Fundamental Reservoir Properties for High Priority Depositional Environments Targeted for CO_2 Storage

Carbon Storage DE-FE1022403

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National Energy Technology Laboratory

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

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Program Overview

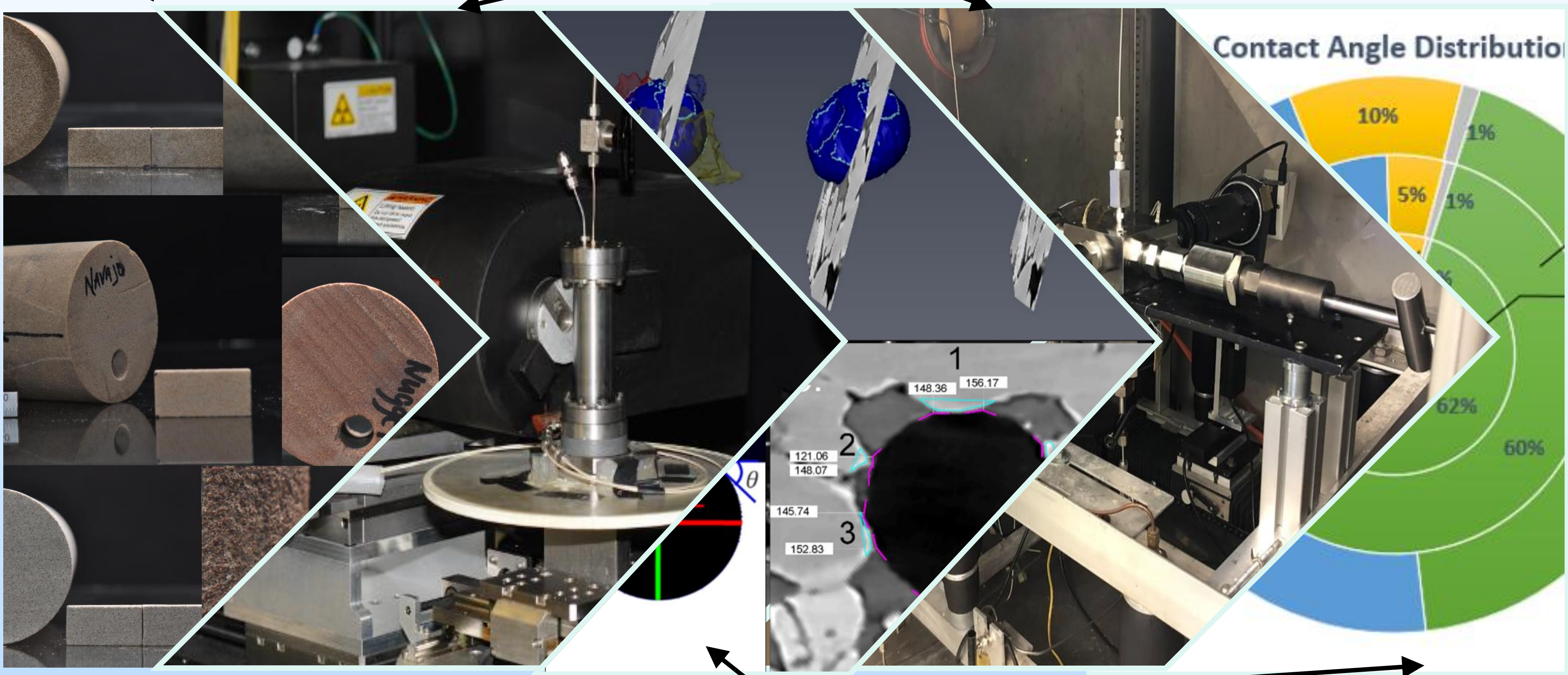
- 2016 - 2020
  - Development of fundamental understanding of how $scCO_2$ moves through, and is trapped in, storage environments.
    - $scCO_2$/brine relative permeability database published
    - $scCO_2$/brine trapping mechanisms described
    - core characterized and reports published
    - 3D printed fracture flow models developed

Program Overview

- TEAM: Angela Goodman, Johnathan Moore, Foad Haeri, Laura Dalton, Deepak Tapriyal, Sean Sanguinito, Cheng Chen, Scott Workman, Karl Jarvis, Terry McKisic, Bryan Tennant, Seth King, Jeong Choi, Fan Shi, John Baltrus, Lauren Burrows, Bret Howard, Christopher Matranga, and many more (full listing in the appendix!)
- OBJECTIVE: Understand and describe how real rocks from active and potential carbon storage locations interact with $scCO_2$ under real sequestration conditions

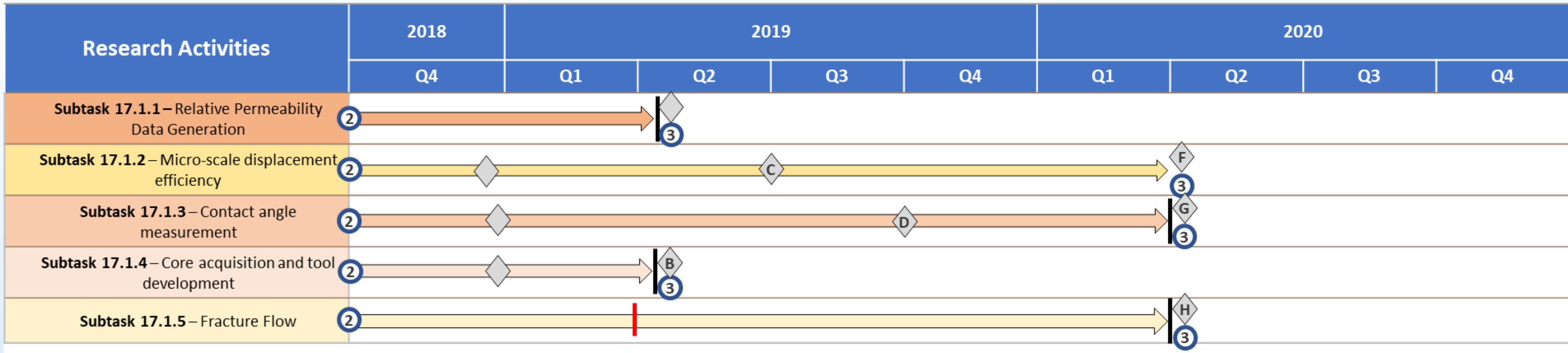
Technology Section

Real rocks, tested under carbon sequestration conditions in controlled systems.



Detailed understanding of trapping and flow, with quantified measurements.

Technical Approach/Project Scope



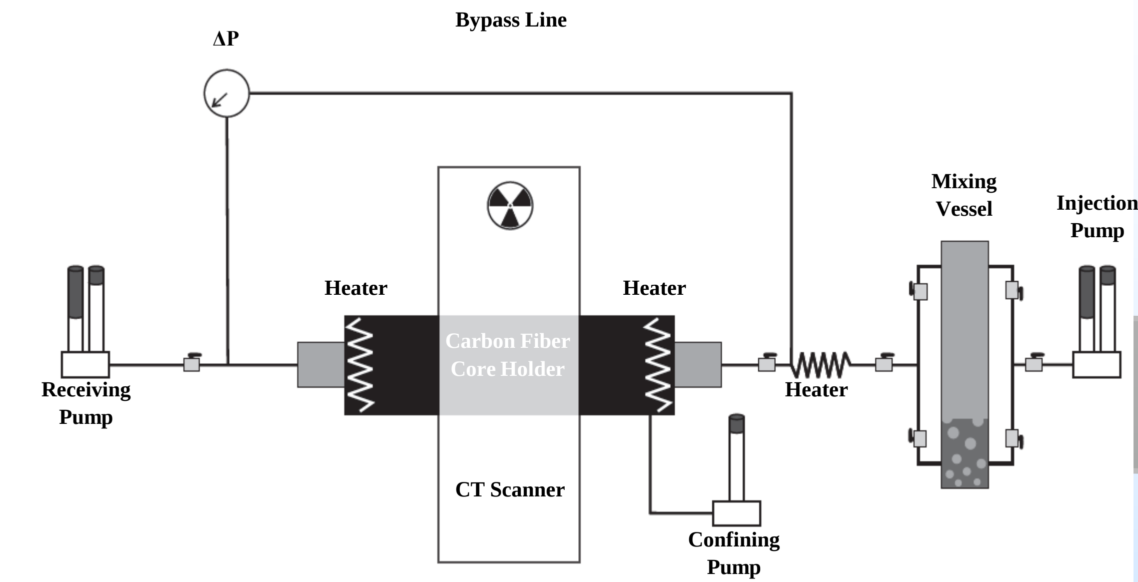
High level milestones for this project

1. Measure relative permeability of $scCO_2$/brine through various rock types and publish data and results.
2. Measure contact angles of $scCO_2$/brine in various rock types and publish results and methods.
3. Obtain core from relevant carbon storage formations, non-destructively characterize and publish technical reports on results.
4. Create 3D printed fractures from computed tomography data and show potential to directly measure flow through these systems.

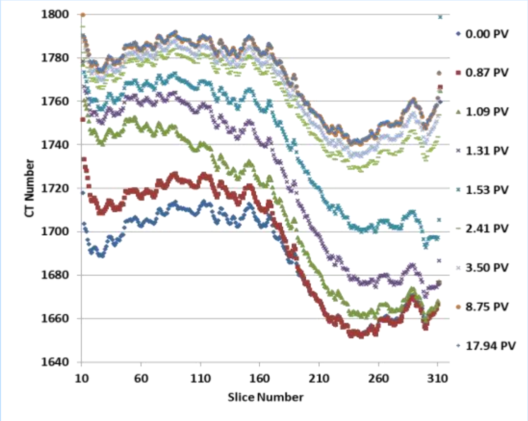
Progress and Current Status of Project

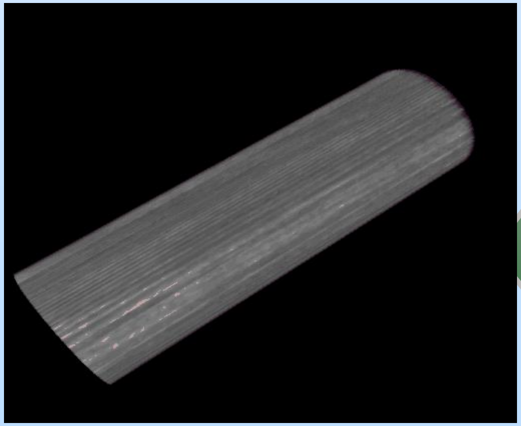
1. Relative permeability of $scCO_2$/brine in various depositional environments
    a. Relative permeability (k_r) defines the movement of multiple fluids in a porous medium. k_r is an imperfect descriptor for capturing the complexity of this behavior, but this is the nail that reservoir simulation hammers can hit.
    b. While there are multiple papers out in the public domain, there is a paucity of detailed data that enables researchers to review/confirm the accuracy of the k_r measurement process.
2. Starting in 2017, we started a series of measurements using a combination of computed tomography scanning and controlled flow systems to measure the saturation of $scCO_2$ displacing brine in various rock cores.
    a. Various flow rates were examined to determine change in flow properties due to mass flux. Not typically captured or described, but we have seen an impact.
    b. Twelve different core types, with multiple flow rates for most, tested. Results for 34 individual tests fully characterized.
    c. Core properties (XRF, baseline permeability, porosity, etc) captured.
    d. Process for calculation of k_r from raw data laid out.

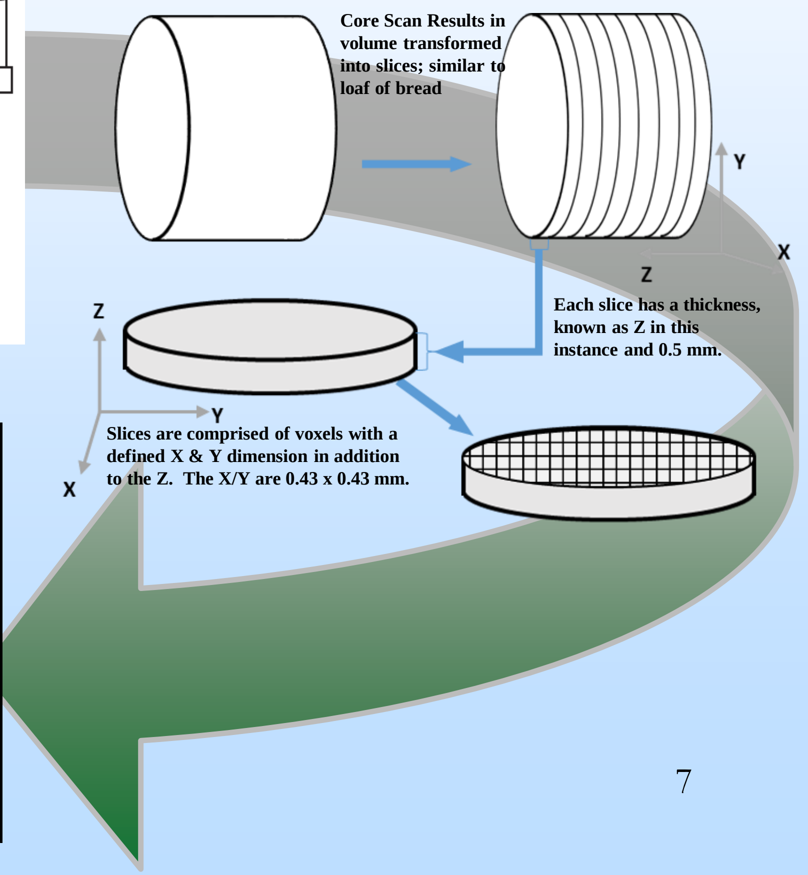
$scCO_2$/Brine Core Flow System



Experimental system flow through system inside of medical computed tomography scanner.

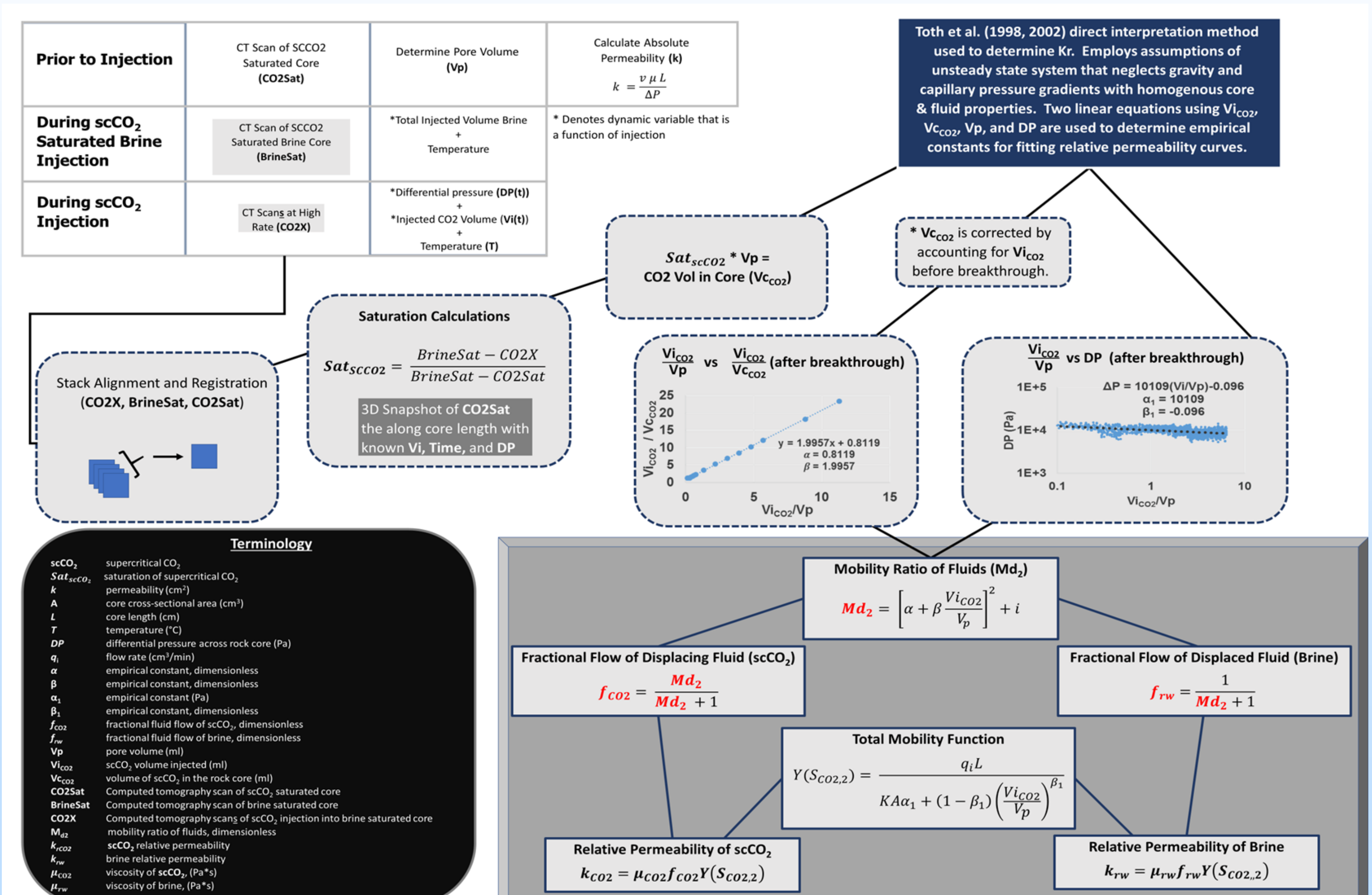






Progress and Current Status of Project

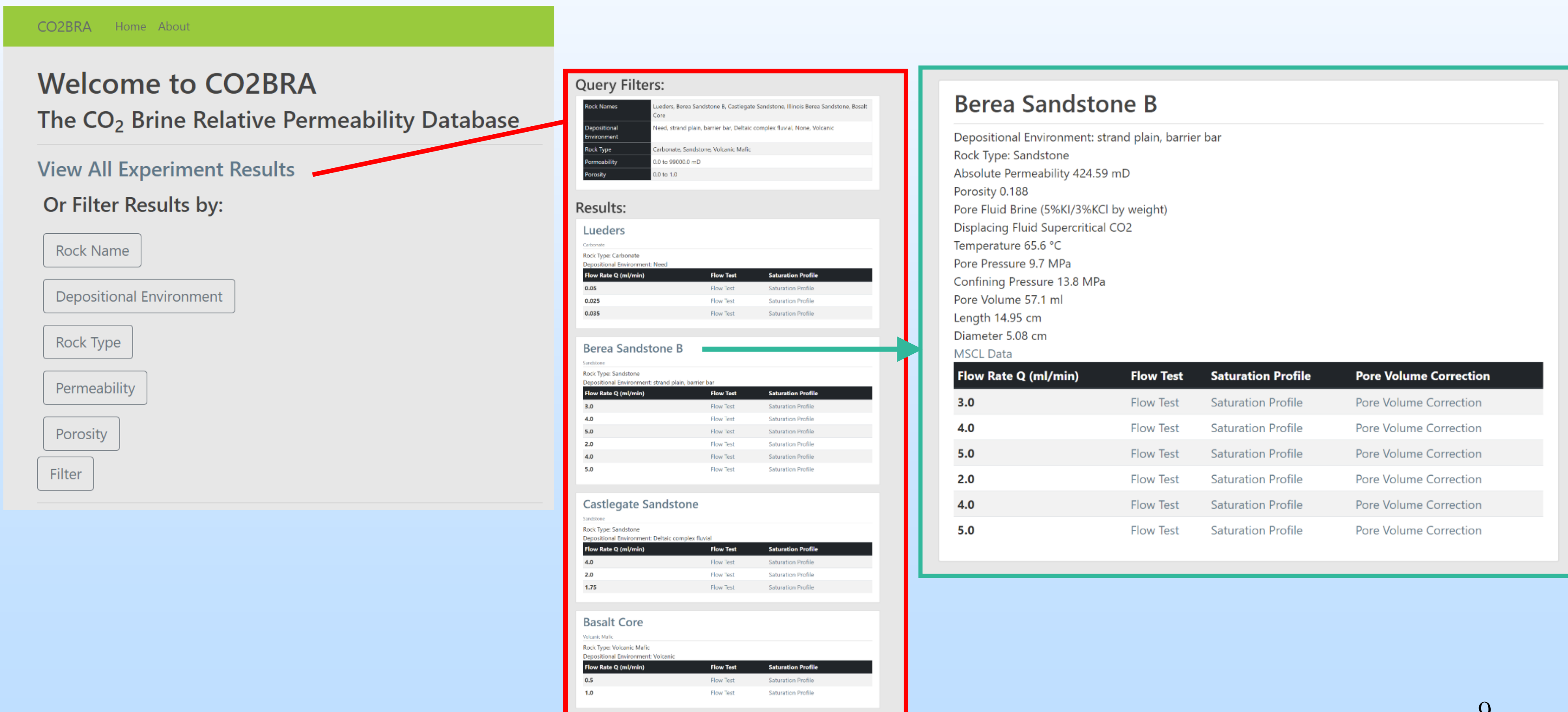
Data analysis process. Modified from Toth et al. (1998, 2002)



Progress and Current Status of Project

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

Data fully available on the **CO_2** **B**rine **R**elative Permeability **A**ccessible Database



Progress and Current Status of Project

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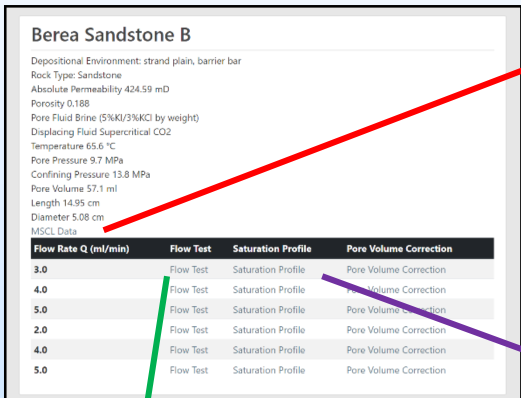
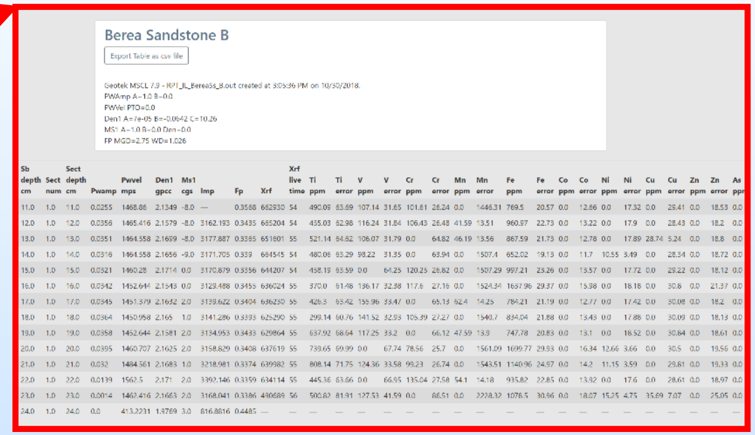
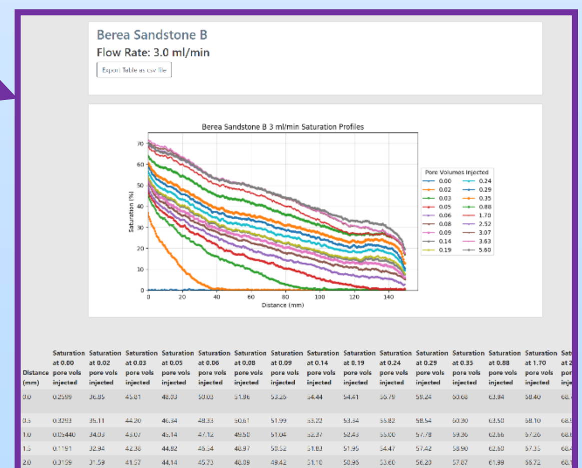




Baseline core characterization including elemental XRF, porosity, permeability and test conditions.

k_r curves and Toth et al (1998, 2002) properties for curve fitting.



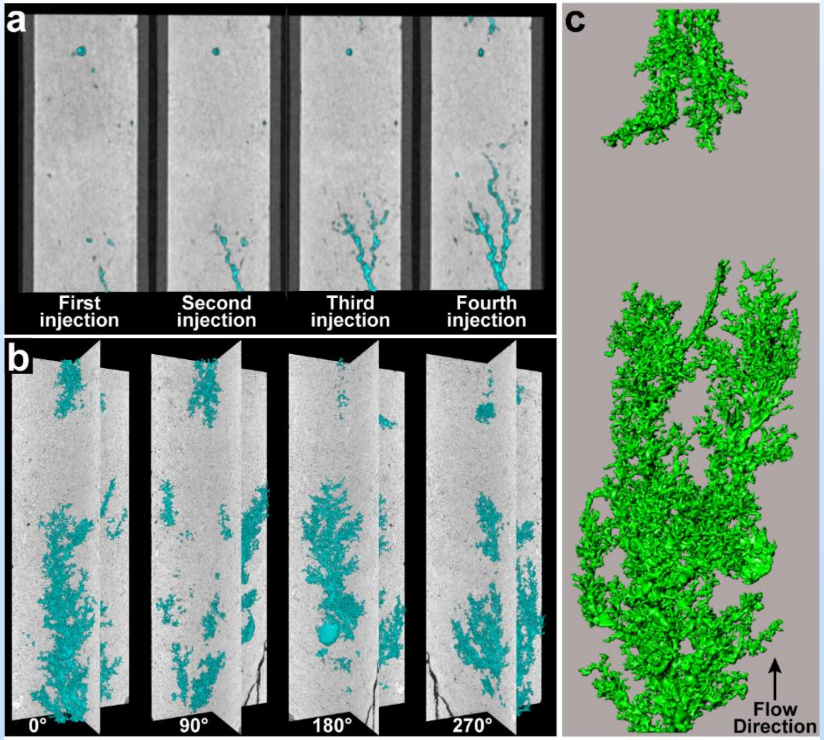
Dynamic CT derived $scCO_2$ saturation in the core.

Progress and Current Status of Project

- For the $scCO_2$/brine a peer-reviewed publication describing the methodology and results has been submitted:
  Moore, J., Holcomb, P., Crandall, D., King, S., Choi, J.-H., Brown, S., and Workman, S. (*submitted*) **Rapid determination of relative permeability curves for brine and supercritical CO_2 systems using CT and unsteady state flow methods,** *Advances in Water Resources*

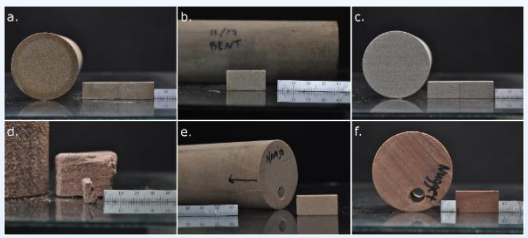
- Data is being mined for internal and external projects and publications derived from this work expected to continue for years.

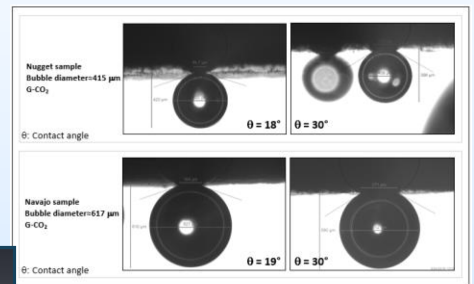
- Side project, we've been able to measure k_r as reactive flow changes the porosity of a carbonate system, which is very cool, informative, and not published elsewhere.

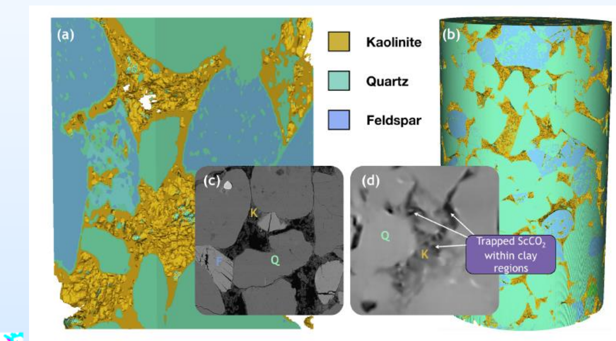


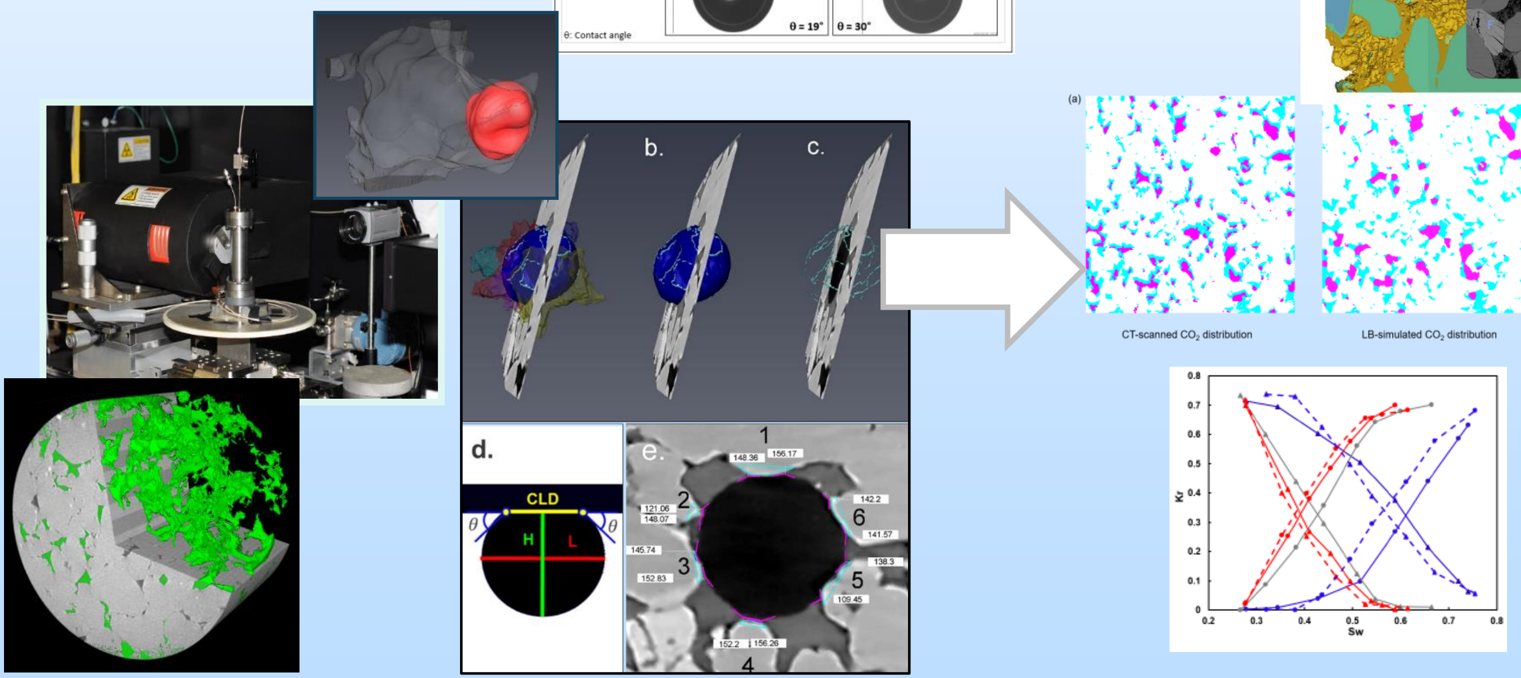
Progress and Current Status of Project

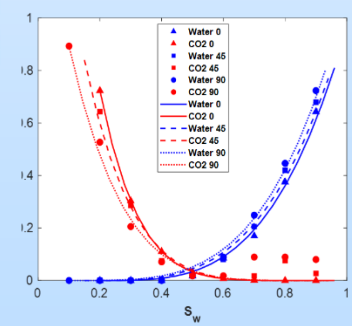
Measurement of $scCO_2$/brine contact angles under in situ conditions, both inside of pores and using traditional techniques, and coupling with pore scale simulations.





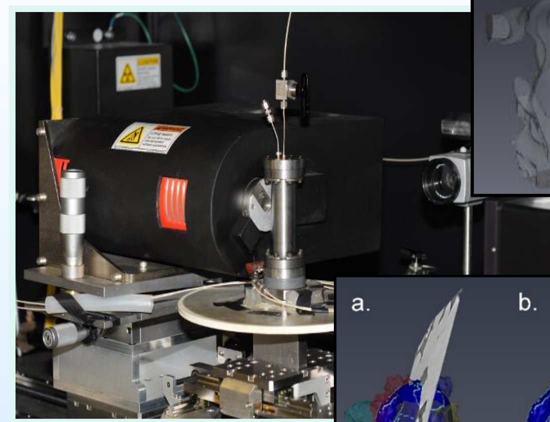


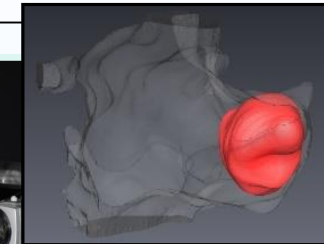


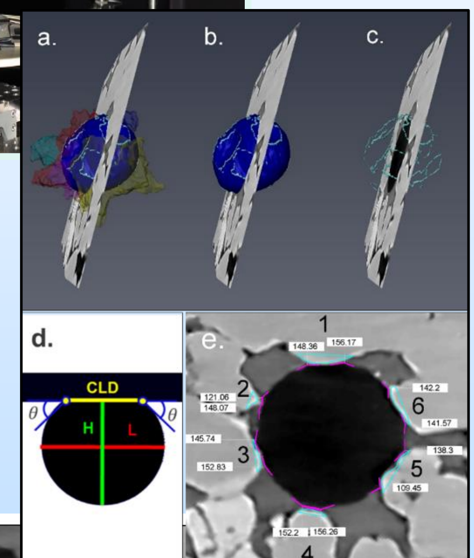


Progress and Current Status of Project

- Micro-CT scanner used to capture $scCO_2$ droplets under residual saturation conditions
  - Trapping shown to be influenced by pore structure.
  - Virtual reality used to measure angles with similar accuracy to standard methods, and faster.
  - Large variation in contact angles in situ; range of wettability types observed.
  - Additional water cycling shown to increase trapped $scCO_2$ volumes.







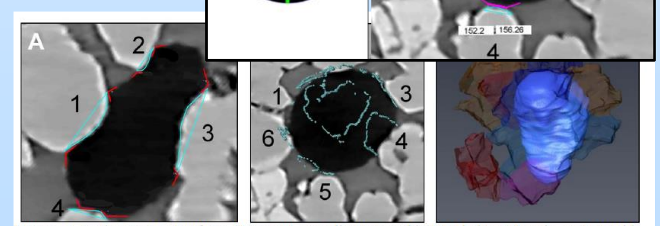
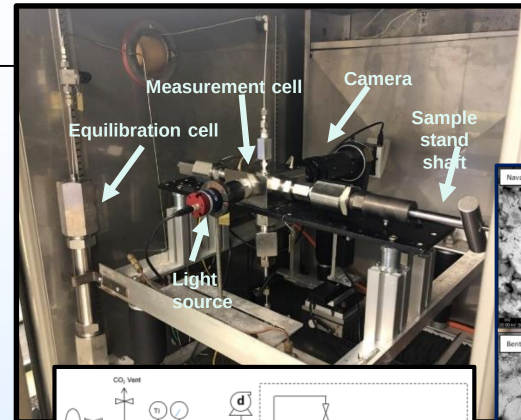
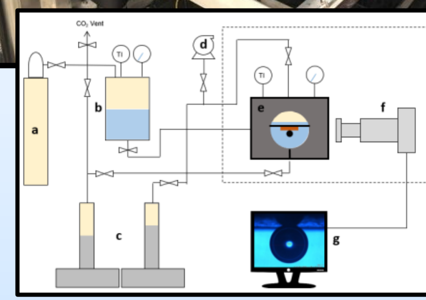


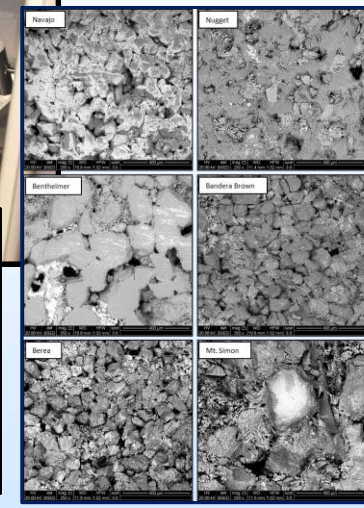
Figure 6. Grain Contact Surface: (A) $scCO_2$ ganglion trapped in Bentheimer Pore in contact with four grain surfaces (geometric contact angles are shown in red on both sides of contact); (B) same $scCO_2$ ganglion trapped in Bentheimer Pore in contact with six grain surfaces (the teal voxels represent the 3D contact line); and (C) 3D view of same pore showing ganglion in contact with six total surfaces where each color represents a different surface.

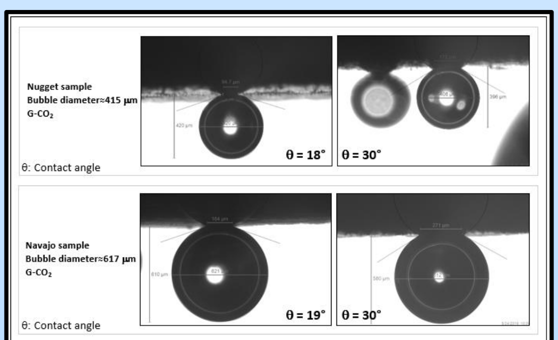
Progress and Current Status of Project

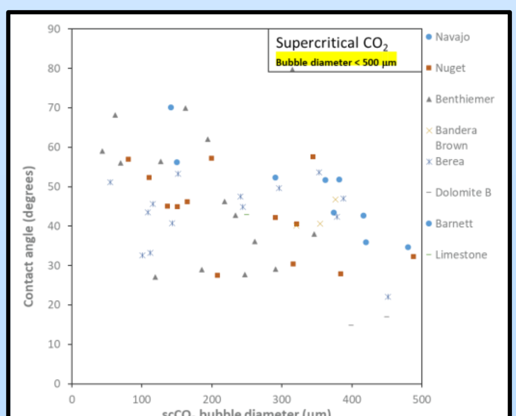
- More than 1100 sessile drop measurements of gas, liquid, and $scCO_2$
  - Samples are primarily water-wet with mean contact angle of 22˚.
  - $scCO_2$ is more wetting than liquid or gas.
  - Surface roughness and localized heterogeneity play a role in contact angle variation, particularly for small bubbles.

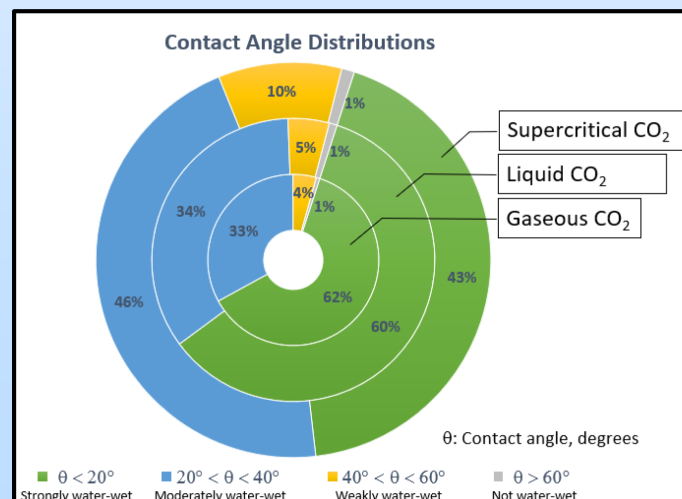








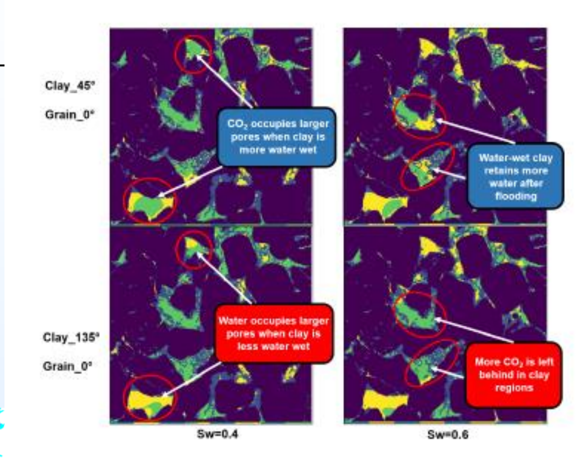


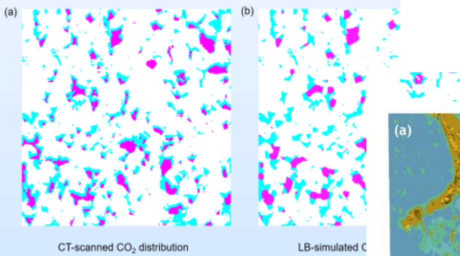


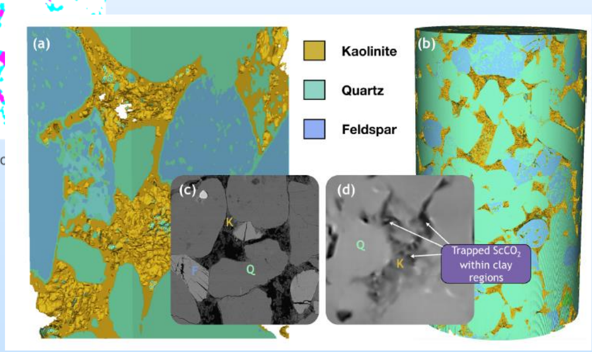
Progress and Current Status of Project

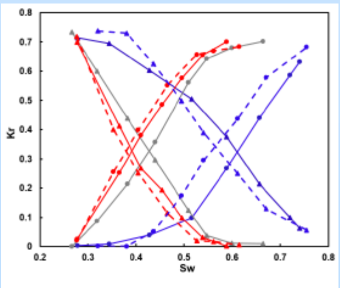
- Porting digital core data to simulations has enabled impact of contact angle to k_r examined.
  - Virginia Tech
  - Impact of localized low wettability clays shown to significantly decrease ability for $scCO_2$ migration

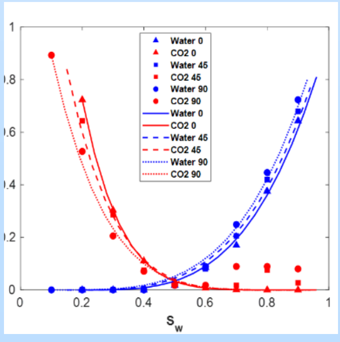
Fan, M., McClure, J.E., Armstrong, R.A., Shabaninejad, M., Dalton, L.E., Crandall, D., and Chen, C. (2020) ***Influence of Clay Wettability Alteration on Relative Permeability***, *Geophysical Research Letters* [*https://doi.org/10.1029/2020GL088545*](https://doi.org/10.1029/2020GL088545)







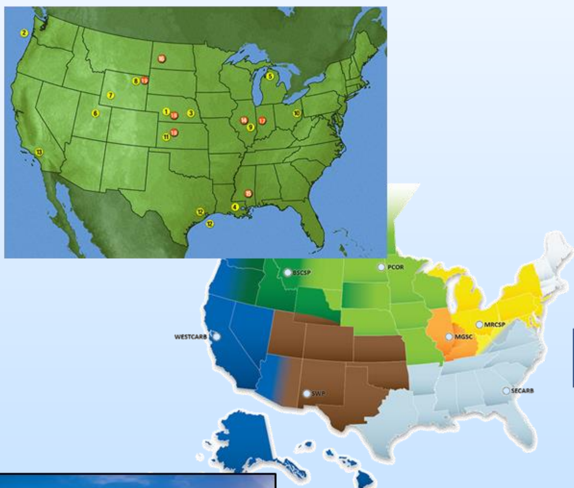


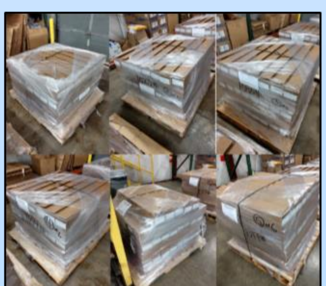


Progress and Current Status of Project

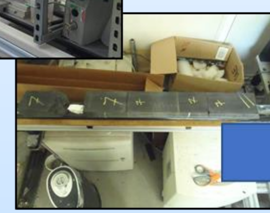
Non-destructive core characterization and public reporting of results.
Reports can be found at: https://edx.netl.doe.gov/group/core-characterization

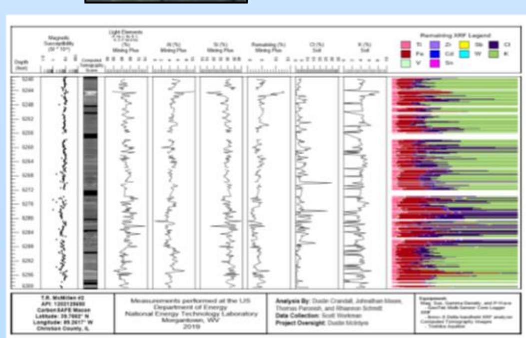
Field Projects Invest in Core Acquisition/Analysis



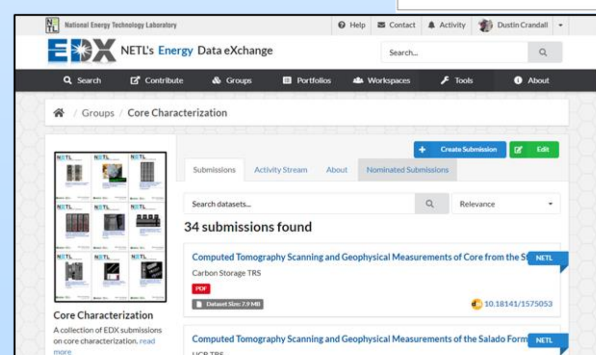


Non-Destructive Characterization Aids Projects





Public Reporting of Data and for Continuing Benefits



Summary Slide

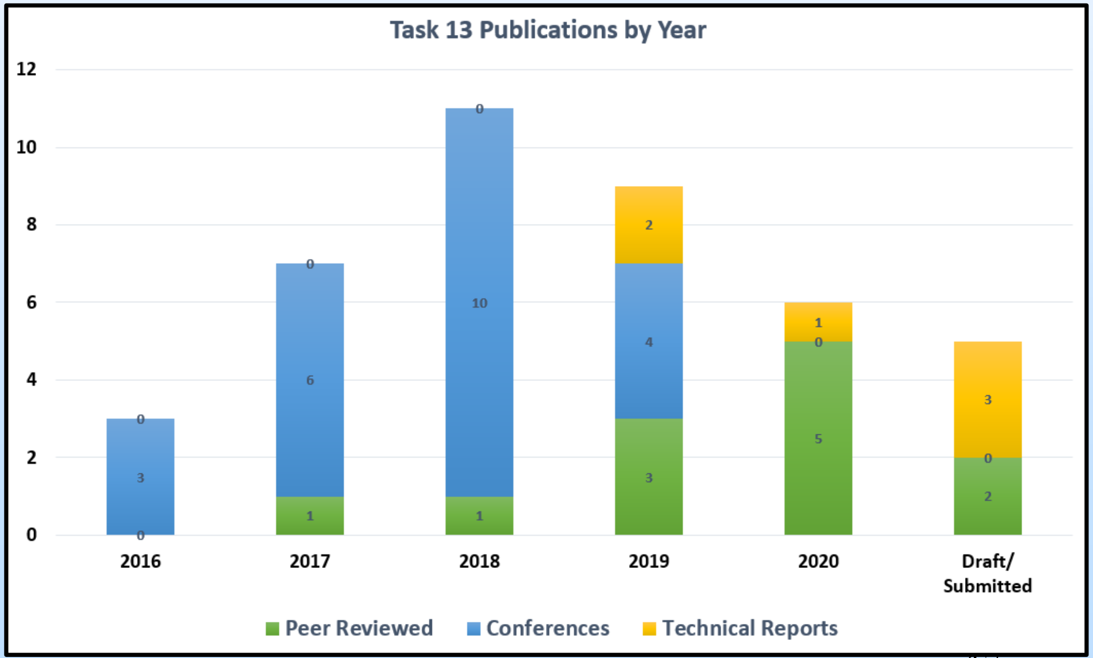
- Project ended in March 2020.
  Couple of reports and publications still working through the system.
- Full listing of publications in the presentation appendix.
  Average impact factor of journals where papers published is 3.2

Published Peer Reviewed Papers – 9

Conference Publications – 23

Published Technical Reports – 3
https://edx.netl.doe.gov/group/core-characterization

Online database of $scCO_2$/brine relative permeability data
https://edx.netl.doe.gov/hosting/co2bra/



Summary Slide

- $scCO_2$/brine relative permeability (k_r) curves developed for 12 different rocks.
  - Data made publicly available, https://edx.netl.doe.gov/hosting/co2bra/
  - Flow rate shown to influence k_r , generally higher flow rates result in more $scCO_2$ saturation and mobility.
  - Method for calculating k_r during carbonate core dissolution developed and described.
- $scCO_2$ contact angles in brine measured in cores and using sessile drop technique.
  - Pore structure and water cycling shown to influence trapped $scCO_2$ droplets.
  - Virtual reality measurement technique developed and proven.
  - Surface roughness shown to influence $scCO_2$ contact angles in sessile drops.
  - Coupling with simulations have shown influence of wettability alteration in constricting throats on k_r.
- Non-destructive core characterization of relevant carbon storage formations completed and reported on.
  - Data publicly available, https://edx.netl.doe.gov/group/core-characterization

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Technical Transfer - 1

- Peer Reviewed Publications
  - 2017
    - Tudek, J., Crandall, D., Fuchs, S., Werth, C.J., Valocchi, A.J., Chen, Y., and Goodman, A. (*2017*) ***In situ* contact angle measurements of liquid CO_2, brine, and Mount Simon sandstone core using micro-CT imaging, sessile drop, and lattice Boltzmann modeling**, J. Petrol Science, 155, 3-10 https://doi.org/10.1016/j.petrol.2017.01.047
  - 2018
    - Soong, Y., Crandall, D., Howard, B.H., Haljasmaa, I., Dalton, L.E., Zhang, L., Lin, R., Dilmore, R.M., Zhang, W., Shia, F and Mclendon, T.R., (2018) **Permeability and mineral composition evolution of primary seal and reservoir rocks in geologic Carbon Storage Conditions,** *Environmental Engineering Science*, 35 (2018) 391-400. https://doi.org/10.1089/ees.2017.0197
  - 2019
    - Dalton, L.E., Klise, K.A., Fuchs, S., Crandall, D., and Goodman, A. (*2018)* **Methods to Measure *In-Situ* Contact Angles in $scCO_2$-Brine-Sandstone Systems**, *Adv. Water Res* 122 278-290. https://doi.org/10.1016/j.advwatres.2018.10.020
    - Fan, M., Dalton, L., McClure, J., Nipepi, N., Westman, E., Crandall, D., Cheng, C. (2019) **On the interactions between the critical dimensionless numbers associated with multiphase flow in 3D porous media**, Fuel, 252 522-533 https://doi.org/10.1016/j.fuel.2019.04.098
    - Akono, A.T., Druhan, J., Gabriela, D., Tsotsis, T., Jessen, K., Fuchs, S., Crandall, D., Shi, Z., Dalton, L., Tkatch, M., Goodman, A., Frailey, S., Werth, C. (2019) A **Review of Geo-Chemical-Mechanical Impacts in Geological Carbon Storage Reservoirs**, *Greenhouse Gases: Science and Technology* https://doi.org/10.1002/ghg.1870
  - 2020
    - Davila, G., Dalton, L., Crandall, D.M., Garing, C., Werth, C.J., Druhan, J.L. (*2020*) **Reactive Alteration of a Mt. Simon Sandstone due to CO_2-Rich Brine Displacement**, *Geochimica et Cosmochimica Acta*, 271, 227-247 https://doi.org/10.1016/j.gca.2019.12.015
    - Haeri, F., Tapriyal, D., Sanguinito, S., Shi, F., Fuchs, S.J., Dalton, L.E., Baltrus, J., Howard, B., Matranga, C., Crandall, D., Goodman, A. (*2020*) **CO_2-Brine Contact Angle Measurement on Navajo, Nugget, Bentheimer, Bandera Brown, Berea, and Mt. Simon Sandstones**, *Energy & Fuels* https://doi.org/10.1021/acs.energyfuels.0c00436
    - Dalton, L.E., Tapriyal, D., Crandall, D., Goodman, A., Shi, F., Haeri, F. (*2020*) **Correlating $scCO_2$ Contact Angles to Sandstone Pore Networks using Shape Analysis,** *Transport in Porous Media* *https://doi.org/10.1007/s11242-020-01415-y*
    - Harbert, W., Goodman, A., Spaulding, R., Haljasmaa, I., Crandall, D., Sanguinito, S., Kutchko, B., Tkach, M., Fuchs, S., Werth, C., Tsotsis, T., Dalton, L., Jessen, K., Shi, Z., Frailey, S. (*2020*) **CO_2 induced geochemical and petrophysical changes in Mount Simon sandstone: Understanding links to seismic monitoring, post CO_2 injection seismicity, and reservoir integrity**, *Int J Greenhouse Gas Control 100, 103109 https://doi.org/10.1016/j.ijggc.2020.103109*
    - *Fan, M., McClure, J.E., Armstrong, R.A., Shabaninejad, M., Dalton, L.E., Crandall, D., and Chen, C. (2020)* ***Influence of Clay Wettability Alteration on Relative Permeability****, Geophysical Research Letters https://doi.org/10.1029/2020GL088545*

  - Submitted and Under Review
    - Moore, J., Holcomb, P., Crandall, D., Choi, J., and Brown, S. (*submitted*) **Rapid determination of relative permeability curves for brine and supercritical CO_2 systems using CT and unsteady state flow methods,** *Fluids*
    - Guo, R., Dalton, L.E., Fan, M., McClure, J., Crandall, D., Chen, C. (*submitted*) **The Role of Spatial Heterogeneity and Correlation Length of Surface Wettability on Multiphase Flow in 3D Porous Media**, Water Resources Research

Technical Transfer - 2

- Conferences (1)
  - 2016
    - Tudek, J., Crandall, D., Goodman, A., Kohanpur, A., and Valocchi, A. (May 2016) **Microstructure of the Mt Simon Sandstone and its interaction with simulated reservoir brine and CO2 under reservoir pressure conditions**, 8th International Conference on Porous Media & Interpore Annual Meeting, Cincinnati OH, May 9-12 2016
    - Kohanpur, A., Chen, Y., Valocchi, A., Tudek, J., and Crandall, D. (May 2016) **Comparison of lattice Boltzmann method and pore-network modeling of CO2 and brine flow in Mt Simon Sandstone**, 8th International Conference on Porous Media & Interpore Annual Meeting, Cincinnati OH, May 9-12 2016
    - Schotte, G., Shanley, K., and Crandall, D. (Nov 2016) **Effects of Geometric Variations on 2D Rough Fracture Flow**, International Mechanical Engineering Congress and Exposition, Phoenix, AZ, November 11-17, 2016
  - 2017
    - Dalton, L.E., Crandall, D., Goodman, A. (March 2017) **In situ contact angle measurements of supercritical CO_2, brine, and sandstone cores using micro-CT imaging**, 3rd Annual review meeting of the Energy Frontier Research Consortium GSCO2, March 29-30, Champaign IL
    - Tkach, M., Goodman, A., Kutchko, B., Crandall, D., Spaulding, R., Harbert, B., Werth, C., Akono, A.-T., Druhan, J., Jessen, K., Tsotsis, T. (March 2017) **Addressing geochemical alterations in reservoir rock and the impacts in seismic properties**, 3rd Annual review meeting of the Energy Frontier Research Consortium GSCO2, March 29-30, Champaign IL
    - Dávila, G., Druhan, J.L., Zahasky, C., Benson, S.M., Crandall, D.M., Werth, C.L. (March 2017) **Real-time in situ imaging of CO_2 transport and transformation through Mt. Simon reservoir core using positron emission tomography**, 3rd Annual review meeting of the Energy Frontier Research Consortium GSCO2, March 29-30, Champaign IL
    - Dalton, L., Crandall, D., Goodman, A. (August 2017) **In situ contact angle measurements of supercritical CO2, brine, and sandstone cores using micro-CT imaging**, Microscopy and Microanalysis 2017, August 6-10, St. Louis, MO
    - Brown, S., Crandall, D., Moore, J., Dalton, L., and Gill, M. (June 2017) **Characterization of CCS Potential: Implications from multi-scale computed tomographic (CT) imaging**, 2017 Gordon Research Conference on Carbon Capture, Utilization and Storage, 11-16 June, 2017, New London, NH.
    - Soong, Y. Howard, B. H., Crandall, D., Mclendon, T.R., Zhang, L., Lin, R., Dalton, L.E. and Haljasmaa, I. (August 2017) **The interactions of CO2/Brine/Rock under CO2 storage conditions**, ACS meeting, August 20-24, 2017, Washington, DC

Technical Transfer - 3

- Conferences (2)
  - 2018
    - Wang, Y., Crandall, D., Wei, N., Moore, J., Li, X., and Bromhal, G.S. (*October 2017*) **CO_2-Brine Core Flooding in Sandstone from Ordos Basin under X-Ray CT,** 2017 Geological Society of America Annual Meeting, 22-25 October, Seattle, WA
    - Dalton, L.E., Crandall, D., and Goodman, A. (*October 2017*) **Evaluation of Methods to Measure *In-Situ* Contact Angles of Supercritical CO_2 and Brine in Sandstone Cores using Micro-CT Imaging,** 2017 Geological Society of America Annual Meeting, 22-25 October, Seattle, WA
    - Dávila, G., Crandall, D., and Druhan, J. (*October 2017*) **Geochemical Alteration of Pore Structure in Mt. Simon Sandstone Resulting from Continuous Injection of CO_2-Saturated Brine**, 2017 Geological Society of America Annual Meeting, 22-25 October, Seattle, WA
    - Dávila, G., Zahasky, C., Crandall, D.M., and Druhan, J. (*December 2017)* **Reactive Alteration of Mt. Simon Sandstone during CO_2-Rich Brine Injection: A Coupled Experimental and Modeling Study**, 2017 American Geophysical Union Annual Meeting, 11-15 December, New Orleans, LA
    - Wang, Y., Crandall, D., Zhang, L., Wei, N., Li, X., Moore, J., and Bromhal, G. (*May 2018*) **Multi-scale CO_2-Brine Core Flooding under X-Ray CT in Sandstone from the Ordos Basin**, 10th Annual International Society of Porous Media Conference, May 14-18, New Orleans LA
    - Dalton, L.E., Crandall, D., and Goodman, A. (*May 2018*) **Contact Angle Measurements of $scCO_2$ and Brine in 3D Printed Models Comprised of Known Geometric Shapes with Varying Surface Roughness,** 10th Annual International Society of Porous Media Conference, May 14-18, New Orleans LA
    - Dalton, L.E., King, S., Fuchs, S., Crandall, D., and Goodman, A. (*May 2018*) **Manual and Automated *In-Situ* Contact Angle Measurements of $scCO_2$ and Brine in Sandstone Cores using Micro-CT Imaging – A Correlation to Pore Connectivity**, 10th Annual International Society of Porous Media Conference, May 14-18, New Orleans LA
    - Goodman, A., Dalton, L., Tapriyal, D., and Crandall, D. (*October 2018*) **Contact Angles in scCO2-Brine-Sandstone Systems Using Sessile Drop and Micro-CT Imaging**, 2018 AIChE Annual Meeting, October 28 – November 1, Pittsburgh PA.
    - Fan, M., Dalton, L., McClure, J.E., Ripepi, N., Westman, E., Crandall, D., Chen, C. (*December 2018*) **On the interactions between the critical dimensionless numbers associated with multiphase flow in 3D porous media**, 2018 AGU Fall Meeting, December 10-14, Washington D.C.
    - Brown, S., Crandall, D., Moore, J., Mackey, P., Paronish, T. (*December 2018*) **Rapid Core Characterization**, 2018 AGU Fall Meeting, December 10-14, Washington D.C.
  - 2019
    - Mofakham, A.A., Ahmadi, G., Crandall, D. (*August 2019*) **Supercritical CO_2 Flows in Brine Saturated Fractured Reservoirs,** ASME Fluids Engineering Conference, July 28 – August 1, San Francisco CA
    - Moore, J., Crandall, D., Choi, J.H., King, S. (August 2019) **Fundamental Reservoir Properties for High Priority Depositional Environments Targeted for CO_2 Storage**, Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, August 26-30, Pittsburgh PA
    - Crandall, D., Brown, S., Moore, J., Paronish, T., Mackey, P., Schmitt, R., Vornlocher, J., Betters, C. (August 2019) **Digital Core Characterization**, Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, August 26-30, Pittsburgh PA
    - Fan, M., Dalton, L.E., McClure, J., Ripepi, N., Westman, E., Armstrong, R., Crandall, D., Chen, C. (August 2019) **Interactions between the critical dimensionless numbers associated with multiphase flow in 3D porous media**, Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, August 26-30, Pittsburgh PA

Technical Transfer - 4

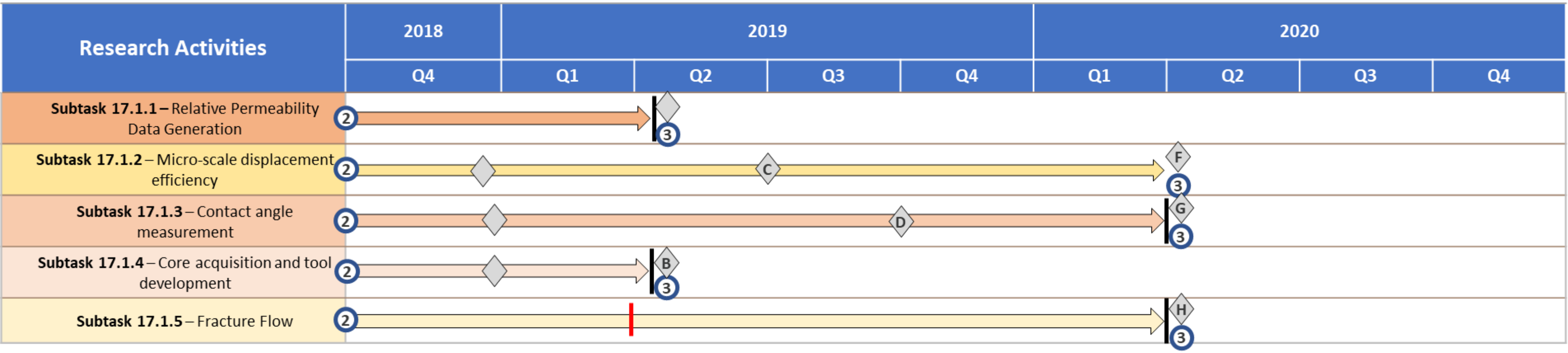
- Published Technical Reports
  - Mackey, P.; Brown, S.; Paronish, T.; Crandall, D.; Moore, J. (*2019)* **Computed Tomography Scanning and Geophysical Measurements of the FutureGen FGA-1 Core,** NETL-TRS-6-2019; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2019; p 80. DOI: 10.18141/1543132.
  - Vornlocher, J.; Betters, C.; Paronish, T.; Crandall, D.; Moore, J.; Schmitt, R.; Harrison, III, W. B. **Computed Tomography Scanning and Geophysical Measurements of Core from the State Charlton #4-30 Well**; NETL-TRS-7-2019; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2019; p 64. DOI: 10.18141/1575053.
  - Schmitt, R.; Paronish, T.; Crandall, D.; Moore, J.; Freiburg, J.T.; Whittaker, S. **Computed Tomography Scanning and Geophysical Measurements of the T.R. McMillen #2 Well**; NETL-TRS-4-2020; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2020; p 32 DOI: 10.18141/1605344.

- Draft Reports
  - CarbonSAFE Wabash core has been scanned
  - Wellington 1-32 and 2-32 wells scanned and draft reports being generated
    - CO_2 site run by Kansas Geological Survey in the queue

Organization Chart

- Dustin Crandall, Angela Goodman, Christopher Matranga, Bret Howard, John Baltrus, Yee Soong – US DOE NETL
- Johnathan Moore, Foad Haeri, Laura Dalton, Deepak Tapriyal, Sean Sanguinito, Karl Jarvis, Tom Paronish, Sarah Brown, Terry McKisic, Seth King, Jeong Choi, Fan Shi, Lauren Burrows – LRST NETL
- Rhiannon Schmitt, Paige Mackey, John Tudek, William Harbert – ORISE NETL
- Jamie Vornlocher, Charity Betters – MLEF NETL
- Scott Workman, Bryan Tennant – SOS NETL
- Samantha Fuchs – ORISE NETL/UT Austin
- Cheng Chen, Ruichang Guo, Ming Fan, James McClure – UCFER NETL/Virginia Tech

Gantt Chart



Milestones

1 - Perform final full relative permeability tests of depositional environments at $scCO_2$ conditions. (April '19)

2 - Complete lattice Boltzmann simulations of $scCO_2$/brine flow through umCT geometry at conditions of experiment. (December '18)

3 - Development of relative permeability curves from lattice Boltzmann simulations that illustrate the influence of contact angle variation. (July '19)

4 - Submission of peer reviewed manuscript that describes the influence of contact angle variation on trapping efficiencies in reservoirs. (April '20)

5 - Complete shakedown of reactor cell and perform 6 in situ contact angle measurements on a synthetic mineral substrate. (December '18)

6 – Completed contact angle measurements of $scCO_2$/brine on reservoir rocks (June '19)

7 - A written report and slide deck of how this approach can be used to correlate surface chemistry, surface composition, and surface roughness with wettability and relative permeability. (December '19)

8 – Report on core characterization of reservoir core submitted. Tool updated with new results. (December '18)

9 - Final relative permeability values incorporated into tool. (March '19)

10 – Calculation of relative permeability curve in 3D printed fracture from experimental data. (April '19)

11 – Experiments in 3D printed fracture completed with 3 different pairs of immiscible fluid. (September '19)

12 - Submission of manuscript describing the influence of fracture properties on multiphase flow transport. (April '20)

Chart Key

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

Go / No-Go

Full descriptions in subtask details.

17.1.2 – Dec '18 No-Go if simulated results do not match experimental results.

17.1.3 – March '19 No-Go if experimental results do not provide insight into surface chemistry, roughness, and composition.

17.1.5 – March '19 No-Go if k_r curves in 3D printed fracture not obtained

Impact

Accomplishments	Value Delivered
Fundamental measurements of CO_2/brine/reservoir rock to understand how trapping and flow occurs at real conditions	Functional, open, and comprehensive database of flow parameters needed for accurate reservoir simulation

Key Accomplishments/Deliverables	Value Delivered
• Over the past year five different depositional environments have been successfully tested using the techniques developed at NETL. • Fundamental measurements of scCO2 contact angles were obtained inside pores and with traditional methods: • 3D printed model of a CT scanned rock fracture was developed and used to test flow properties.	• The product of this work is to deliver a database with measurements of relative permeability, residual saturation, and wettability for high priority depositional environments targeted for CO_2 storage and accessible tools for reservoir modelers to access this data and reduce uncertainty in their estimates.