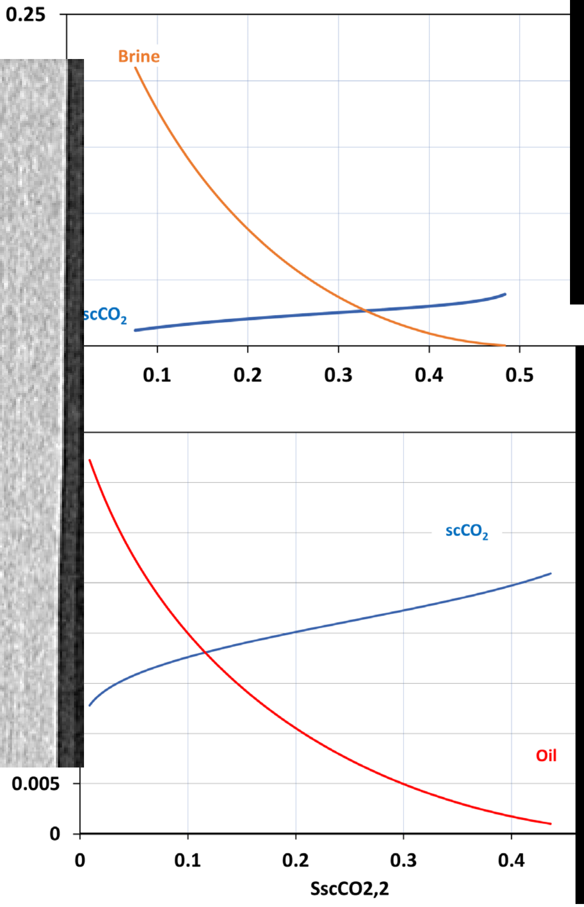
Receiving b q ml min	Delivery a p psi	Delivery a vol ml	Delivery a q ml min	Delivery b p psi	Delivery b vol ml	Delivery b q ml min	Diff p high psi	Setra delivery p psi	Setra receive p psi	Diff p low psi	Temperature °C
0.0	1175.6	0.059	0.0	1412.6	1265.4705	8.022	4.534	1452.182	-13.157	8.836	17.33
0.0	1174.6	0.059	0.0	1408.8	1264.802	8.022	4.356	1447.041	-8.016	7.864	17.388
0.0	1173.8	0.059	0.0	1408.6	1264.1335	8.022	3.086	1447.041	-13.157	5.369	17.411

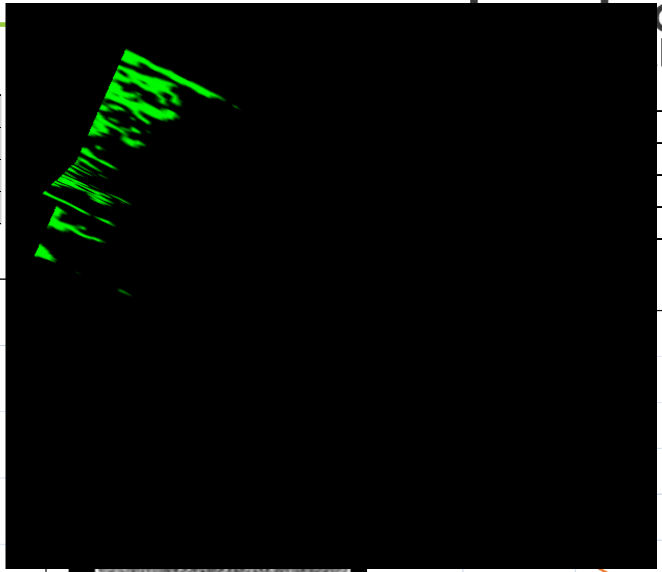
Example Data Sets

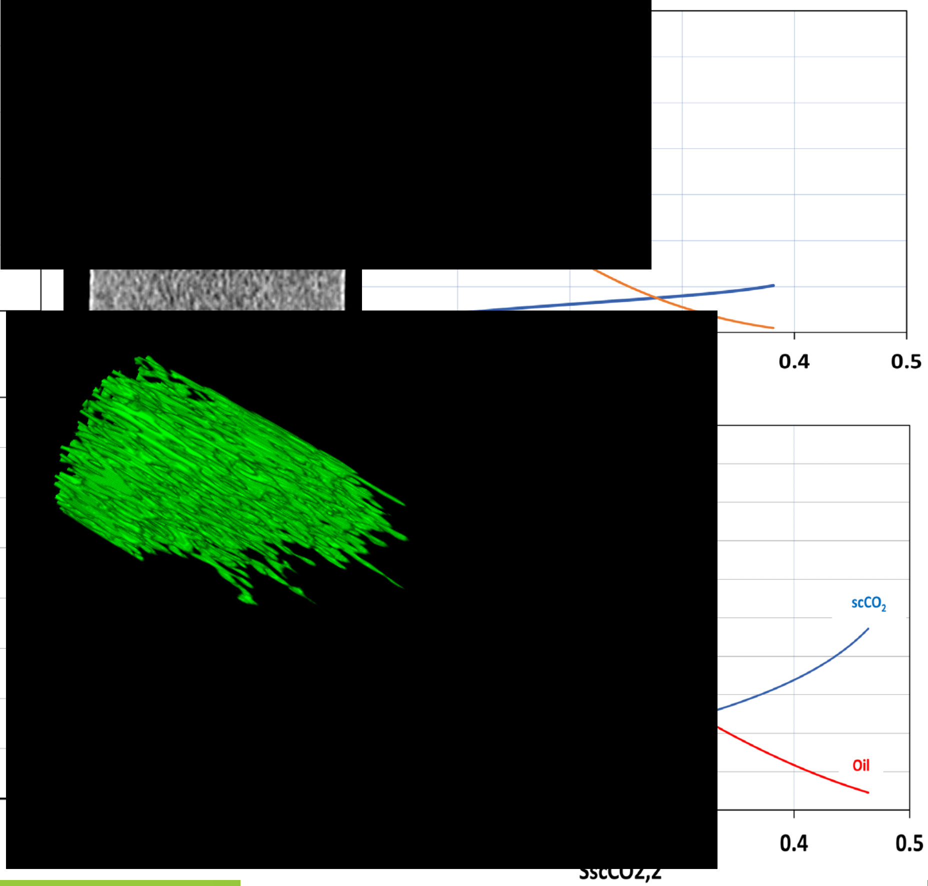
Rock name	Berea Sandstone
Absolute Permeability (k, mD)	737.45
Porosity (Ø)	0.19
Pore Volume	59.6

Bandera Brown Sandstone
261.33
0.26
74.6









Project Updates

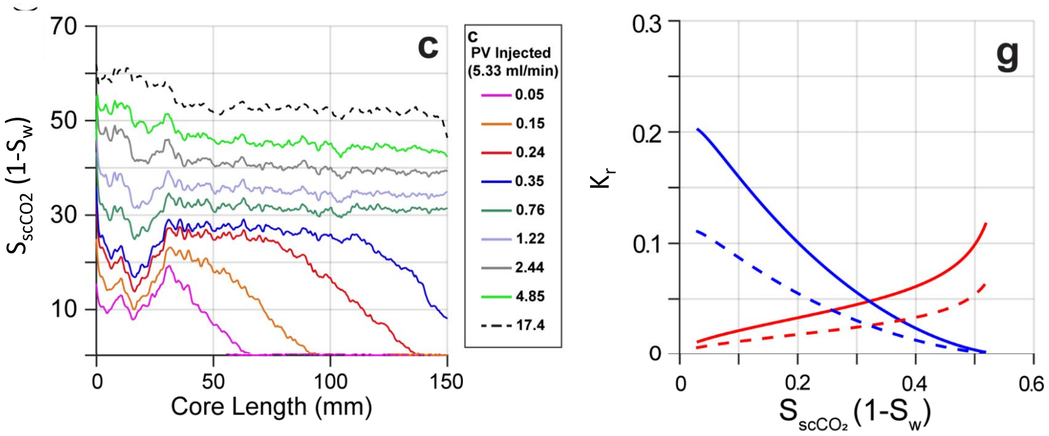
Data collection underway

- There was a slow down on these experiments due to COVID, but we recovered on time
  - Have completed 9 experiments
  - 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
  - Early on had to deal with 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 refine our image analysis protocol to accommodate, but it works

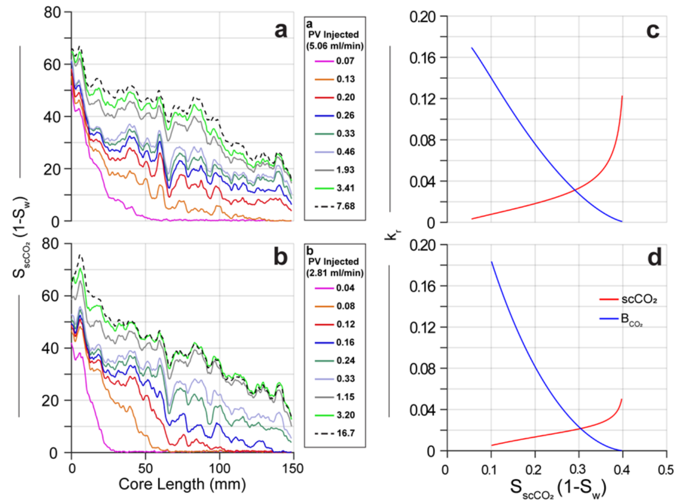
Project Final Steps

Mine data for variations flow behavior critical for Offshore HPHT environments

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



Low permeability (24 mD) Edwards Yellow



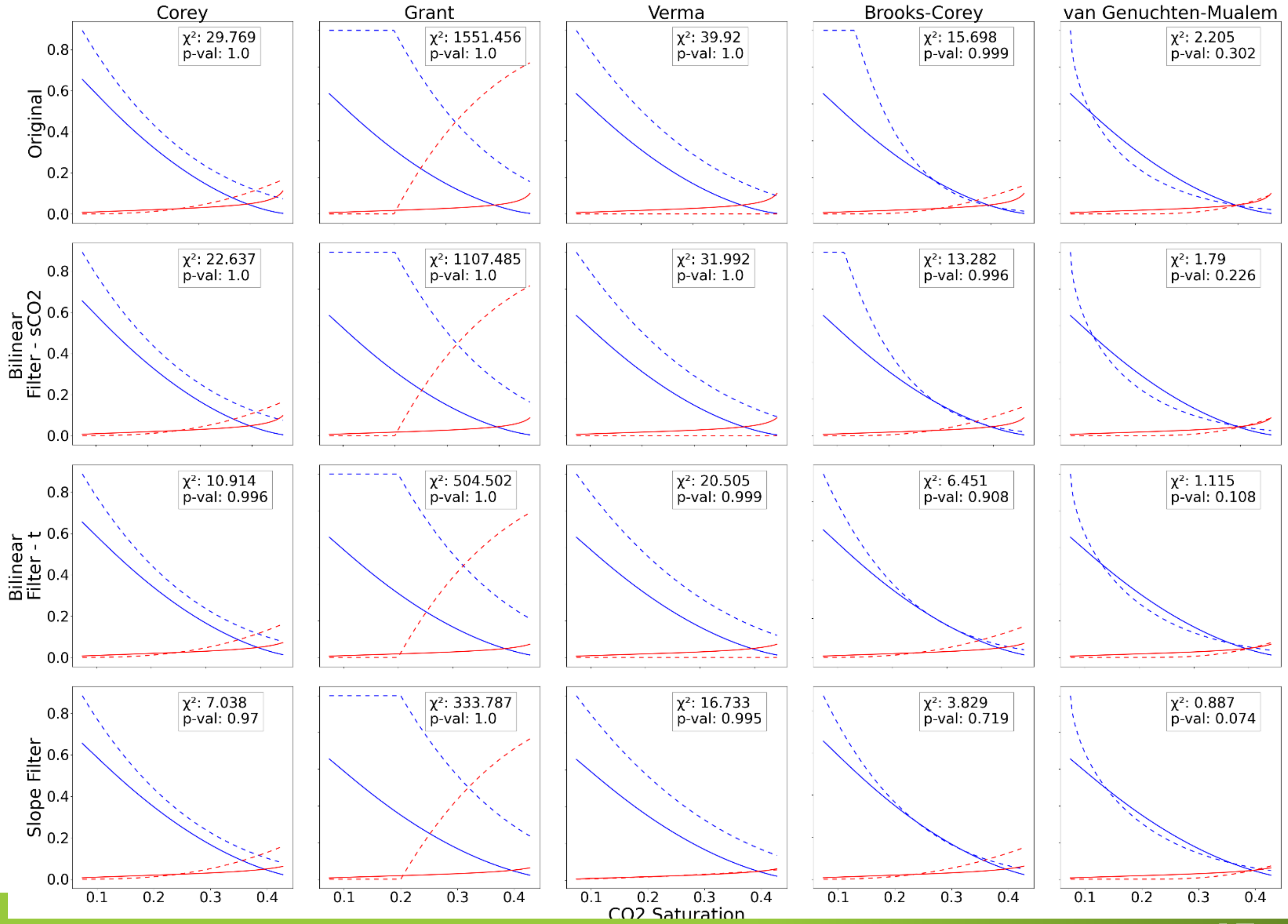
High permeability (760 mD) White Rim

Technology-to-Market Path

- Finish adding data to the CO_2BRA platform in 2022

Initial Data Mining

- **Leveraged ML 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 of representative offshore high porosity and permeability cores in HPHT enviroments, 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

Thank you

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

Thank you for your interest today!

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