Driving Innovation ♦ Delivering Results

Reservoir Performance
RIC Storage FY2016-2020 – Task 2

Johnathan Moore
NETL/AECOM

Thursday August 18, 2016

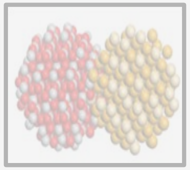
Presentation Outline

- Project background and context within portfolio
- Project overview and structure
- High-level results across task
- Detailed discussion on $scCO_2$ relative permeability measurements
- Synergy opportunities
- Summary
- Mandatory appendix

NETL's R&IC Carbon Storage Portfolio

Enhancing Effectiveness and Reducing Uncertainty in Long-Term CO_2 Storage and Efficiency

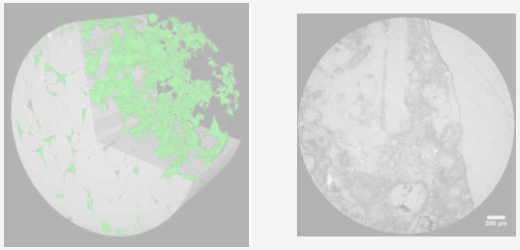
CO_2 Reuse
- Novel Systems for CO_2 Conversion



Monitoring CO_2/Brine Plumes and Groundwater Impacts
- Develop and Demonstrate Tools and Protocols for Detection of CO2/Brine Interface and Groundwater Monitoring

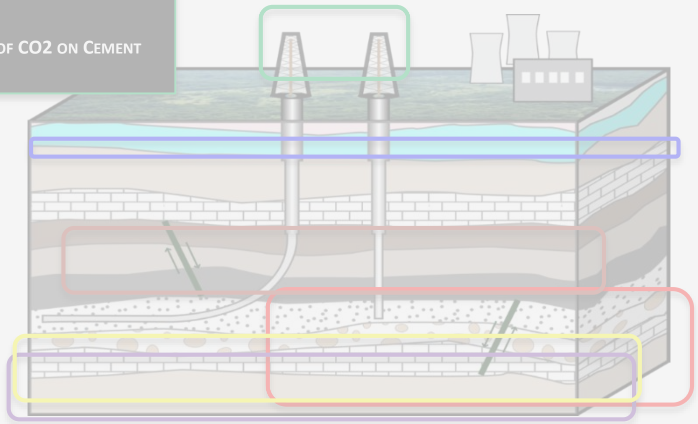
MVA Field Activities
- Support Large-Scale Field Activities

Reservoir Performance
- Experimental measurements of Relative Permeability, Residual Saturation, and Porosity needed For Reservoir simulations

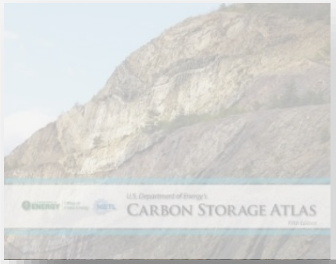


Wellbore Integrity and Mitigation
- Evaluate Geochemical Impacts of CO2 on Cement

SubTER
- DOE Crosscutting Subsurface Technology



Shales as Seals and Unconventional Reservoirs
- Improve characterization of shales as seals and storage reservoirs



NATCARB
A National Look at Carbon Sequestration
Regional Carbon Sequestration Partnerships

Resource Assessments and Geospatial Resources (EDX and NATCARB)
- Develop Defensible DOE Storage Methods for the Onshore and OffShore
- Develop, Maintain, and Utilize Geospatial Platforms to Support CO2 Storage research

EDX Energy Data eXchange

Benefit to the Program

- **Program goals addressed:**

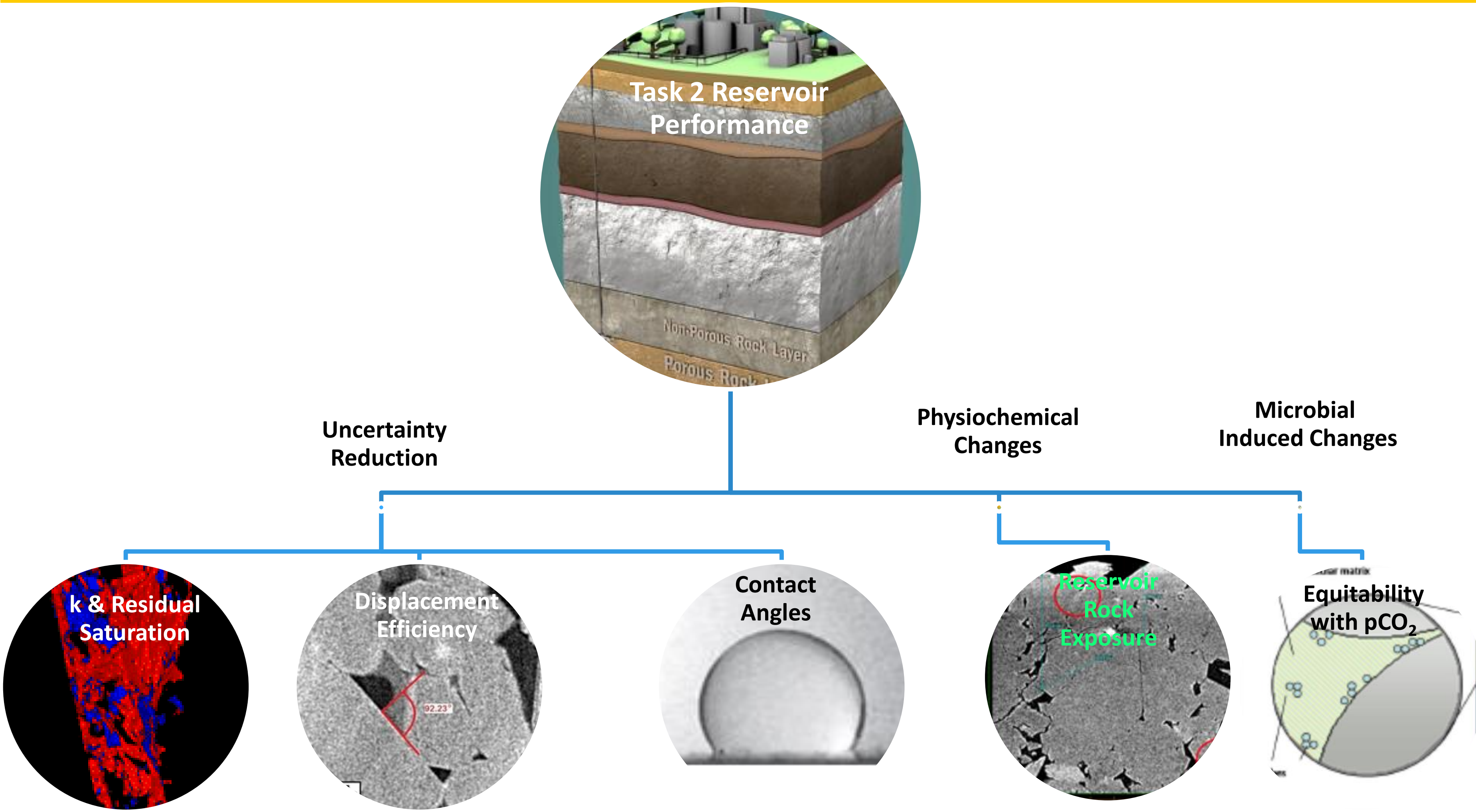
  Develop technologies that ensure safe, secure, efficient, and cost effective CO_2 containment in diverse onshore and offshore applications, protecting the environment for commercial readiness by 2030.

- **Project benefits statement:**

  The research project includes basic research to understand the interaction of CO_2 in geologic storage applications. **Long term exposure tests on reservoir and seal formations**, analysis of the **impact of CO_2 plumes on microbiological communities**, and **reductions in efficiency factor** uncertainty are the primary goals of this task.

  This research contributes to the Carbon Storage Program's efforts to develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness and support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30%.

Project Overview



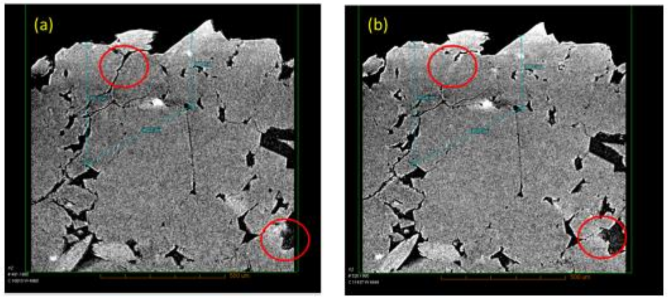
Project Overview: Goals and Objectives

Improve assessments of CO_2 storage for key reservoir classes by providing experimental measurements of critical properties at in situ conditions and characterizing critical property changes as CO_2 interacts with the reservoirs and seals.

1. **Impact of CO_2/brine exposure on seal/reservoir rock examined**
   Long term interaction experiments continue to yield results/publications on real rock at real conditions.
2. **Subsurface microbial community resilience to CO_2 injection studied**
   The ability to analyze metagenomics and perform genomic sequencing of subsurface microbial communities in CO_2 enriched environments is now possible at NETL, and the results are providing insight into the impact of CO_2 on various sub surface environments.
3. **Uncertainties in CO_2 migration properties being quantified experimentally**
   Relative permeability & wettability measurements of CO_2/brine/reservoir rock is ongoing with improved NETL infrastructure to accurately measure these poorly understood, yet **critical, characteristics of GCS**.

(1) CO_2-Brine-Rock Chemistry

- Long term interactions at subsurface T&P of CO_2+brine with reservoir and sealing formations are rarely performed
- Batch reaction tests have been performed at T&P (and are ongoing) examining relevant formations for changes in permeability and structure after six months of exposure
  - Mount Simon (two locations from IGS): FutureGen proposed injection
  - Lower Tuscaloosa Sandstone and Selma Chalk: Cranfield site, Plant Daniel/SECARB injection site
  - Lawson Formation: Tampa Electric Co proposed injection site, Florida
- Core permeability and porosity measured before after
- Subsample XRD, SEM, and CT scanning before & after



(1) CO_2-Brine-Rock Chemistry

Formation	T (°C)	P (MPa)	Pre-k (mD)*	Post-k (mD)*	Pre-ϕ (%)	Post-ϕ (%)
Mt Simon 1 (Vermillion Co)	85	23.8	1.6	0.85	7.9	6.3
Mt Simon 2 (Knox Co)	85	23.8	20-130	25-240	1.4	1.1
Tuscaloosa	85	23.8	2175-2250	1880-2000	26.8	25.0
Selma Chalk	85	23.8	2-2.8	0.9-2.7	12.4	13.0
Lawson	85	23.8	58-64	TBD	25.9	TBD

* Permeability ranges over various effective pressures

- Core scale changes in reservoir k & ϕ generally show a small changes
- Linkage to the constituents of the formations to observed changes and surface precipitation as measured by SEM is being combined across tests

(1) CO_2-Brine-Rock Chemistry

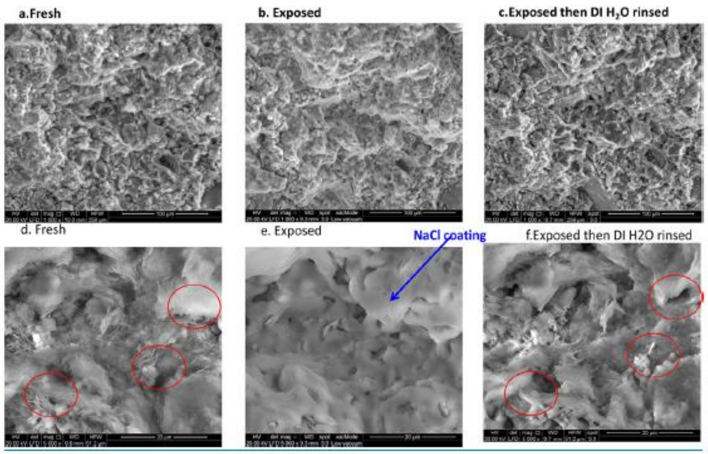


Figure 4. The SEM images of the Lower Tuscaloosa sandstone fresh (a,d) vs. exposed (b,e) to CO_2/brine for six months. (c, f) images of (b,e) rinsed with DI water a second time to remove residual NaCl.

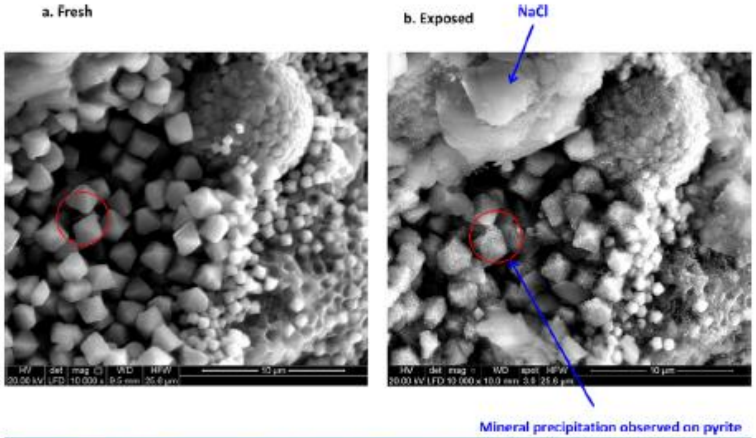


Figure 7. The SEM images of the Selma chalk sample fresh (a) vs. exposed to CO_2/brine for six months (b).

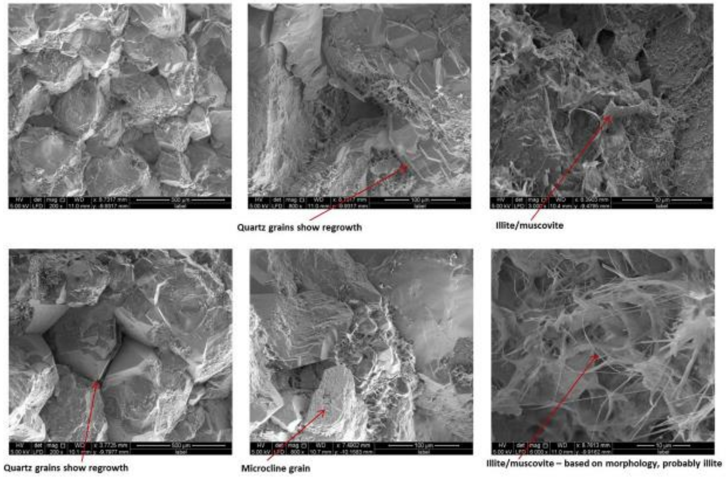


Fig. 1. The SEM images of fresh sandstone obtained from Vermillion County, IN.

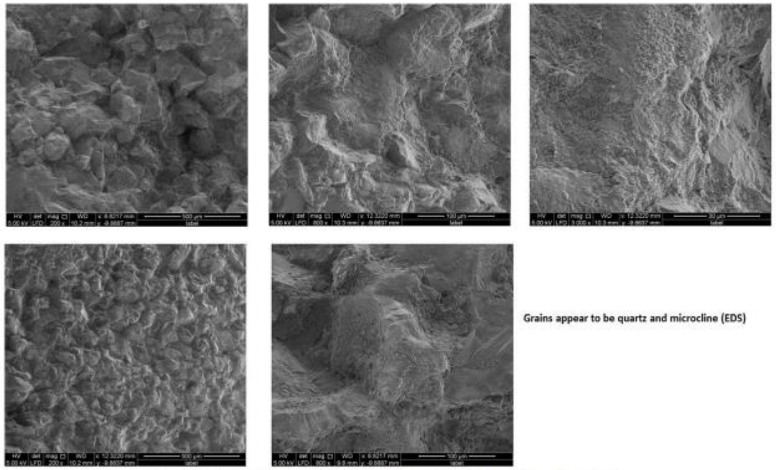
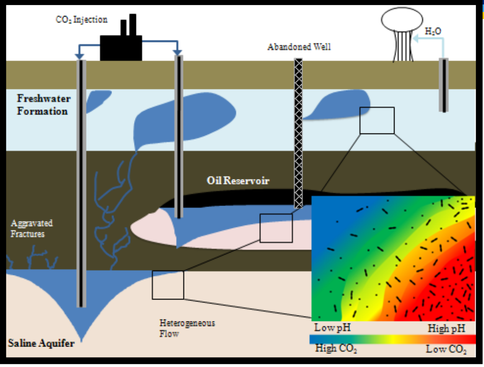
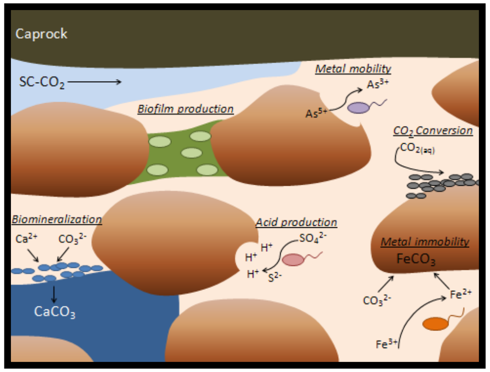


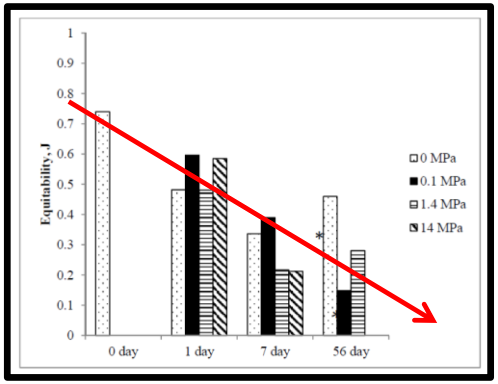
Fig. 2. The SEM images of fresh sandstone obtained from Knox County, IN.

(2) Microbial Response to CO_2

- Understand how CO_2 exposure will impact subsurface microbial communities at T & P that is relevant to GCS and CO_2 leakage scenarios.
  - Microbial communities were examined in fluid samples and suspended solids from the proposed carbon storage site: Plant Daniel, injecting into the Arbuckle Aquifer, Kansas
  - Microbial were exposed to 0, 0.1, 1.4 & 14 MPa pCO_2 for 1, 7 and 56 days of exposure (Gulliver et al 2016)
  - Results show that increasing pCO_2 decreases microbial diversity (right).



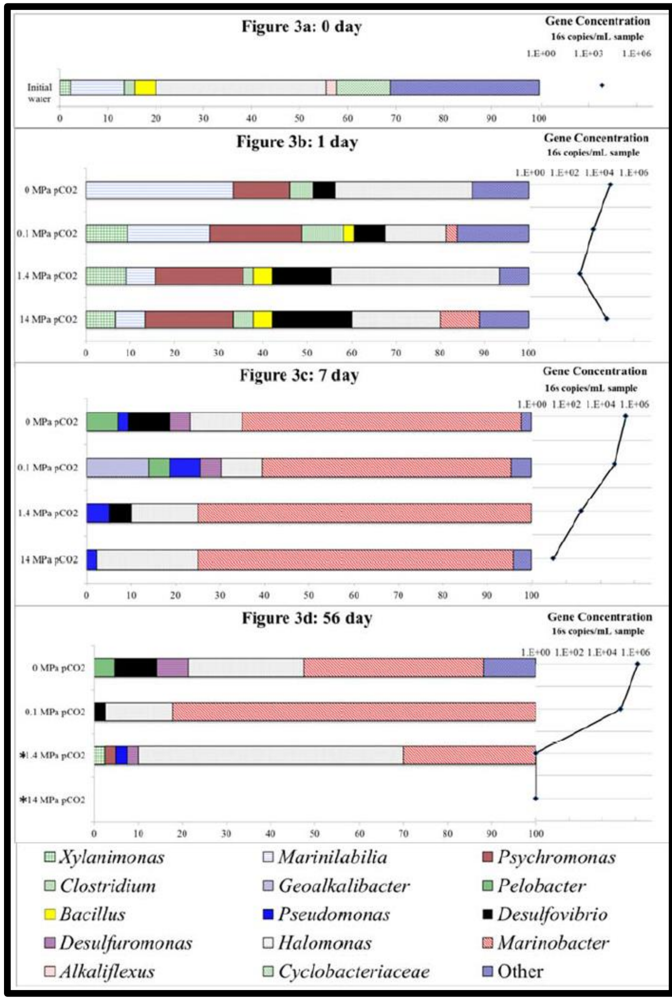




Gulliver, D. M.; Gregory, K. B.; Lowry, G. V. *Impact of CO2 on the Evolution of Microbial Communities Exposed to Carbon Storage Conditions, Enhanced Oil Recovery, and CO2 Leakage*; NETL-TRS-7-2016; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Pittsburgh, PA, 2016; p 64.

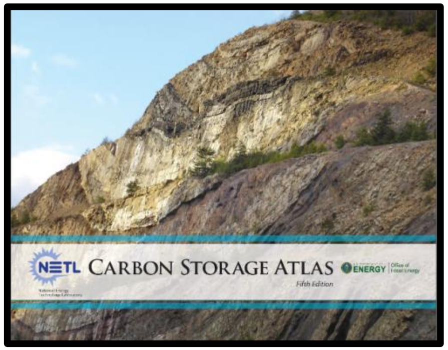
(2) Microbial response to CO_2

- Fewer unique 16S rRNA genes were recovered over both increasing exposure times and increasing pCO_2 greater than 0.1 MPa.
- In order to separate the impact of CO_2 exposure versus the corresponding pH reduction, the microbial communities were exposed to chemically reduced pH without CO_2.
  - Microbial population is highly dependent on the pH with minimal viable population at exposures above 0.1 MPa. The selected CO_2-resilient community is specific to the Arbuckle Aquifer.
- **Concurrent work with different sites further demonstrates pH affects the microbial population size, but the CO_2-selected microbial communities are unique to each site.**



(3) $scCO_2$ transport uncertainty

- **Why continue research on $scCO_2$ transport?**
  - With 15+ years of active research in this area, there are still fundamental questions that remain unanswered.
    - What is the contact angle of $scCO_2$ in formations of interest?
    - How do we determine geologic properties that can be measured to the physical parameters needed to describe k_r?
    - What is the appropriate curve fit for this relationship?
    - How do we want to be able to implement these at the reservoir scale - - - Storage Efficiency Factor



$$G_{CO2} = A_t \, h_g \, \phi_{tot} \, \rho \, E$$

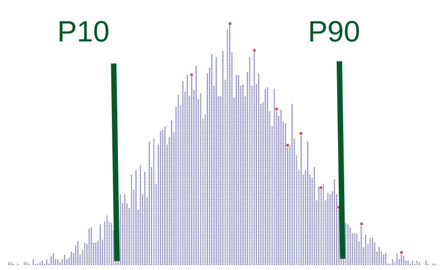
$$E_{saline} = E_{An/At} \, E_{hn/hg} \, E_{\phi e/\phi tot} \, E_v \, E_d$$

Source: Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B.,and Guthrie, G. "U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control (2011)

(3) $scCO_2$ transport uncertainty

$$E_{saline} = E_{An/At} \, E_{hn/hg} \, E_{\phi e/\phi tot} \, E_v \, E_d$$

- **Direct linkage of $scCO_2$ k_r to volumetric and microscopic efficiency terms**
- **Reduction in the P_{10}/P_{90} values of these terms via direct measurement of the processes influencing displacement is the goal of this subtask**



Term	Symbol	P_{10}/P_{90} Values by Lithology			Description
		Clastics	Dolomite	Limestone	
Geologic terms used to define the entire basin or region pore volume					
Net-to-Total Area	$E_{An/At}$	0.2/0.8	0.2/0.8	0.2/0.8	Fraction of total basin or region area with a suitable formation.
Net-to-Gross Thickness	$E_{hn/hg}$	0.21/0.76*	0.17/0.68*	0.13/0.62*	Fraction of total geologic unit that meets minimum porosity and permeability requirements for injection.
Effective-to-Total Porosity	$E_{\phi e/\phi tot}$	0.64/0.77*	0.53/0.71*	0.64/0.75*	Fraction of total porosity that is effective, i.e., interconnected.
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector.					
Volumetric Displacement Efficiency	E_V	0.16/0.39*	0.26/0.43*	0.33/0.57*	Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in-situ water.
Microscopic Displacement Efficiency	E_d	0.35/0.76*	0.57/0.64*	0.27/0.42*	Fraction of pore space unavailable due to immobile *in-situ* fluids.

*Values from IEA (2009)/Gorecki (2009)

(3) $scCO_2$ transport uncertainty

- **Basic properties**
  - Contact angle/wettability
  - Relative permeability in different formations
- **How to address**
  - Fundamental experiments where we can control/view the system of interest
    - Lab scale
    - Reservoir conditions
    - Time efficient
  - Database of Parameters

Lithology	Depositional Environment
Clastics	Clastics
Dolomite	Dolomite
Limestone	Limestone
Clastics	Alluvial fan
Clastics	Delta
Clastics	Eolian
Clastics	Fluvial
Clastics	Peritidal
Clastics	Shallow shelf
Clastics	Shelf
Clastics	Slope basin
Clastics	Strand plain
Limestone	Peritidal
Limestone	Reef
Limestone	Shallow shelf

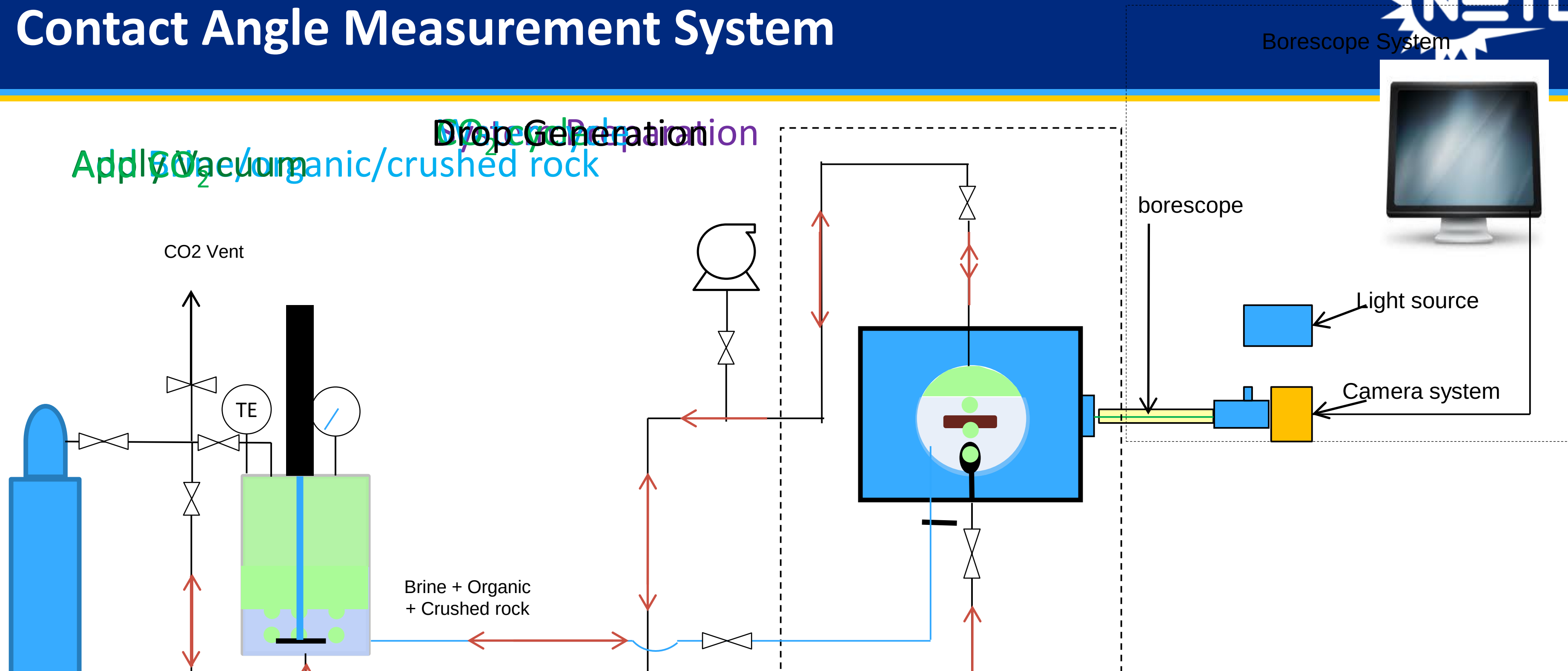
IEA, 2009/13. Development of Storage Coefficients for CO2 Storage in Deep Saline Formations, IEA Green house Gas R&D Programme (IEA GHG) October.

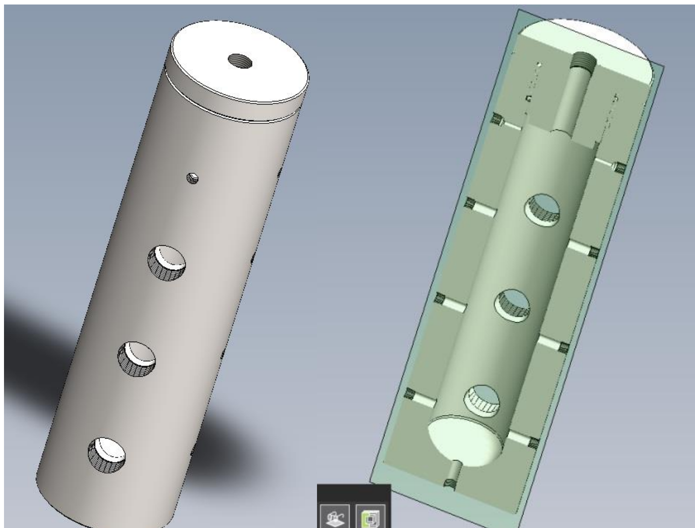
(3) $scCO_2$ transport uncertainty

Contact Angle Measurement System

Drop Generation

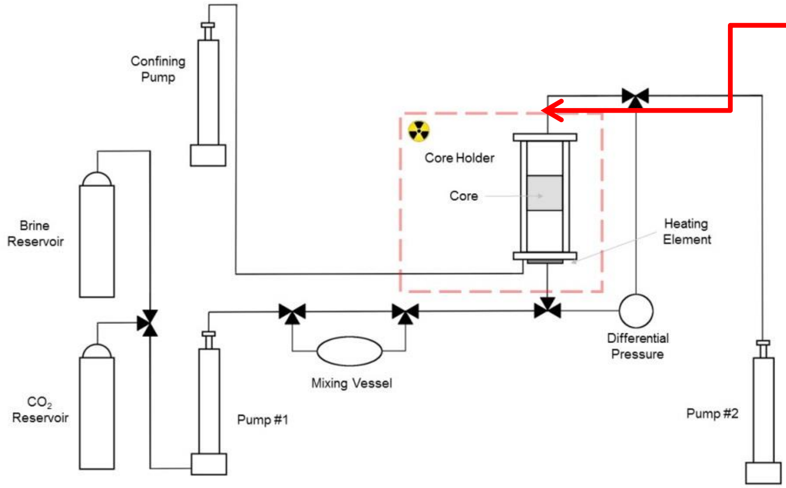
Apply Vacuum

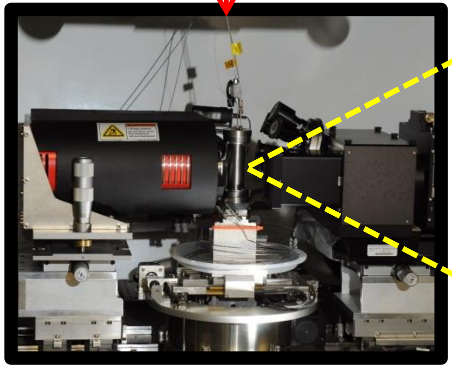


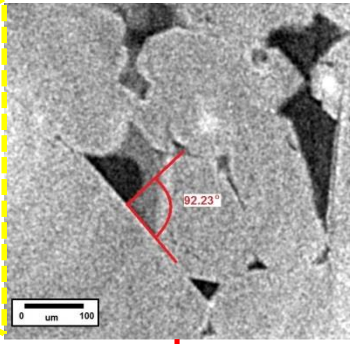


(3) $scCO_2$ transport uncertainty

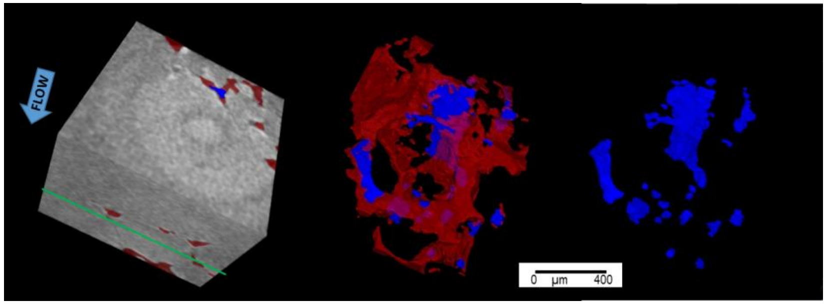
CT – Displacement Efficiency and Contact Angles

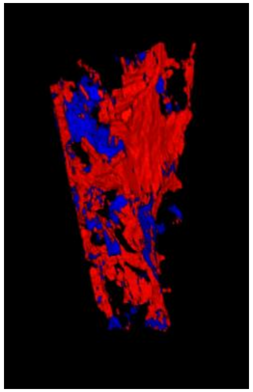


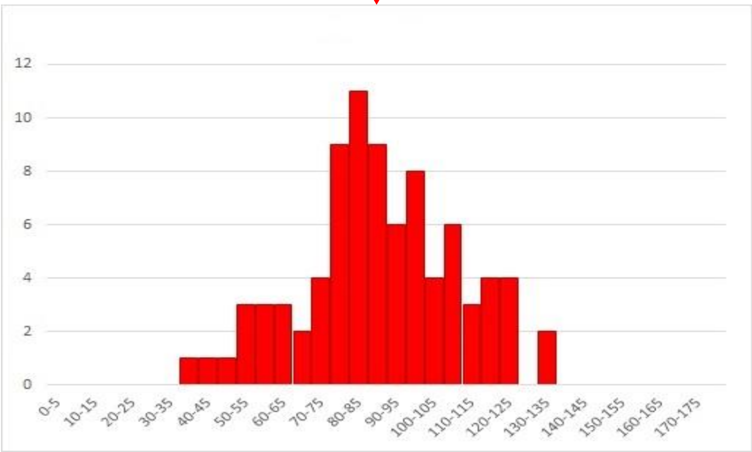




A series of images deconstructing an imaged cube. Left is the entire cube. Center is both CO2 (red) and brine (blue). Right is brine.



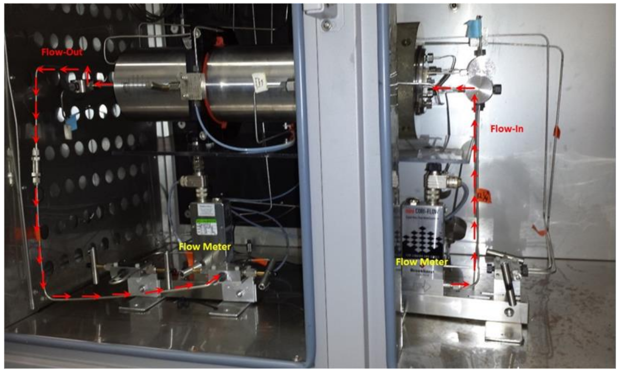


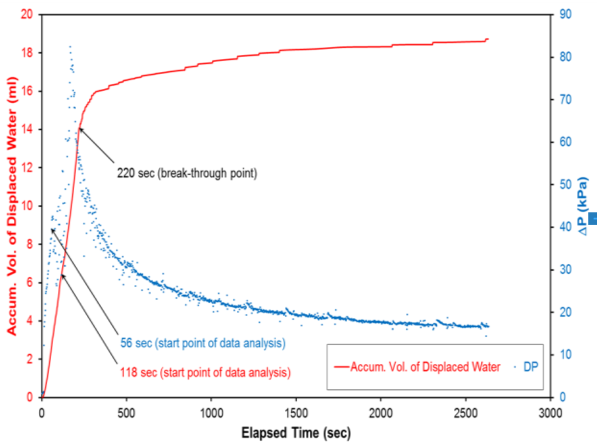


(3) $scCO_2$ transport uncertainty
k_r Measurements & Residual Saturation

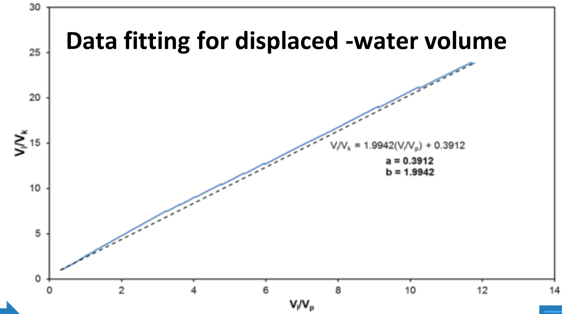
$scCO_2$ Relative Permeability (kr) laboratory measurements improve fidelity in simulations of fluid flow through storage reservoirs

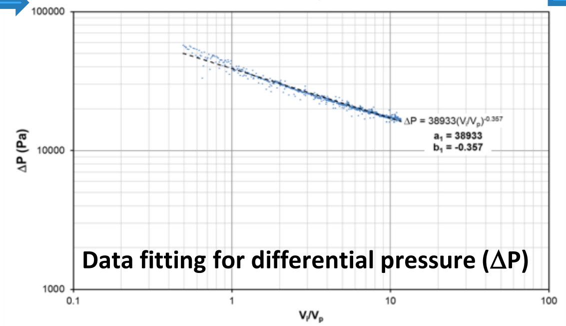
- Upgraded core-flow test system (with Coriolis mass flow meters): enables measurements of effluent fluid-volume change under pressure and temperature applied to core sample
- $scCO_2$-water rel. permeabilities of Berea sandstones under a subsurface condition (P = 10.3 MPa; T = 50 °C)

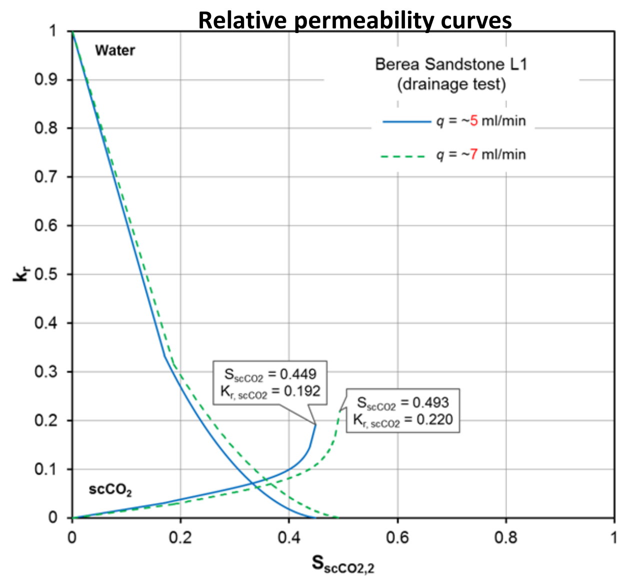




Accumulated displaced-water volume and differential pressure (ΔP) from unsteady-state test

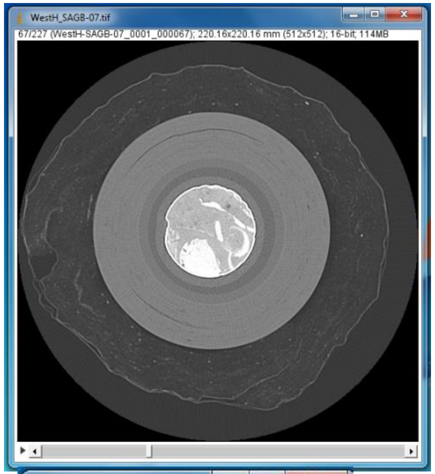


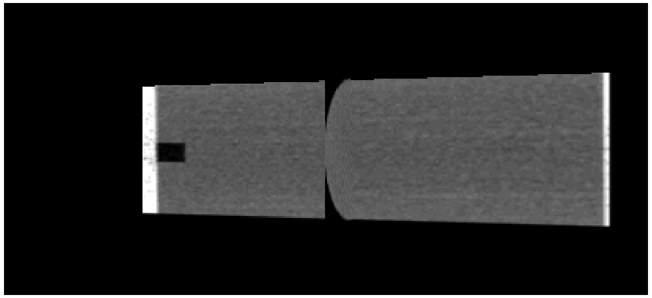


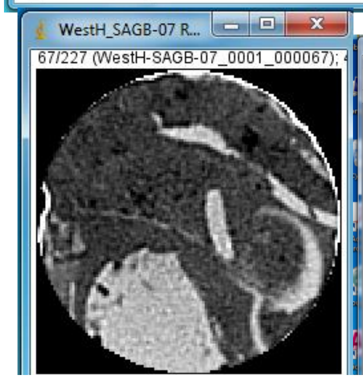


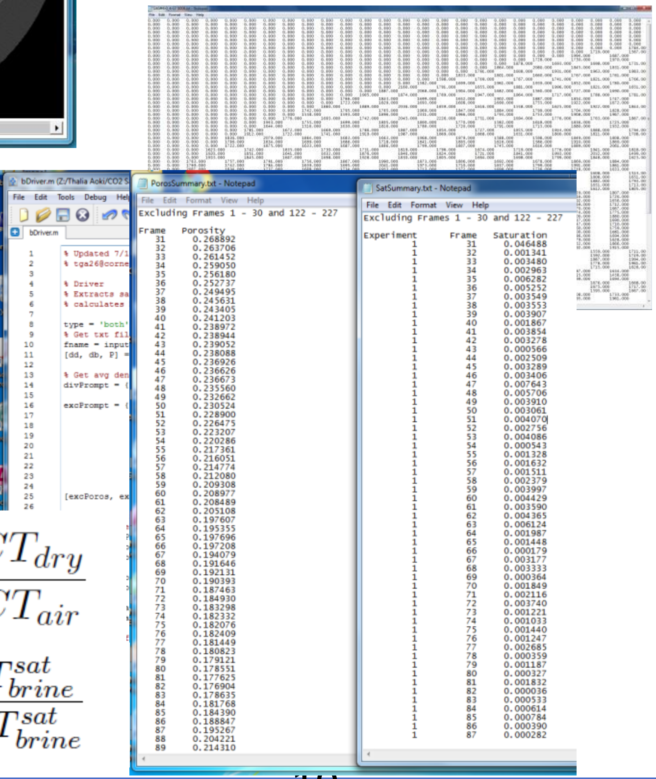
(3) $scCO_2$ transport uncertainty

CT Scanning to Measure Saturation



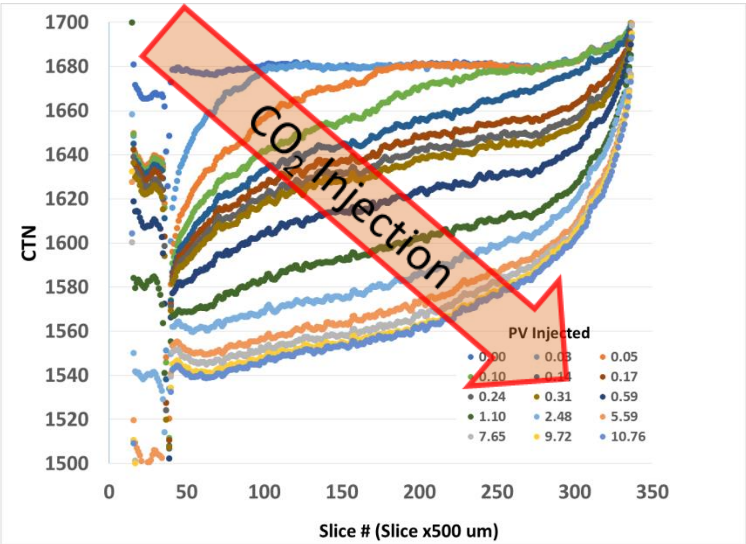


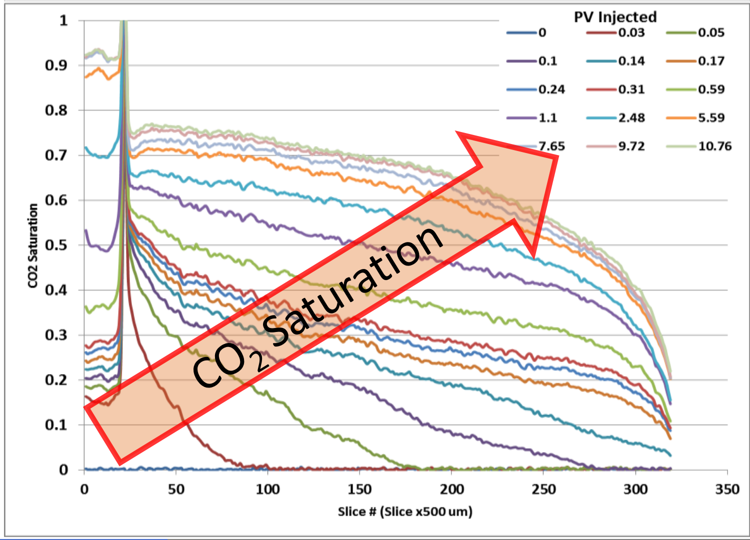




$$\Phi = \frac{CT_{brine}^{sat} - CT_{dry}}{CT_{brine} - CT_{air}}$$

$$S_{CO_2} = \frac{CT_{exp} - CT_{brine}^{sat}}{CT_{CO_2}^{sat} - CT_{brine}^{sat}}$$





Accomplishments to Date

- **CO_2-brine-rock chemistry impact on storage formations and seals**
  - TECO and FutureGen(Mt. Simon) cores currently being exposed and being analyzed
    - Moderate reductions; mostly invariant
- **Microbial Responses to CO_2**
  - Two publications in peer review & TRS
  - Completed micro-model experiments
  - Enhanced metagenomics characterization equipment
- **Uncertainty Reduction**
  - Contact angle/wettability system construction underway
  - Kr methodologies and experimental develop still ongoing in MGN
  - Kr methodologies in PGH being refined with new equipment
  - Residual saturation experiments completed with umCT
    - Repairs made to improve data acquisition

Synergy Opportunities

- **RSCP**
  - Same interests in CO_2 distribution in reservoirs
    - Critical to understand Saturation, Contact Angles, Wettability, etc.
- **NRAP**
  - Seal and reservoir interface
- **Other Tasks within R&IC Carbon Storage FWP**
    - Shale interactions with CO_2
    - Resource assessment and methodologies
    - EDX tool implementation; Database Development
- **Task 2 in R&IC Onshore Unconventional FWP**
  - Fundamentals in shale multilab efforts

Summary

- **Key Findings**
  - Microbe equitability decreases with exposure to CO_2
  - Reservoir rocks have little change in fundamental physical attributes from long term exposure to CO_2 at reservoir conditions
- **Lessons Learned**
  - Key parameters in characterizing storage reservoir efficiency are non-trivial and require multiple experimental methodologies to accurately characterize
  - pH due to CO_2 exposure is the driving force in the reduction of microbial equitability
    - CO_2 resistant microbial communities within reservoirs are site dependent
- **Future Plans**
  - Parameterization of multiple storage reservoir rocks and creation of a database to disseminate said parameters
  - Additional microbial characterization in formations of interest and evaluation of impacts on reservoir properties
  - Additional experiments on reservoirs/seals for long term CO_2 exposure effects

NETL Research Presentations and Posters

TUESDAY, AUGUST 16, 2016

- **12:40 PM** Monitoring Groundwater Impacts - Christina Lopano
- **1:55 PM** Multi Variate Examination of the Cause of Increasing Induced Seismicity – Kelly Rose
- **4:40 PM** Exploring the Behavior of Shales as Seals and Storage Reservoirs for CO_2 – Ernest Lindner
- **5:05 PM** Risk Assessment for Offshore Systems – Kelly Rose
- **5:30 PM** Metal-based systems in Extreme Environments – Jeff Hawk
- 6:15 p.m. **Poster Session**
  - Kelly Rose - Developing a carbon storage resource assessment methodology for offshore systems
  - Doug Kauffman - Catalytic Conversion of CO2 to Ind. Chem. And eval. Of CO2 Use and Re-Use
  - Liwel Zhang - Numerical simulation of pressure and CO2 saturation above an imperfect seal as a result of CO2 injection: implications for CO2 migration detection

WEDNESDAY, AUGUST 17, 2016

- **12:30 PM** MVA Field Activities – Hank Edenborn
- **1:20 PM** Microseismicity –Erik Zorn
- **2:35 PM** Resource Assessment – Angela Goodman
- **2:35 PM** Understanding Impacts to Air Quality from Unconventional Natural Gas – Natalie Pekney
- **4:05 PM** Improving Science-Base for Wellbore Integrity, Barrier Interface Performance – Nik Huerta
- **5:20 PM** Wellbore Integrity and Mitigation – Barbara Kutchko

THURSDAY, AUGUST 18, 2016

- **1:00 PM** Advances in Data Discovery, Mining, & Integration for Energy (EDX) – Vic Baker
- **1:25 PM** Methods for Locating Legacy Wells – Garrett Veloski
- **2:40 PM** Reservoir Performance – Johnathan Moore
- **3:05 PM** Geochemical Evolution of Hydraulically-Fractured Shales – Ale Hakala

UCR Unconventional Resources

https://edx.netl.doe.gov/carbonstorage/
https://edx.netl.doe.gov/offshore/
https://edx.netl.doe.gov/ucr/

NETL RESEARCH CARBON STORAGE PROGRAM

Organization Chart

- **Project team**
  - Team Portfolio Lead – Angela Goodman
  - Task Technical Lead – Dustin Crandall
  - Subtask PIs, planners, and participants
    - Jerry Boyle, Bob Dilmore, Dustin McIntyre, Bret Howard, Wu Zhang, Yee Soong, Johnathan Moore, Djuna Gulliver, Jim Fazio, Sean Sanguinito, Deepak Tapriyal, Jeong Choi, Karl Jarvis, Bryan Tennant, Roger Lapeer, Magdalena Gill, Mathew Stadelman, Kevin Shanley, Goodarz Ahmadi, John Tudek, Neal Sams, Jonathan Levine, Emily Dixon, Liwei Zhang, Igor Haljasmaa, **I'M SURE I'M MISSING SOME!**

THANK YOU TO EVERYONE!

Appendix

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

Gantt Chart

	Project Dates for each Task/Subtask		FY16			
	Start	Finish	Q1	Q2	Q3	Q4
2. Reservoir Performance	**10/01/2015**	**09/30/2020**		DP.16.2.01 ◇		
2.1 Understanding Relative Permeability, Residual Saturation, and Porosity in Reservoirs to Reduce Uncertainty	10/01/2015	09/30/2020				
2.1.1 Database of residual permeability and residual saturation for CO2-brine-rock systems	10/01/2015	09/30/2016				
2.1.2 Scaling relationships for incorporating pore- and core-level data into flow models	10/01/2015	09/30/2016				
2.1.3 Reservoir simulation	10/01/2015	09/30/2016				
2.1.4 Targeted permeability reduction in sandstone core for thief zone plugging/sealing	10/01/2015	09/30/2016				
2.1.5 Experimental Measurements of Geologic and Displacement Efficiency Parameters of Geologic Systems	10/01/2015	09/30/2016				
2.1.6 Database of Contact Angle+IFT Measurements for CO2-Brine-Rock Systems	10/01/2015	09/30/2016				
2.2 Improve Characterization of Physical Changes in Reservoir and Seal Rock due to CO2	10/01/2015	09/30/2019				
2.2.1 Characterization experiments on RSCP or other relevant formations	10/01/2015	09/30/2016				
2.2.2 Imaging experiments of RSCP or other relevant formations	10/01/2015	09/30/2016				
2.2.3 XRD and SEM analysis on RSCP or other relevant formations	10/01/2015	09/30/2016				
2.2.4 Brine analysis on RSCP or other relevant formations	10/01/2015	09/30/2016				
2.3 Determine Impact of Microbial Induced Changes on Reservoir Performance	10/01/2015	09/30/2018				
2.3.1 Microbial Studies of Geologic Systems Exposed to Supercritical CO2	10/01/2015	09/30/2016				
2.3.2 Evaluating Impact of Microbial Growth on CO2 Reservoir Properties	10/01/2015	09/30/2016				
2.3.3 Description of Potential Impacts of Altered Microbial Growth in CO2 Reservoirs	10/01/2015	09/30/2016				

Bibliography

Peer-reviewed papers

- Seven submitted or accepted

Presentations

- Eleven

Technical Report Series

- One

Report of Invention

- One

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Moore, J., Gill, M., Tudek, J. and Crandall, D. (*submitted*) **Understanding micro-to-macro scale control on multiphase phenomena in CO_2 reservoir rock,** *International Journal of Greenhouse Gas Control*

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Crandall, D., Moore, J., Enick, R., Aoki, T., and Smales, L. (May 2016) **Carbon Dioxide Migration in Permeable Cores: Characterizing and Controlling Flow for Geosequestration and Enhanced Oil Recovery,** 8^{th} International Conference on Porous Media & Interpore Annual Meeting, Cincinnati OH, May 9-12 2016

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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 CO_2 under reservoir pressure conditions,** 8^{th} International Conference on Porous Media & Interpore Annual Meeting, Cincinnati OH, May 9-12 2016

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Bibliography – Task 2.2

Peer-reviewed papers

Zhang, L., Soong, Y. and Dilmore, R.M. (2016) **Investigation on porosity and permeability change of Mount Simon sandstone (Knox County, IN) under geological CO_2 sequestration conditions: a numerical simulation approach** *Greenhouse Gases: Science and Technology*, 5, p1-14, 2016

Soong, Y., Howard, B.H., Dilmore, R.M., Haljasmaa, I., Crandall, D., Zhang, L., Zhang, W., Lin, R. Irdi, G.A., Romanov V.N., and Mclendon,T.R. (accepted) **CO_2/brine/rock interactions in lower Tuscaloosa Formation,** *Greenhouse Gases Science and Technology*

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Zhang, L., Soong, Y., and Dilmore, R. M., **"Method of reservoir permeability modeling for CO_2 sequestration"** was filed on May 2016.

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Gulliver, D.M., Lowry, G.V., and Gregory, K.B. (submitted 2016) **“Comparative study of the effects of CO_2 concentration and pH on microbial communities from a saline aquifer, a depleted oil reservoir, and a freshwater aquifer”,** *Environmental Engineering Science*, in review.

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Gulliver, D.M., Lowry, G.V., and Gregory, K.B., 2016. “**Impact of CO_2 on the evolution of microbial communities exposed to carbon storage conditions, enhanced oil recovery, and CO_2 leakage**”, *TRS Report,* NETL-DOE.