A Coupled Geomechanical, Acoustic, Transport and Sorption Study of Caprock Integrity in CO2 Sequestration

Project Number: DE-FE0023223

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U.S. Department of Energy

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Presentation Outline

- Introduction and Relevance to Program
- Objectives and Goals
- Methodology
  - Equipment, Samples, Procedures
- Personnel and Organization Chart
- Tasks
- Deliverables
- Risk Management

Benefit to the Program

- Carbon Storage Program goals addressed:
  - Area of Interest #2: Fractured Reservoir and Seal Behavior
  - Goal: Develop and validate technologies to ensure 99% storage permanence

- Project Benefits
  1. Appropriate assessment of storage security
  2. Provide the tools to monitor and identify damaged regions in the caprock after CO2 injection

Project Overview: Goals and Objectives

- Project goal:

  Develop a complete understanding of how shale responds to CO_2-induced deformation and reaction

- Project objectives:

  1. Assess the risk of CO_2 leakage arising from geomechanically damaged shale
  2. Provide the tools with which to monitor and identify regions in which shale has been damaged

Project Overview:
Relation to Program Goals and Objectives

Research Area #2: needs: "improved tools and techniques to asses seal behavior":

1. CO_2 migration "*once fractures / faults are formed*"
2. Permeability changes by mechanical (plastic deformation) and chemical (adsorption and swelling)
3. In situ fracture development and "*fracture opening*"
4. "I*n-depth understanding of fracture network geometry for CO_2 and other fluid migration*"
5. Acoustic "*tools and methodologies to characterize and validate the effects of faults and fractures on the containment and migration of injected CO_2*"

Project Overview:
Goals and Objectives: Success Criteria

Success Criteria
Selection of sample population for BP1 and BP2
Protocol for creating fracture network and measuring permeability
Protocol for measuring adsorption at relevant conditions
Protocol for monitoring acoustic waves during adsorption
Plastic vs. brittle response of shale to damage
Adsorption/diffusion significantly affects to storage/migration
Significant changes of acoustic properties with adsorption

Project Overview:
Goals and Objectives: Success / Alternatives

Success Criteria for **Experimental Protocols**

1. Experiments on shales must produce fracture networks and simultaneously measure permeability at in situ conditions (Task 2)
2. Our measurement of CO2 diffusion in shale samples must yield reliable estimates of mass transfer/diffusion coefficients within a reasonable amount of experimental time (Task 4)

Project Overview:
Goals and Objectives: Success Criteria

- Success Criteria for **Experimental Results**

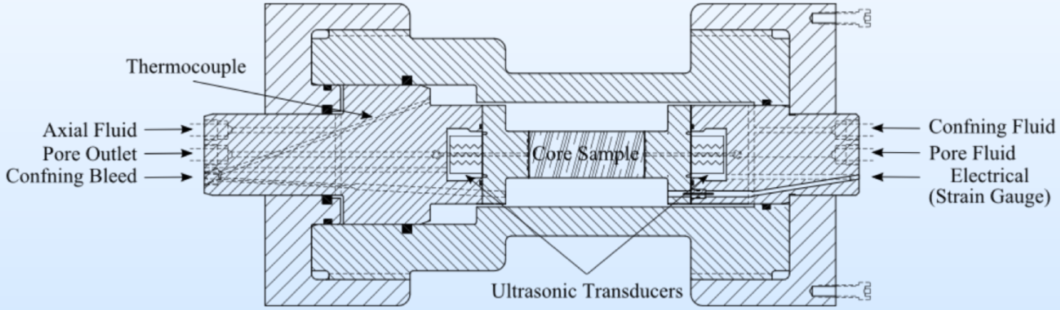
1. If permeability does not decline with confining pressure due to plastic behavior, stop pursuing this research since shales behave as brittle materials (Task 2)
2. If CO2 sorption in shales at reservoir PT is negligible, abandon this task since shales do not contribute to storage capacity (Task 3)
3. No change in acoustic properties with CO2 adsorption: use same equations (Task 5)

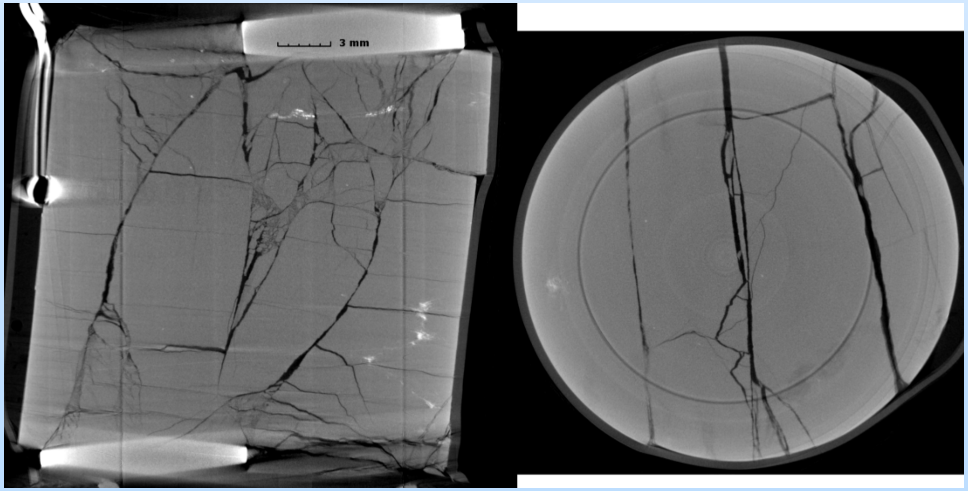
Methodology - 1

Experiments on the coupled mechanical behavior and permeability of CO_2 associated with the development of faults/fractures in shale samples.

Coupled Geomechanics and Permeability

- Triaxial coreflood system with integrated x-ray tomography and acoustics
- Direct measurement of conditions of mechanical failure and permeability of damaged shale to brine and CO_2





Methodology - 2

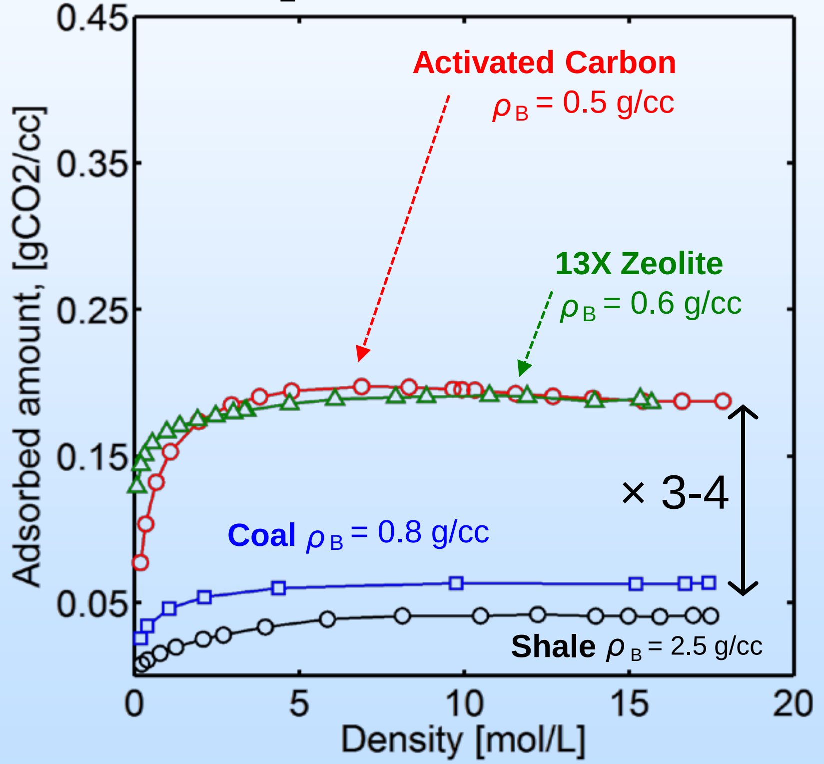
Experiments on CO_2 sorption and mass transfer into selected shale samples at relevant pressure and temperature conditions.

Adsorption in nanoporous materials

Adsorption is a key mechanism for gas storage

- Adsorbed phase is "dense" due to a physical interaction with the solid
- Typical adsorbents are highly porous
  - *Activated carbons, zeolites, silica gels,…*
- *"Unconventional"* nanoporous rocks can adsorb significant amount of gas
  - *Only 3-4 times less than our best adsorbents!*
- Quantification of adsorption to assess caprock sealing potential

CO_2 adsorption at 45°C



Pini R. et al. **2006** *Adsorption* 12:393-403

Pini R. et al. **2008** *Adsorption* 14:133-141

Pini R. et al. **2010** *Int J Greenhouse Gas* 4:90-101

Estimation of storage capacity

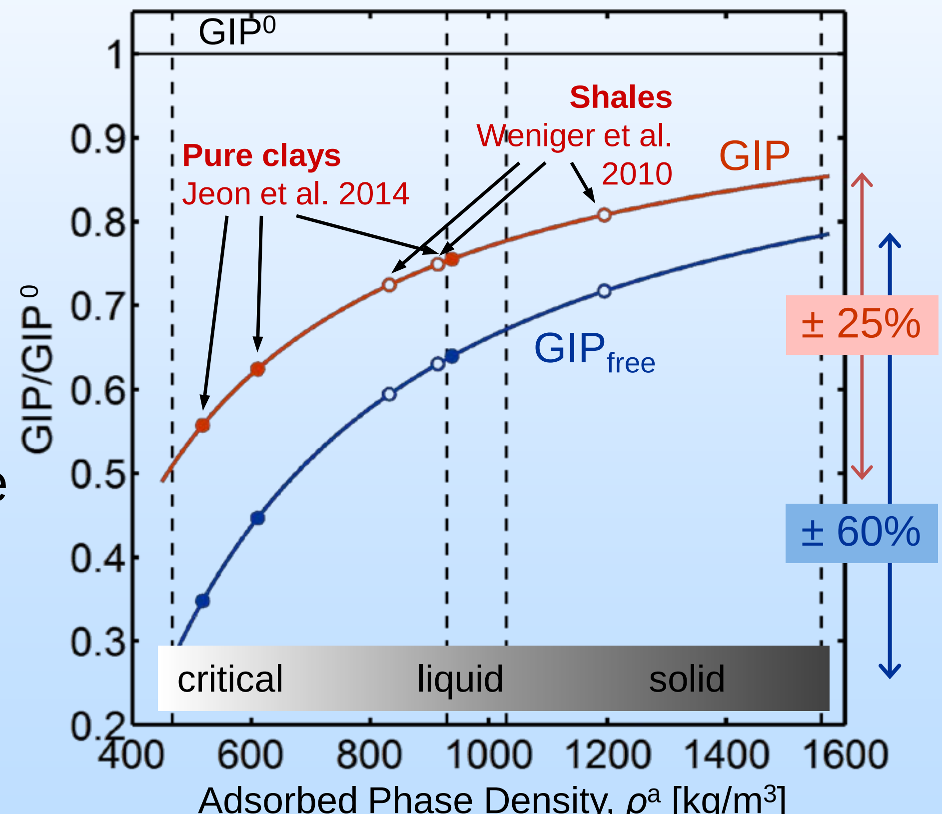
A volumetric approach is commonly adopted

- Three terms (…at least!):

$$GIP = free\ gas + adsorbed\ gas$$
$$= \rho\left[Ah\phi - \frac{n^{a}}{\rho^{a}}\right] + n^{a}$$

- Industry standard overestimates GIP by neglecting the volume of the adsorbed fluid (GIP^0)
  - Density of the adsorbed fluid??
  - From critical up to the solid density of the fluid![2]

Carbon Dioxide (CO_2) capacity



[2] Pini R. **2014**, *Energy Procedia*, GHGT-12.

Design of the HPHT sorption system

- HPHT conditions: up to 30 MPa and 80°C
- Equilibrium *and* dynamic measurements
- Integrated acoustic module
- Single- and multicomponent fluids

Methodology - 3

Experiments on seismic velocities and elastic moduli under reservoir conditions in the presence of supercritical CO_2.

Elastic Properties: Fluid Substitution

Homogeneous Saturation

$$K_{bulk} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{solid}}\right)^2}{\left(\frac{\phi}{K_{fluid}} + \frac{(1-\phi)}{K_{solid}} - \frac{K_{dry}}{K_{solid}^2}\right)}$$

$$\mu_{sat} = \mu_{dry}$$

Gassmann , 1951

Methodology - 4

Development of constitutive relationships between permeability, stress condition, elastic properties and sorption characteristics of shales (link perm – acoustics – mass balance – composition - strength)

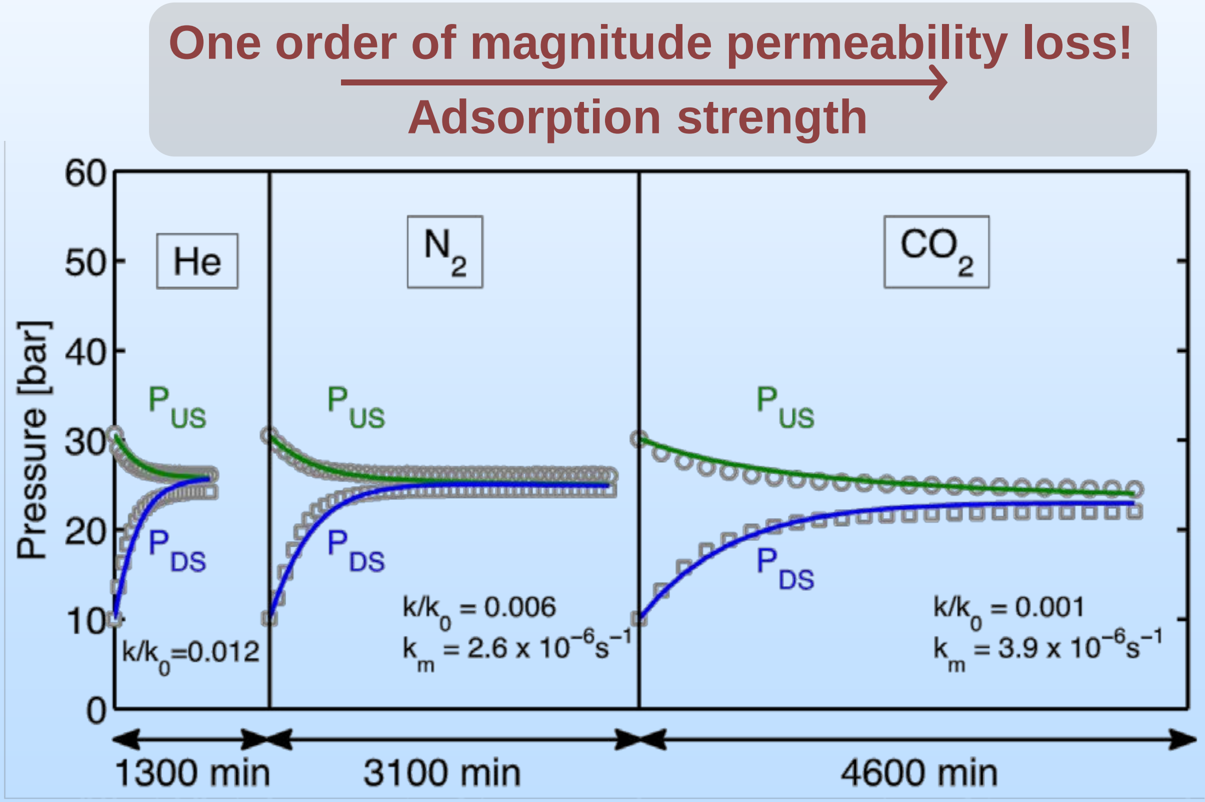
Permeability and gas sorption

Is shale behaving similarly to coal?

- Effects of gas sorption on the permeability of coal
- Basic competitive mechanisms:
  - adsorption-induced swelling
  - elastic compression of the framework
- (First) exposure to CO_2 leads to micro-fracturing

[Hol et al. **2012** *Fuel* 97:569-584]

Gas injection experiments in coal cores



[Pini R et. al **2009** *J Geophys Res*, 114:1-14]

Expected Outcomes: Task 2

- Task 2.0 – In situ measurement of permeability of fractured shale caprock

  Subtask 2.1: X-ray tomographic characterization of shale samples

  Subtask 2.2: Triaxial coreflood experiments and permeability characterization

  Outcome: Integrated analysis of tomography-coreflood experimental results

Expected Outcomes: Task 3

- Task 3.0 - Supercritical CO_2 adsorption in shales

  Subtask 3.1: Characterization of selected samples

  Subtask 3.2: Supercritical CO_2 sorption isotherms

  Subtask 3.3: Parameterization of isotherms with available adsorption models

Outcome: Estimation of CO_2 storage capacity of shales for fractured and unfractured samples

Expected Outcomes: Task 4

- Task 4.0 – Diffusion, mass transfer and permeability of supercritical CO_2 in shales

  Subtask 4.1: Dynamic uptake capacity of shales

  Subtask 4.2: Appropriate mass transfer models

  Subtask 4.2: CO_2 mass transfer / diffusion coefficients

  Subtask 4.3: Permeability of samples and model validation for gas injection shales

  Subtask 4.3: Dynamic acoustic velocity measurement

  Outcome: Determine CO_2 mass transfer coefficients and acoustic velocities

Expected Outcomes: Task 5

- Task 5.0 - Understanding and detecting damaged caprock by acoustic properties

  Subtask 5.1: Acoustic velocity measurements

  Subtask 5.2: Seismic and NMR measurements

  Subtask 5.3: Adsorbed CO2 effect on velocity

  Subtask 5.3: Gassman's model for sorbed fluids

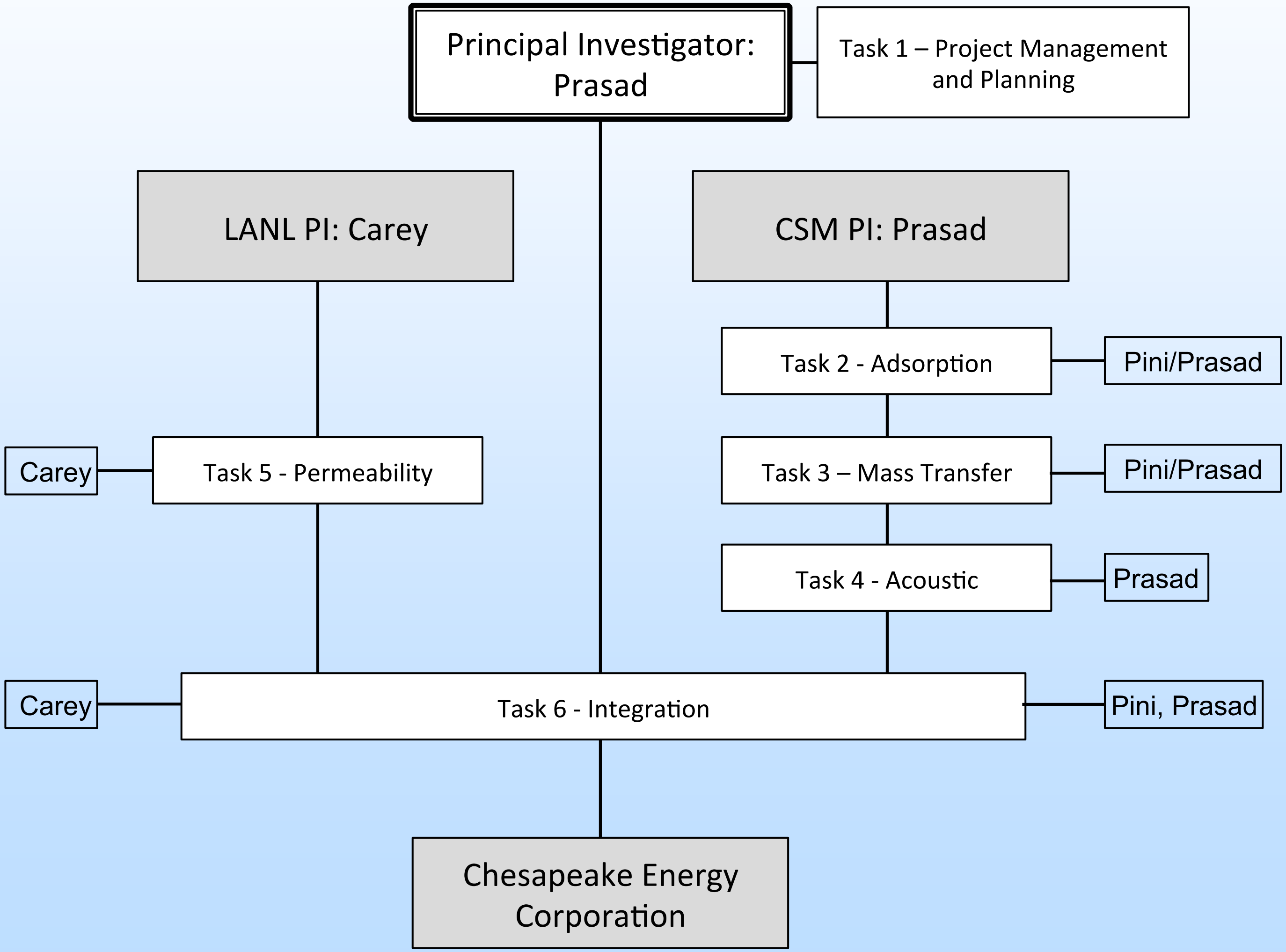
  Subtask 5.4: Acoustic and attenuation database

Outcome: Quantify acoustic velocity and correlate to CO2 sorption

Expected Outcomes: Task 6

- Task 6.0 - Integrated analysis of the mechanical, acoustic, geochemical and hydrologic behavior of shales
  - Integration of the adsorption, mechanical, acoustic, permeability, acoustic emission measurements
  - Establish constitutive relationships between the measured parameters.
  - Protocols for shale characterization in terms of fluid transmissibility and uptake capacity.
  - Guidelines for assessing the sealing capacity of damaged caprocks.

Organization Chart



Communication Plan

1. PI-Prasad will coordinate overall tasks
2. Specific project tasks evaluated by co-Is
3. Regular face to face meetings and/or teleconferences convened by PI
4. Bi-annual meetings held at one of the institutions in turn convened by all co-Is
5. Cost-share partners provide feedback on the research and to suggest future steps.

Communication Plan

1. Dedicated meeting time to evaluate:
   - Progress of project; achievement of proposed milestones and deliverables;
   - Recommend, as needed, re-direction of sub-tasks to fulfill timeline; achieve objectives.
2. Communication with DOE via work progress reports
3. Progress reports at scientific conferences

PI Communication Report

- First face-to-face meeting held at CSM on November 6
  - Samples to be used
  - Measurements and equipment
  - Initial experimental plan
  - Students involved and joint advising
  - Communication plan
  - Kickoff meeting planning

Task/Subtask Breakdown
Task 2: Permeability of fractured shales

2.1. X-ray tomography to detect

- Anisotropy and heterogeneity
- Fractures through layers and interaction with layering
- Determine fracture apertures, distribution, connectivity

2.2. Triaxial coreflood experiments

- shear fracture generation from over-pressure; pure-shear stress failure; tensile failure from excess pore pressure
- Amount of strain prior to enhancement of permeability
- Permeability dependence on deformation mode
- Elastic properties and permeability dependence on confining and injection pressures
- Plastic deformation due to pressure and temperature
- Influence of sorption and swelling (CO_2 or N_2/Ar)

Task/Subtask Breakdown
Task 3: Supercritical CO2 adsorption

3.1. Sample characterization

- Pore structure from Mercury intrusion and helium pycnometry; pore volume, bulk and mineral density

3.2. Static sorption experiments

- On intact and ground samples at reservoir PT conditions; Consolidated samples before and after triaxial stress
- Quantify contribution of adsorption vs. dissolution into formation fluids on the total storage capacity

3.3. Data analysis and integration

- Quantify storage capacity; assess contribution of adsorption; compare with commercial nanoporous materials; evaluate available models.

Task/Subtask Breakdown

Task 4: Diffusion, Mass Transfer; Perm

4.1. Mass transfer in intact and ground samples

- Pore structure from Mercury intrusion and helium pycnometry; pore volume, bulk and mineral density

4.2. Mechanisms of mass transfer

- Interpret results with transport models (SOL and POR)
- Use more complex model to includes multiple resistances to separate macropores and fractures

4.3. Role of adsorption on CO2 injection in shale

- Intrinsic permeability in presence of adsorbing fluid.
- Simultaneous velocities and attenuation experiments
- Develop gas flow, adsorption and mechanical constitutive equations

Task/Subtask Breakdown

Task 5: Detect damage with acoustics

5.1. Acoustic wave measurements

- Ultrasonic measurements to determine damage from CO_2
- Acoustic measurements as functions of time at discrete CO_2 partial pressures.
- Analyze altered rock with Rock-Eval, TGA NMR, and FTIR

5.2. Simultaneous NMR and acoustic measurements

- Acoustic and NMR signals at CO_2 adsorption / desorption
- Study diffusive mobility of CO_2 in fractured shale; relate to pore structure, fracture properties and adsorption

Task/Subtask Breakdown
Task 5: Detect damage with acoustics

5.3. Include adsorption in Gassmann equations

- Quantify velocity change with adsorbed gas volume
- Evaluate Gassmann equation to account for adsorbed gas

5.4. Data analysis for acoustic monitoring

- Establish correlation between CO2 storage, elastic and anelastic wave propagation, and mechanical properties
- Evaluate formations damage with long-term CO2 storage
- Assess potential application to seismic monitoring

Task/Subtask Breakdown
Task 6: Integration of all results

6.1. Integrate experimental work

- Develop protocols for shale characterization in terms of fluid transmissibility and uptake capacity
- Investigate potential relationships between flow properties (permeability), elastic rock's parameters and adsorption
- Develop constitutive relationships for reservoir modeling

Deliverables: Task 2

- X-ray tomographic characterization of shale samples
- Triaxial coreflood experiments and permeability characterization
- Integrated analysis of tomography-coreflood experimental results.

Deliverables: Task 3

– Structural characterization of the selected samples
– Supercritical CO_2 sorption isotherms
– Parameterization of isotherms with available adsorption models
– Estimation of CO_2 storage capacity of shales for fractured and unfractured samples.

Deliverables: Task 4

- Dynamic uptake capacity of shale samples
- Identification of appropriate models to describe mass transfer in shales
- Estimation of CO_2 mass transfer/diffusion coefficients
- Permeability of samples and model validation for gas injection shales
- Equilibrium and dynamic acoustic velocity measurements

Deliverables: Task 5

- Equilibrium and dynamic acoustic velocity measurements
- Velocity and attenuation measurements and NMR
- Velocity changes as a function of adsorbed CO2
- Modified Gassman’s equation for adsorbing fluids
- Assessment of acoustic and attenuation measurements

Deliverables: Task 6

- Integration of the adsorption, mechanical, acoustic, permeability, acoustic emission measurements from Task 2, 3, 4 and 5 to establish constitutive relationships between the measured parameters.
- Protocols for shale characterization in terms of fluid transmissibility and uptake capacity.
- Guidelines for assessing the sealing capacity of damaged caprocks.

Milestones

Task	Milestone Title	Planned Completion Date	Verification Method
1.0	Kickoff Meeting with co-PI's and Chesapeake	10/23/14	Minutes from the meeting
1.0	Kickoff Meeting at NETL	11/12/14	Presentation files
1.0	Annual Meeting	6/30/15	Presentation files
1.0	Annual Meeting with co-PI's, students and Chesapeake	1/31/16	Presentation files
1.0	Annual Meeting	6/30/16	Presentation files
1.0	Annual Meeting with co-PI's, students and Chesapeake	1/31/17	Presentation files
1.0	Closure Meeting with co-PI's, students and Chesapeake	7/31/17	Presentation files
2.1.1	Completion of tomographic characterization of samples prior to experiments	6/30/15	Report and presentation
2.2.1	Complete triaxial study of shale samples subject to compression	9/1/15	Report and presentation
2.2.2	Complete triaxial study of shale samples subject to pure shear	6/30/16	Report and presentation
2.2.3	Complete triaxial study of shale samples subject to hydraulic fracturing	10/31/16	Report and publication
2.2.4	Complete triaxial study comparing permeability behavior of inert gases with scCO2	3/31/17	Report and publication
2.1.2	Completion of tomographic characterization of samples after experiments	6/30/17	Final report and publication
2.3	Integrated analysis of stresss-fracture-permeability relations	9/30/17	Report and presentation
2.2.1	Measurement of permeability in shale subject to compression	6/30/15	Report and presentation
2.1.2	Completion of tomographic characterization of samples after experiments	6/30/16	Report and presentation
3.1	Sample characterization	9/30/15	Report/Presentation file
3.2.1	Protocol for high-pressure equilibrium adsorption measurements	10/31/15	Lab Manual
3.2.2	Equilibrium adsorption data of supercritical CO2 on various shale samples	1/31/17	Report/Presentation file
3.3	Parametrization of experimental data with suitable adsorption isotherm models	4/30/17	Publication
4.1.1	Protocol for high-pressure dynamic adsorption measurements	10/31/15	Lab Manual
4.1.2	Dynamic adsorption data of supercritical CO2 on various shale samples	1/31/17	Report/Presentation file
4.2	Mass transfer/diffusion coefficients of supercritical CO2 on various shale samples	4/30/17	Publication
4.3	Permeability and acoustic/elastic properties of shale with/without adsorption	9/30/16	Report from ETH
5.1	Acoustic and attenuation measurements at various CO2 pressures on intact and damaged samples	1/31/16	Report and presentation
5.2	Simultaneous acoustic and NMR measurements with selected sample	9/30/16	Report and presentation
5.3	Evaluation of the Gassman equation for CO2-shale systems	1/31/16	Report and publication
5.4	Assessment of acoustic experiments for monitorning purposes	5/31/16	Report and presentation
6.1	Sample selection/distribution	11/30/15	Minutes to meeting
6.2	Inegration assessment and gaps indentification	1/31/16	Minutes to meeting
6.3	Integrated protocol for caprock characterization	9/30/17	Presentation files

Decision Points and their Success Criteria

	Decision point	Success Criteria
BP1	Basic characterization of samples	Selection of sample population for BP1 and BP2
BP2	Coupled fracture-permeability measurements	*Protocol* for creating fracture network and measuring permeability
	Adsorption and diffusion in shales	*Protocol* for measuring adsorption at relevant conditions
	Seismic velocities and gas adsorption	*Protocol* for monitoring acoustic waves during adsorption
BP3	Coupled fracture-permeability relations	Plastic vs. brittle response of shale to damage
	Storage capacity of shales	Adsorption/diffusion significantly affects to storage/migration
	Revisiting Gassman equation	Significant changes of acoustic properties with adsorption

Risk Matrix - 1

Every experimental study has risks, such as

- Sample acquisition – Low Risk: Chesapeake routinely collects and characterizes shale samples
- Representative sample selection – Medium Risk as in any study with natural materials
- Experimental systems – Low Risk: Equipment fully operational (Task 2 and 5)
- Technical difficulties – Medium risk: minimized by subdivision into independent tasks with separate systems for tasks

Risk Matrix - 2

- Project tasks exploit capabilities at PI laboratories and institutional access to facilities in the case of a major failure to experimental systems.
- Triaxial coreflood with x-ray tomography (Task 2.0) – Medium Risk due to integration in these first-time experiments: pre- and post-experiment tomography
- Manometric system (Tasks 3 and 4) – Medium Risk in construction and operation of a new experimental system: co-I have experience with similar systems and have technical support. A similar, low pressure (up to 1600 psi) system exists in PI laboratory

Risk Matrix - 3

- Impact or significance of the results – Medium Risk: Shale properties will lead to discovery of CO_2 migration processes as distinct from conventional reservoir rocks; shale ductility will limit CO_2 fracture transmissivity; CO_2 sorption will retard migration, modify mechanical properties, and swell/collapse clays; shale - CO_2 interactions will modify the acoustic properties in measurable ways
- Shale may behave conventionally – High Risk: limits impact of our research. But, negative results will reduce uncertainty in CO_2 sequestration operations

Proposed Schedule

		YEAR 1 Nov 2014-Oct 2015)			YEAR 2 (Nov 2015 - Oct 2016)			YEAR 3 Nov 2016 - Oct 2017)		
		Nov-Feb	Mar-June	July-Oct	Nov-Feb	Mar-June	July-Oct	Nov-Feb	Mar-June	July-Oct
		Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer
Task 1	1.0	m1		m2	m3		m4	m5		m6
Task 2	2.1			M2.1.1					M2.1.2	
	2.2			M2.2.1			M2.2.2	M.2.2.3	M2.2.4	
	2.3									M2.3
Task 3	3.1			M3.1						
	3.2				M3.2.1			M3.2.2		
	3.3								M3.3	
Task 4	4.1				M4.1.1			M4.1.2		
	4.2								M4.2	
	4.3						M4.3			
Task 5	5.1				M5.1					
	5.2						M5.2			
	5.3							M5.3		
	5.4								M.5.4	
Task 6	6.0	M6.1			M6.2					M6.3

Summary

Comments?
Collaboration and Data Exchange Suggestions?