The Coal-Seq Consortium: Advancing the Science of CO_2 Sequestration in Coal Bed and Gas Shale Reservoirs

Project Number (DE FE0001560)

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Advanced Resources International, Inc.

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

August 21-23, 2012

Presentation Outline

- Benefit to the Program
- Project Overview
- Technical Status
- Accomplishments to Date
- Summary
- Appendix

Benefit to the Program

- Program goal being addressed:
  - *Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.*
- Project benefits statement:
  - This research seeks to develop a set of robust mathematical modules to predict how coal and shale permeability and injectivity change in the presence of CO_2. When complete, this work will more readily predict permeability/porosity in these reservoir types and contribute to the Carbon Storage Program's goal of predicting CO_2 storage capacity in geologic formations to within ±30%.

Project Overview:
Goals, Objectives and Success Criteria (SC)

Overall Goal: Develop a set of robust mathematical modules (SC) to accurately predict how coal and shale permeability and injectivity change with CO_2 injection.

- Use coal and shale samples to perform laboratory CO_2 core-flood experiments (SC), observing and measuring any changes in mechanical properties ("weakening") in the presence of high-pressure CO_2.
- Investigate matrix shrinkage during production and matrix swelling during CO_2 injection, using laboratory core flood experiments (SC) conducted at in-situ pressures and stresses.
- Develop improved algorithms and adsorption models (SC) to facilitate realistic simulation of CO_2 sequestration in wet coal seams and shale gas reservoirs.
- Generate quantitative formulations (SC) that rigorously account for coal permeability changes during CO_2 injection and storage, and incorporate these formulations within simulation codes and modules to deliver an advanced and bench-marked model.

Technical Status

Coal-Seq is a public-private partnership seeking to improve the understanding of CO_2 within coal and shale reservoirs.

Funders:

Performers:

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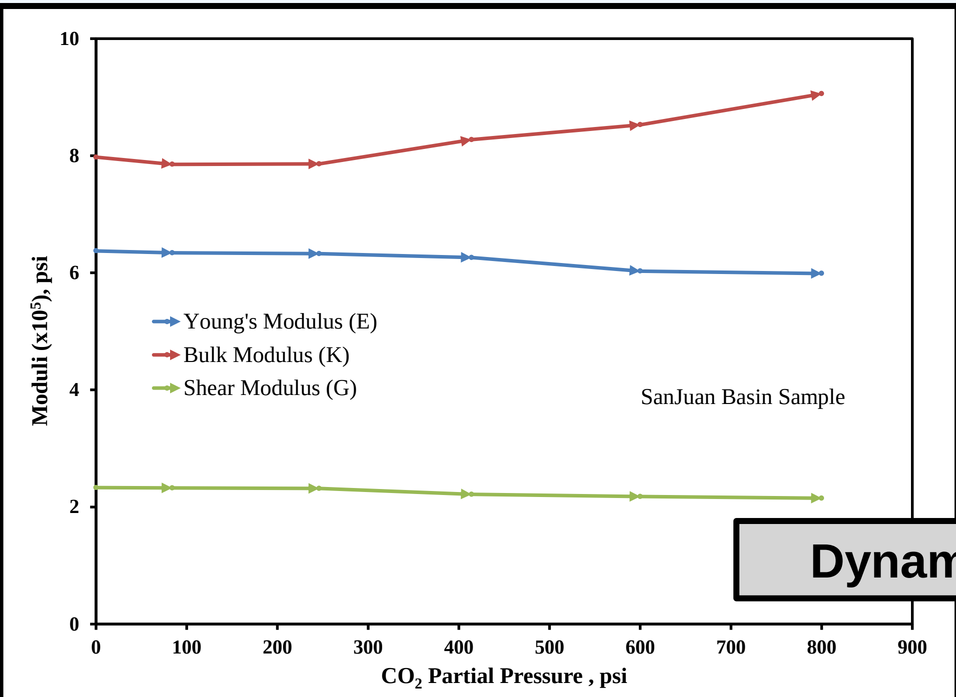
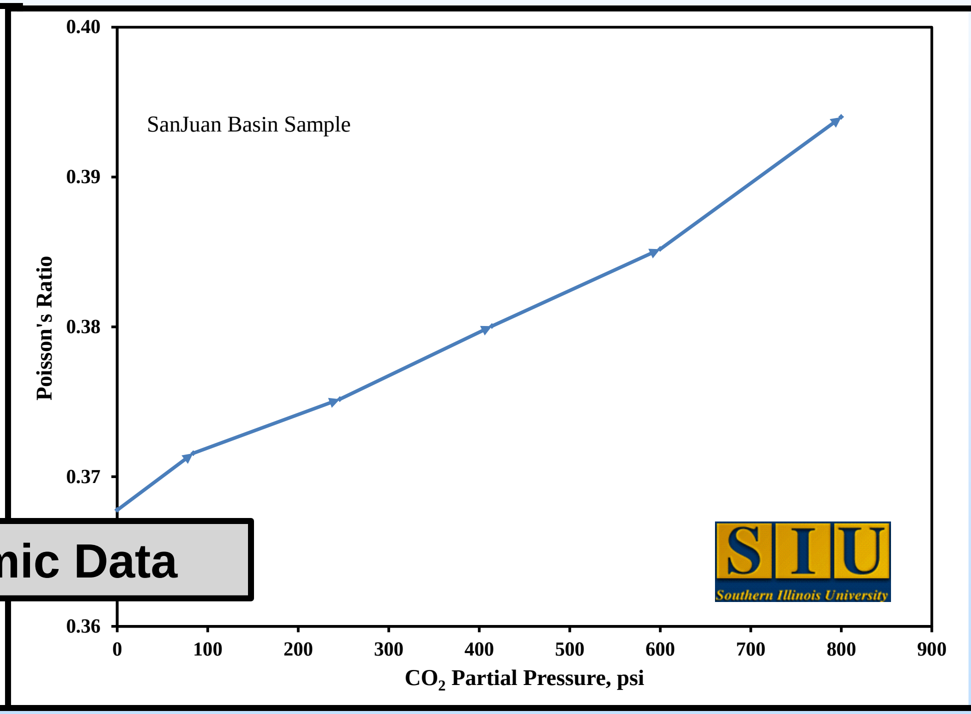
Task 2) Changes in Coal Properties with Exposure to CO_2

Variation in Moduli and Poisson's ratio with Methane Displacement by CO_2 Injection (San Juan Basin Coal Sample)



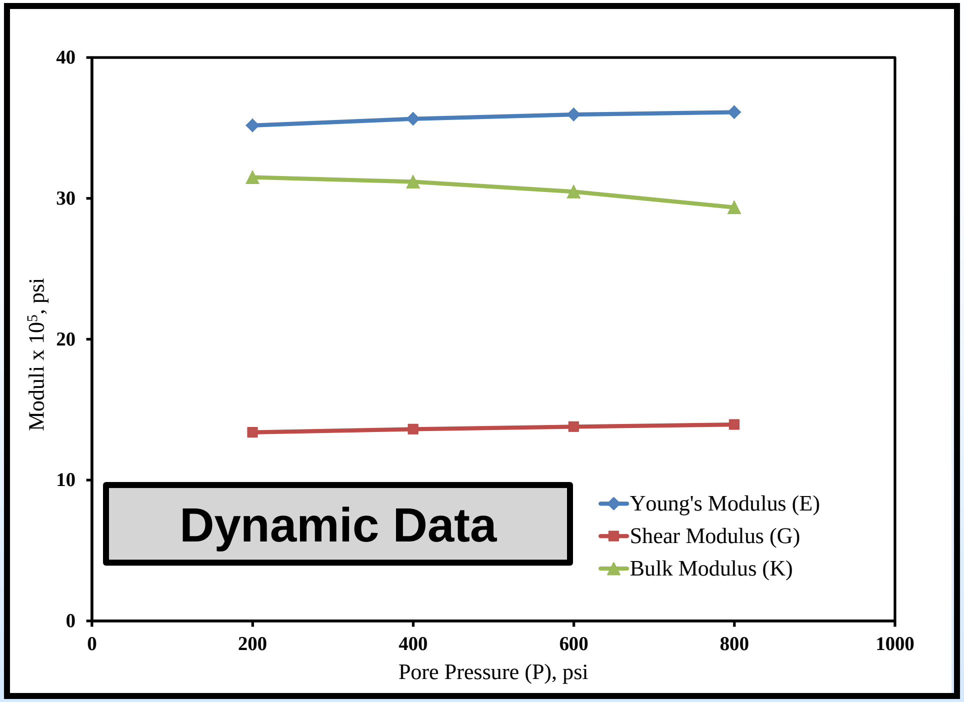


Dynamic Data

The variation in the Young's modulus and Poisson's ratio is not significant although, qualitatively speaking, the coal did become softer. It is unlikely that the strength of the core was actually affected significantly with injection of CO_2.

Changes in Shale Properties with Exposure to CO_2

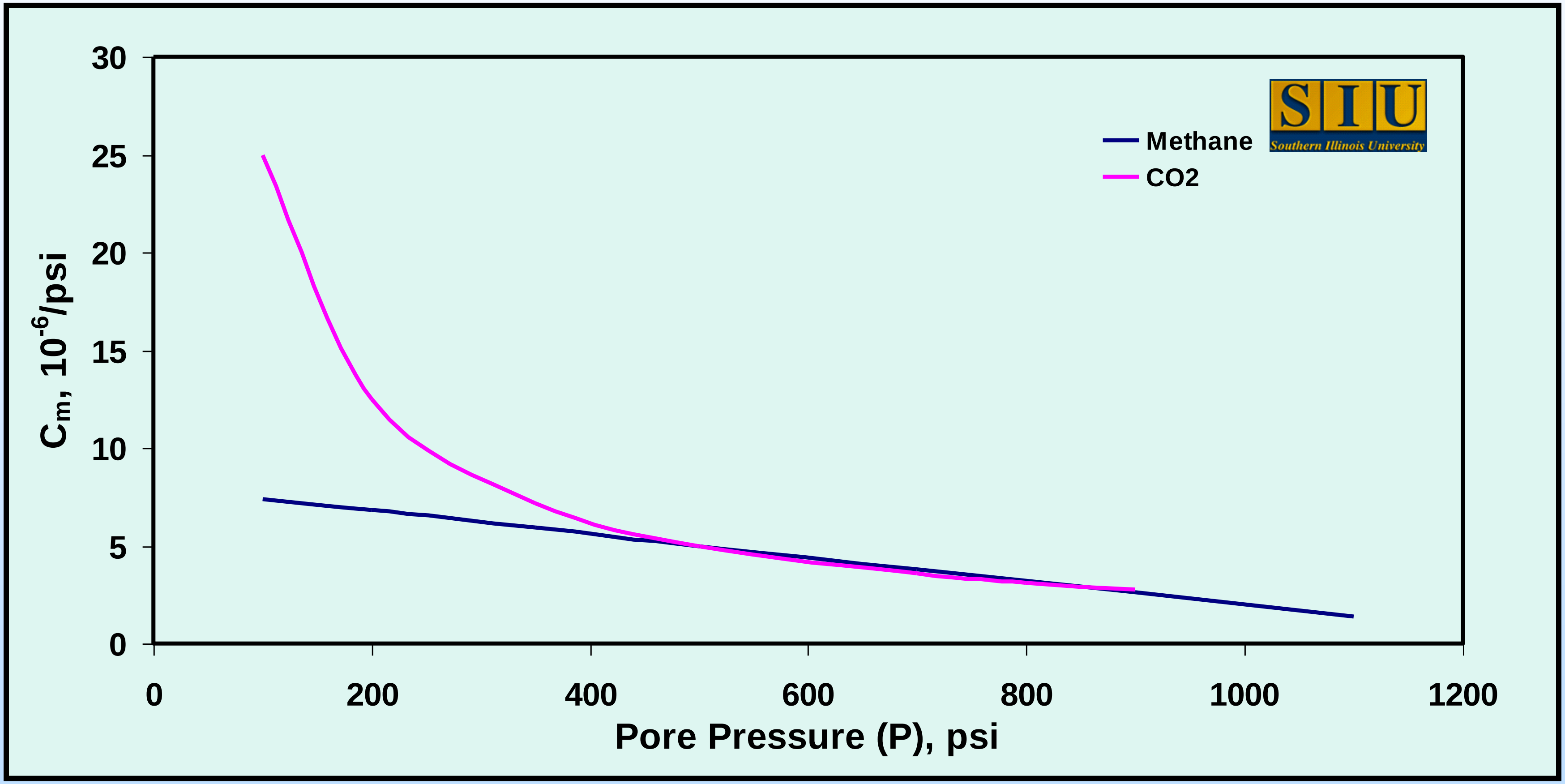
- The New Albany shale sample had to be artificially fractured due to a very low gas flow rate on the intact sample
- More representative of field conditions



- Slight decrease in Young's modulus and increase in Poisson's ratio from 0.29 to 0.31
- Results indicate that **the sample does get softer when CO_2 is injected, although the changes are not significant.**

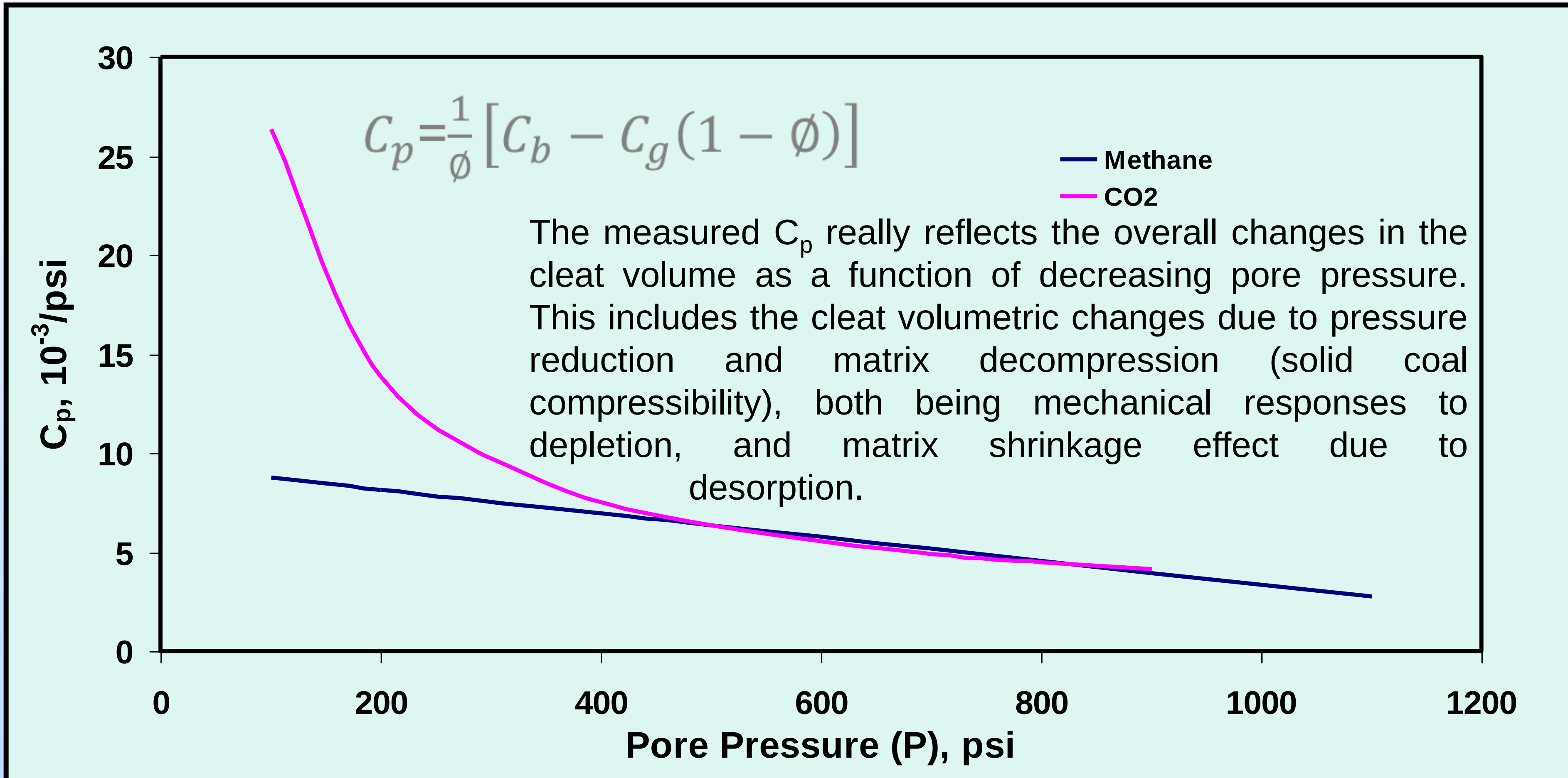
Task 3) Cleat and Matrix Swelling/ Shrinkage Compressibility under Field Replicated Conditions

Matrix Compressibility – Methane and CO_2 (SJB)



Cleat and Matrix Swelling/ Shrinkage Compressibility under Field Replicated Conditions

Cleat Compressibility – Methane and CO_2 (SJB)



Task 4a) Modeling of CO_2 Injection under In-Situ Conditions (Adsorption)

- A new density meter was integrated within the high-pressure gas adsorption apparatus at OSU. This will allow to investigate the effect of moisture in coals on:
  - *In-Situ* gas densities of CO_2
  - Adsorption isotherm data reduction
  - Estimates of gas adsorption capacity on wet coals
- Density meter uses the vibrating U-tube principle that is widely regarded as one of the most accurate methods for measuring fluid densities.
- Calibrations showed that the gas densities of methane, nitrogen and CO_2 can be predicted well within the expected experimental uncertainties.
  - This corresponds to an average error of 0.0001 g/cc or 0.05%.
- The density meter-equipped adsorption apparatus will be used to measure gas adsorption isotherms on wet coals.

OSU
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Modeling of CO_2 Injection under In-Situ Conditions (EOS)

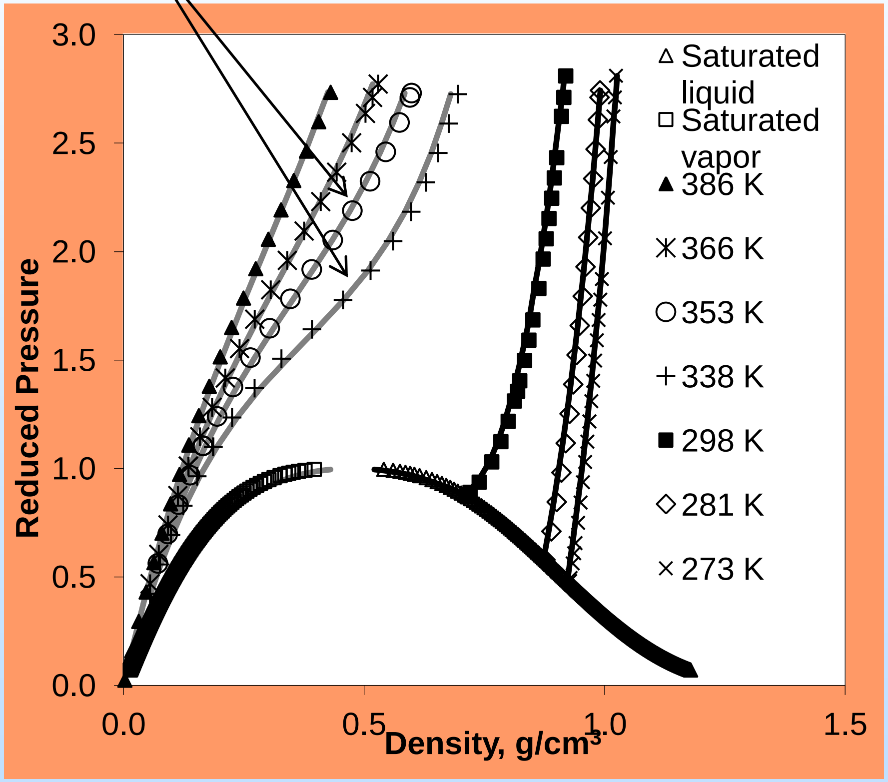
- Working on a new Volume Translated Equation of State: OSU-VTPR (from Peng-Robinson)
  - capable of predicting the density of pure components and mixtures involving the wet CBM gases CH_4, CO_2, and N_2 at typical reservoir conditions

%AAD: Average absolute deviation percentage		Literature Models			OSU-VTPR			
		Original PR EOS	Ahlers and Gmehling (2001)	Lin and Duan (2005)	Direct Fit	Generalized Model Case 1	Generalized Model Case 2	Generalized Model Case 3
Saturated Densities	% AAD for 65 Fluids	6.7	1.7	1.6	0.6	1.0	0.8	0.8
Saturated Densities	% AAD for 20 Validation Fluids	6.2	1.6	1.7	-	1.1	1.0	1.2
Single-phase Densities	% AAD for 10 Fluids	11.0	6.8	7.0	--	1.8	1.8	--

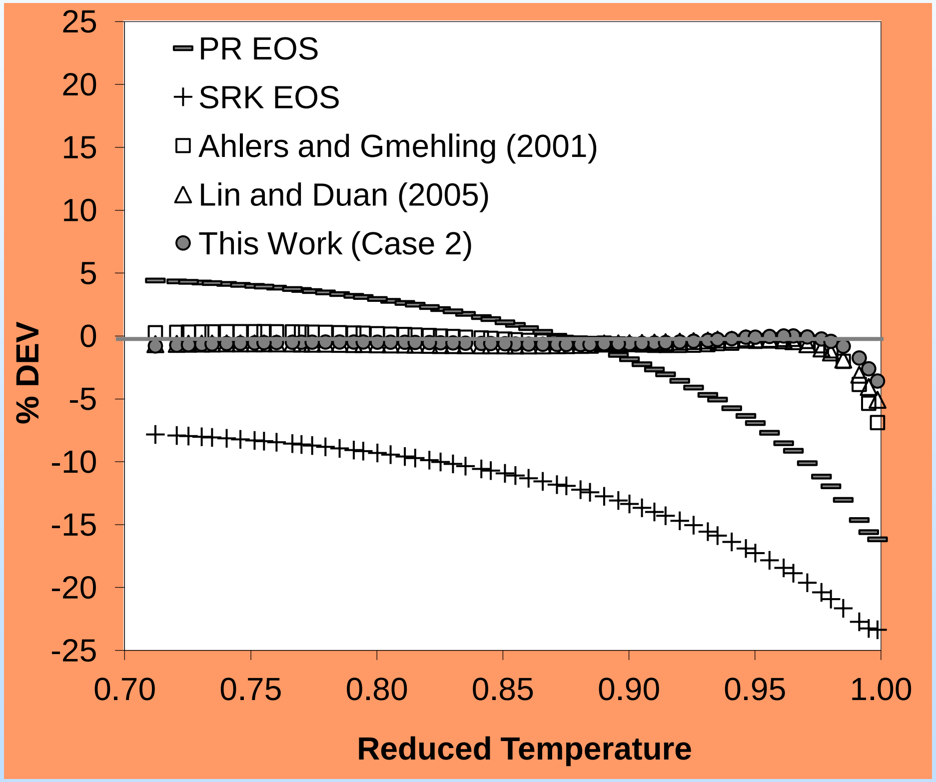
Modeling of CO_2 Injection under In-Situ Conditions (EOS)

OSU-VTPR Results for CO_2

This work
(all solid lines)



Phase Diagram for CO_2



Percentage Deviations for CO_2: Saturated Liquid Densities

Task 4b) Modeling of CO_2 Injection under In-Situ Conditions (Swelling)

Adsorption-induced Strain in Coal → **Coal Permeability** → **CO_2 Injectivity**

Extend OSU-SLD adsorption model to account for coal swelling.

Relate volumetric strain to permeability changes.

Predict CO_2 injectivity from calibrated models for adsorption, swelling and permeability.

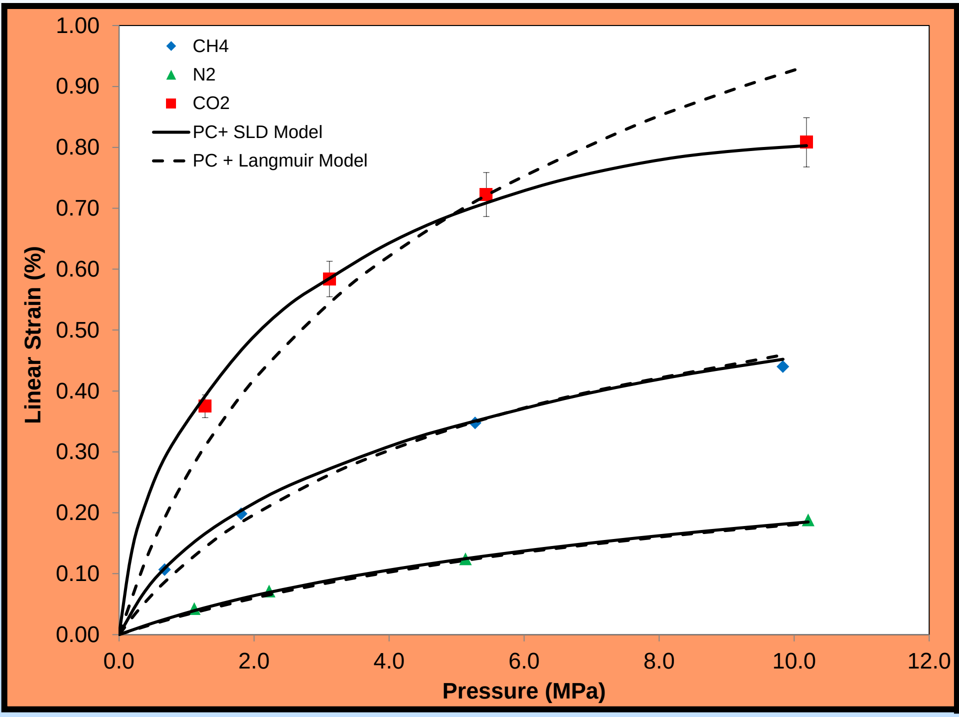
OSU OKLAHOMA CITY

- A theoretical coal-swelling model (Pan and Connell, 2007) was integrated with the simplified local-density (SLD) adsorption model.
- SLD model, when combined with the Pan and Connell swelling model, provided improved predictions for CO_2-induced swelling than the predictions with the Langmuir model.
- Linear relation observed between strain and surface potential for methane, nitrogen and CO_2 confirming similar observations in the literature.

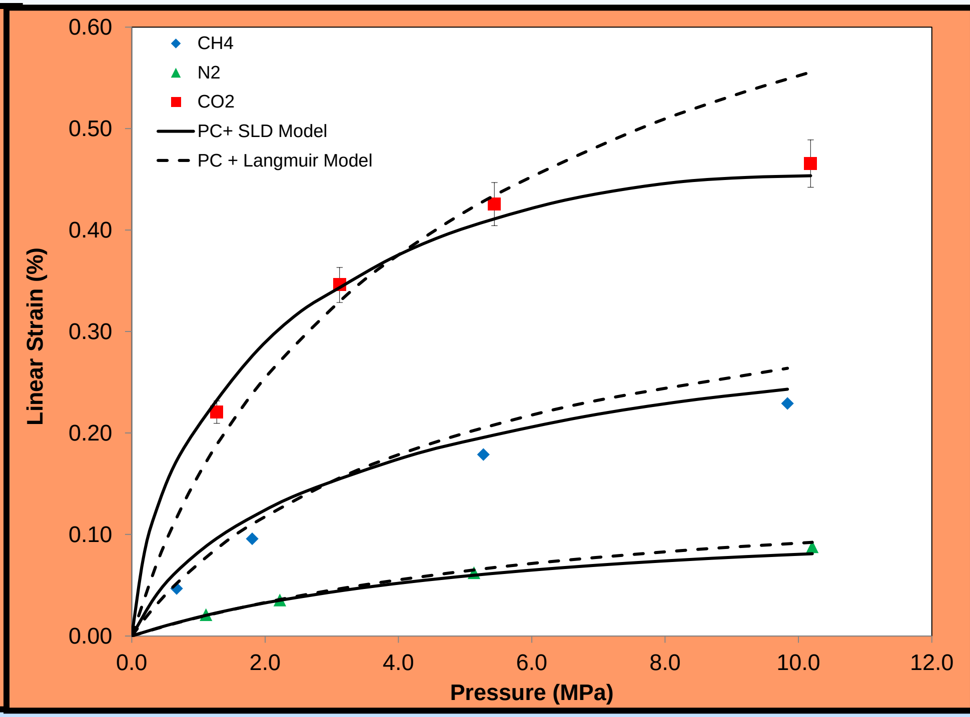
Modeling of CO_2 Injection under In-situ Conditions (Swelling)

Adsorption-Induced Strain

Perpendicular to Bedding Plane of Coal



Parallel to Bedding Plane of Coal

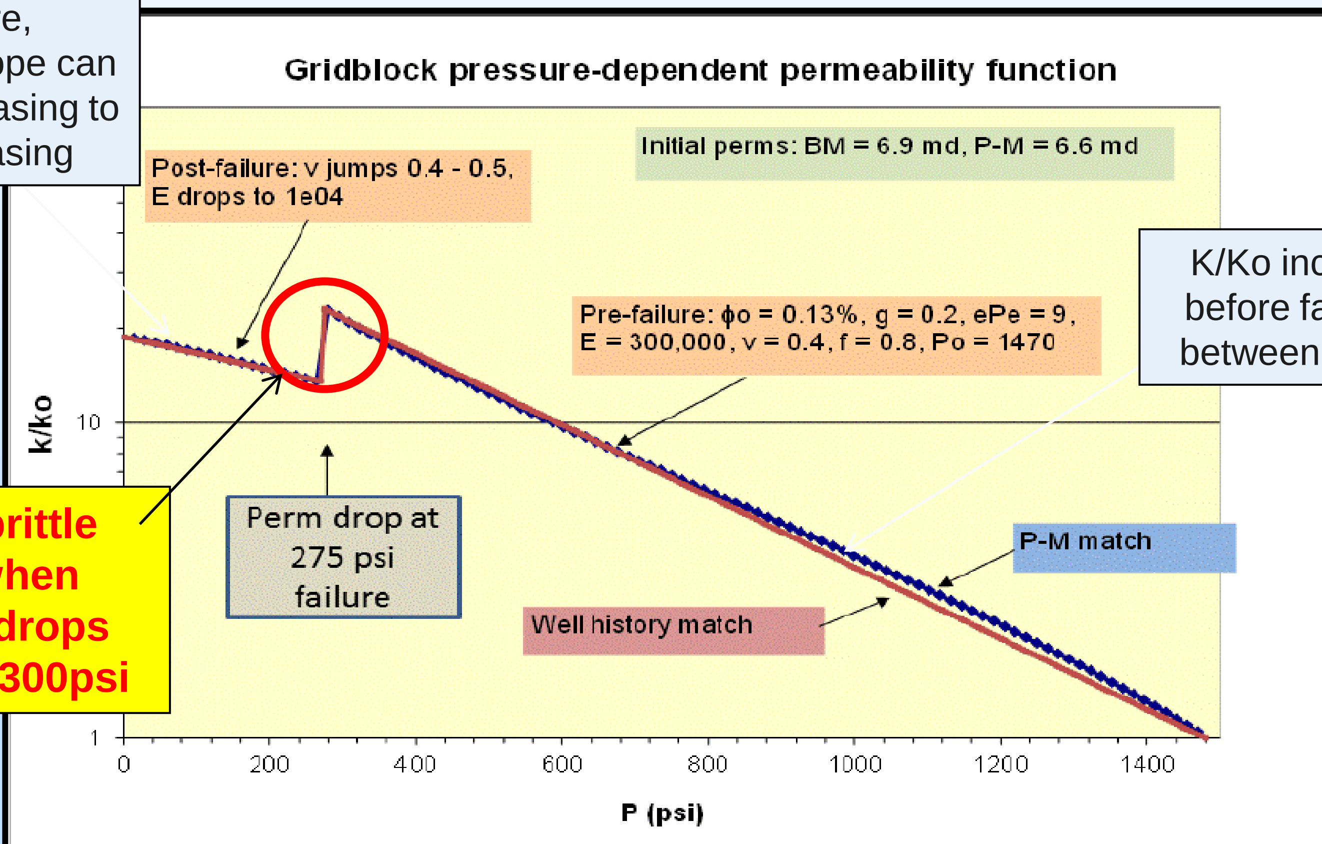


PC refers to Pan and Connell (2007) swelling model

Task 5) Advanced Modeling of Permeability Changes during CO_2 Sequestration (Weakening)

- Detailed history-matching of several CBM wells in the fairway of the San Juan Basin (Colorado area) show permeability increase with depletion

After failure, permeability slope can vary from increasing to flat to decreasing

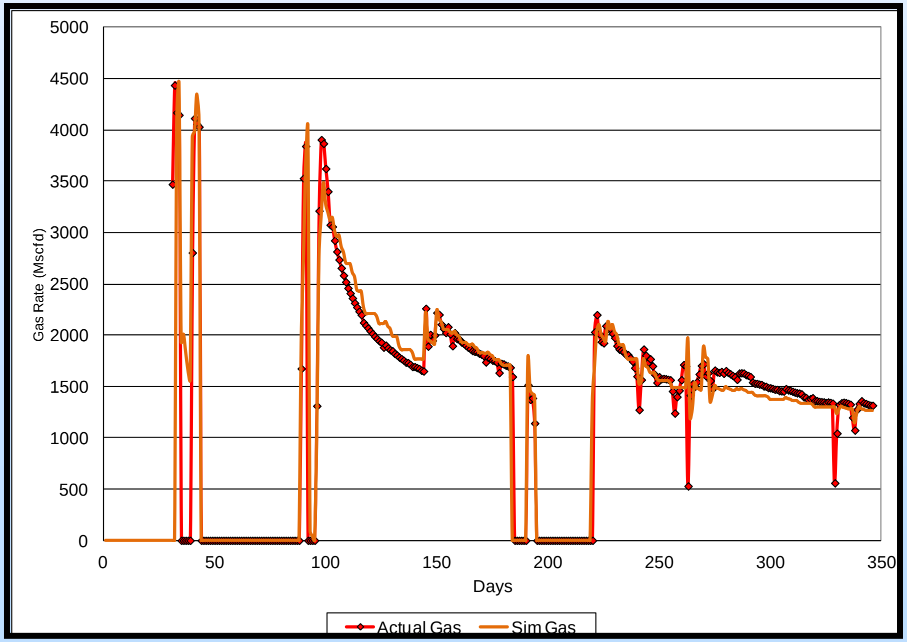


K/Ko increase ratio before failure varies between 16 and 170

Sudden brittle failure when pressure drops below 250-300psi

Task 6) Technical Transfer

1. Flow and storage modeling for shale sequestration
2. Testing of code against large-scale projects.
3. Basin-oriented review of coal and shale storage potential.
4. Coal-Seq Website (www.coal-seq.com)
5. Coal-Seq Forums



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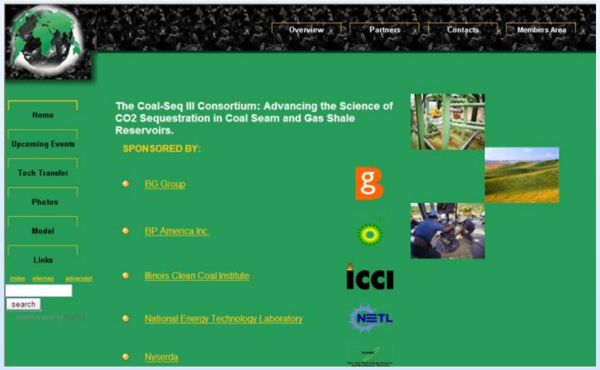
Technology Transfer

- The next CoalSeq forum, number VIII, will be held in Pittsburgh on October 23rd and 24th at the Sheraton Station Square.

www.coal-seq.com



Accomplishments to Date

- Forum VII completed.
- Coal (San Juan) and Shale (New Albany) mechanical properties completed.
- Coal compressibility work completed.
- Improved equation of state density prediction model developed.
- Coal depletion studies completed
- Detailed history match of a Marcellus Shale well completed.

Key Findings/Lessons Learned

- Coal and shale appear to soften under both methane and CO_2 depletion.
- Coal compressibility varies with pressure and is not constant.
- Coal permeability (and porosity) may increase with depletion.
- Coal may fail at low pressure, but there does not appear to be failure during CO_2 injection (prior to hydraulic parting).

Future Work

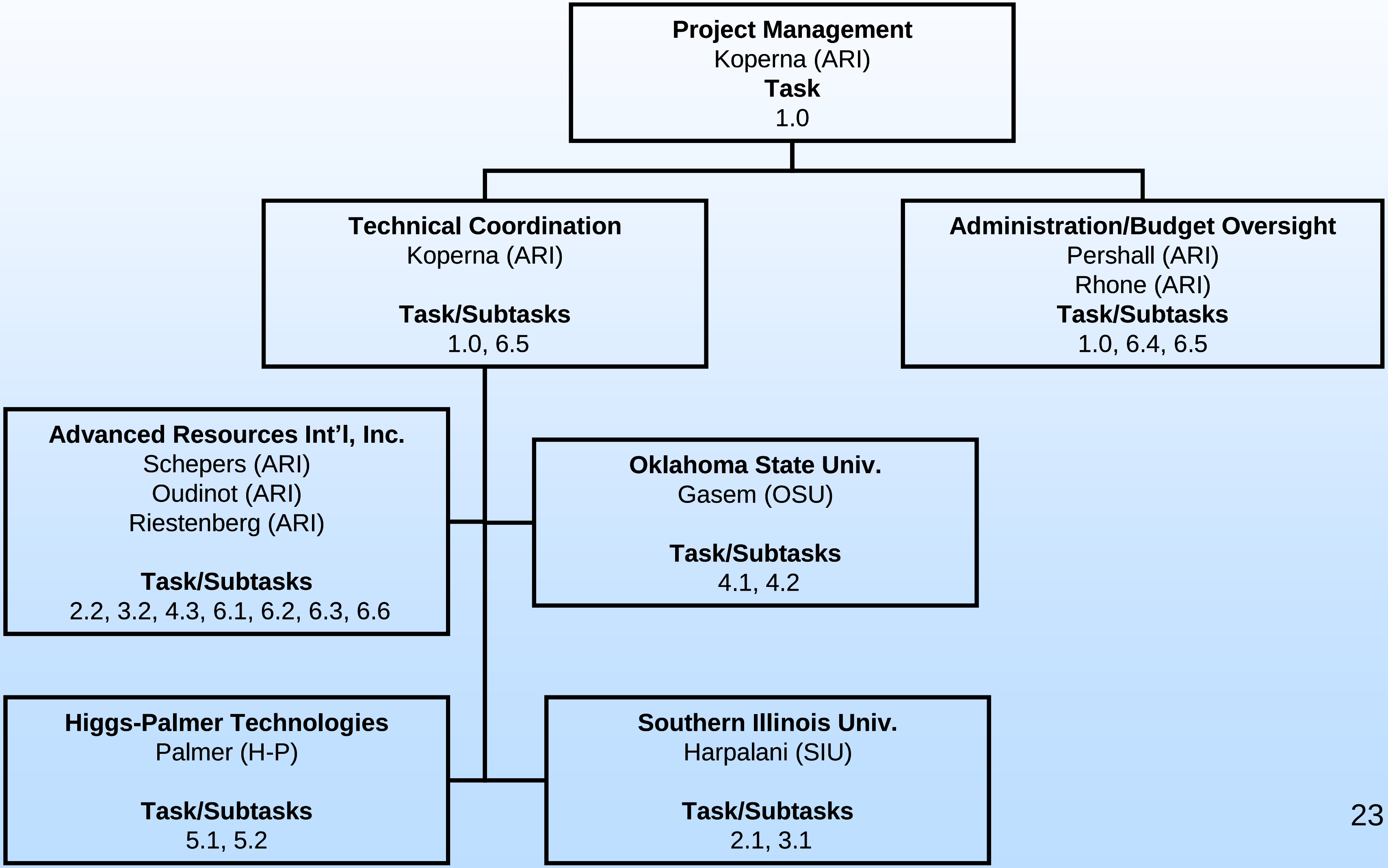
- Changes in coal/shale properties with exposure to CO_2
  - Dynamic data (elastic moduli and Poisson's ratio) may have to be translated to static data before they can be integrated into a new module. Correlations have been found and all agree that dynamic moduli are greater than the static ones whereas static Poisson's ratios tend to be greater than those for dynamic
- Cleat and Matrix Swelling/ Shrinkage Compressibility under Field Replicated Conditions
  - The cleat compressibility as defined previously (and measured in the lab) are different from the pore compressibility Cp in numerical simulators. Laboratory data will have to be translated so that they can be properly integrated into a simulator.

Future Work

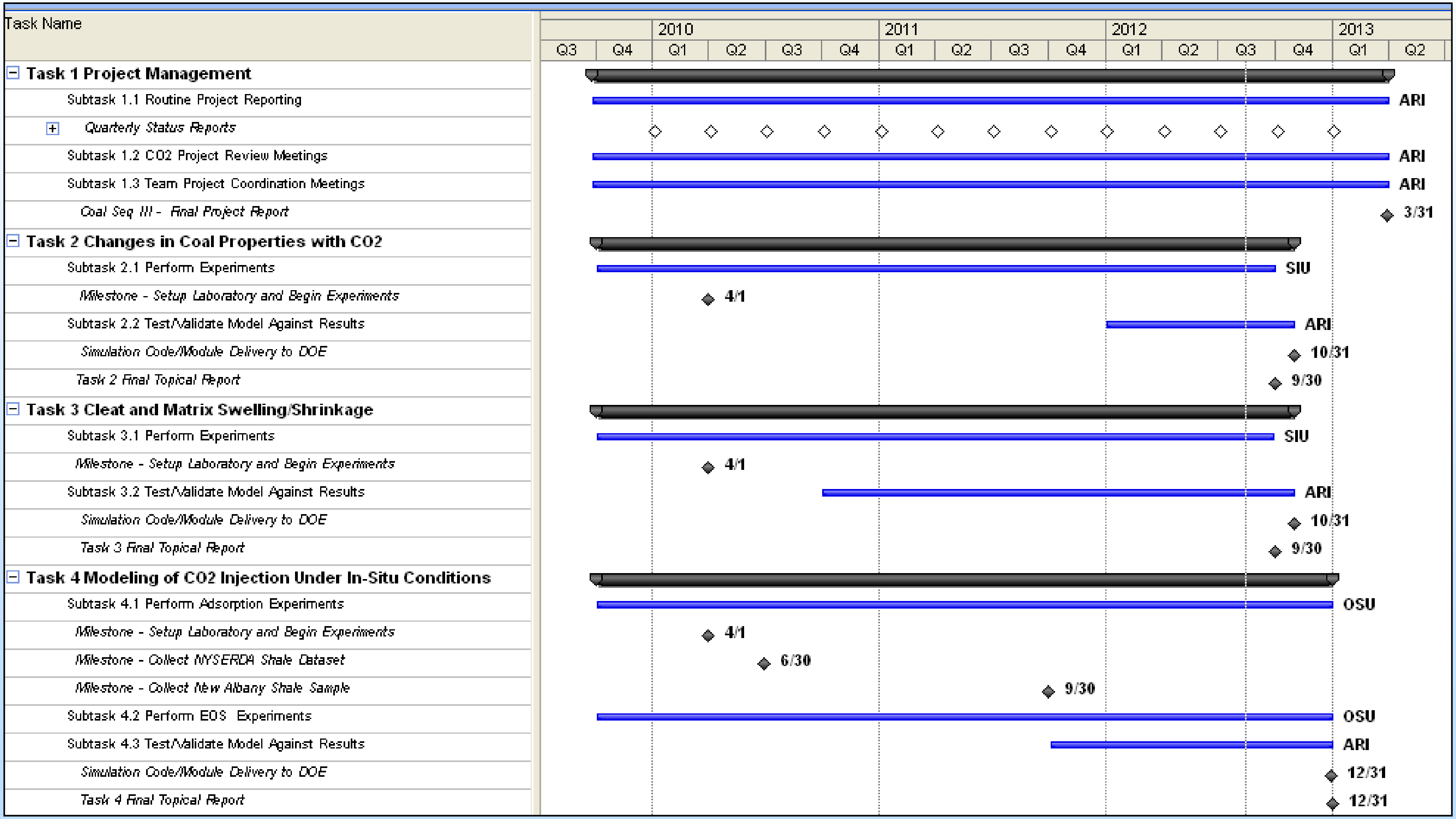
- Modeling of CO_2 Injection under In-situ Conditions
  - Measure CO_2 gas adsorption on two wet coals with the density meter-equipped adsorption apparatus.
  - Extend the equation-of-state volume translation method to fluid mixtures by devising suitable mixing rules.
  - Investigate the relationship between adsorption-induced volumetric strain in coals, permeability and gas injectivity.
- Advanced Modeling of Permeability Changes during CO_2 Sequestration
  - Study how CO_2 injection permeability varies with depletion pressure at which injection begins (eg, 400 psi instead of 200 psi).
  - Consider ways to model the injectivity of CO_2 in the above described situations.

Appendix

Organization Chart



Gantt Chart



Task Name
2010
2011
2012
2013
Q3
Q4
Q1
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Q3
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Q3
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Q1
Q2
Q3
Q4
Q1
Q2
Task 1 Project Management
Subtask 1.1 Routine Project Reporting
ARI
Quarterly Status Reports
Subtask 1.2 CO2 Project Review Meetings
ARI
Subtask 1.3 Team Project Coordination Meetings
ARI
Coal Seq III - Final Project Report
3/31
Task 2 Changes in Coal Properties with CO2
Subtask 2.1 Perform Experiments
SIU
Milestone - Setup Laboratory and Begin Experiments
4/1
Subtask 2.2 Test/Validate Model Against Results
ARI
Simulation Code/Module Delivery to DOE
10/31
Task 2 Final Topical Report
9/30
Task 3 Cleat and Matrix Swelling/Shrinkage
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Task 3 Final Topical Report
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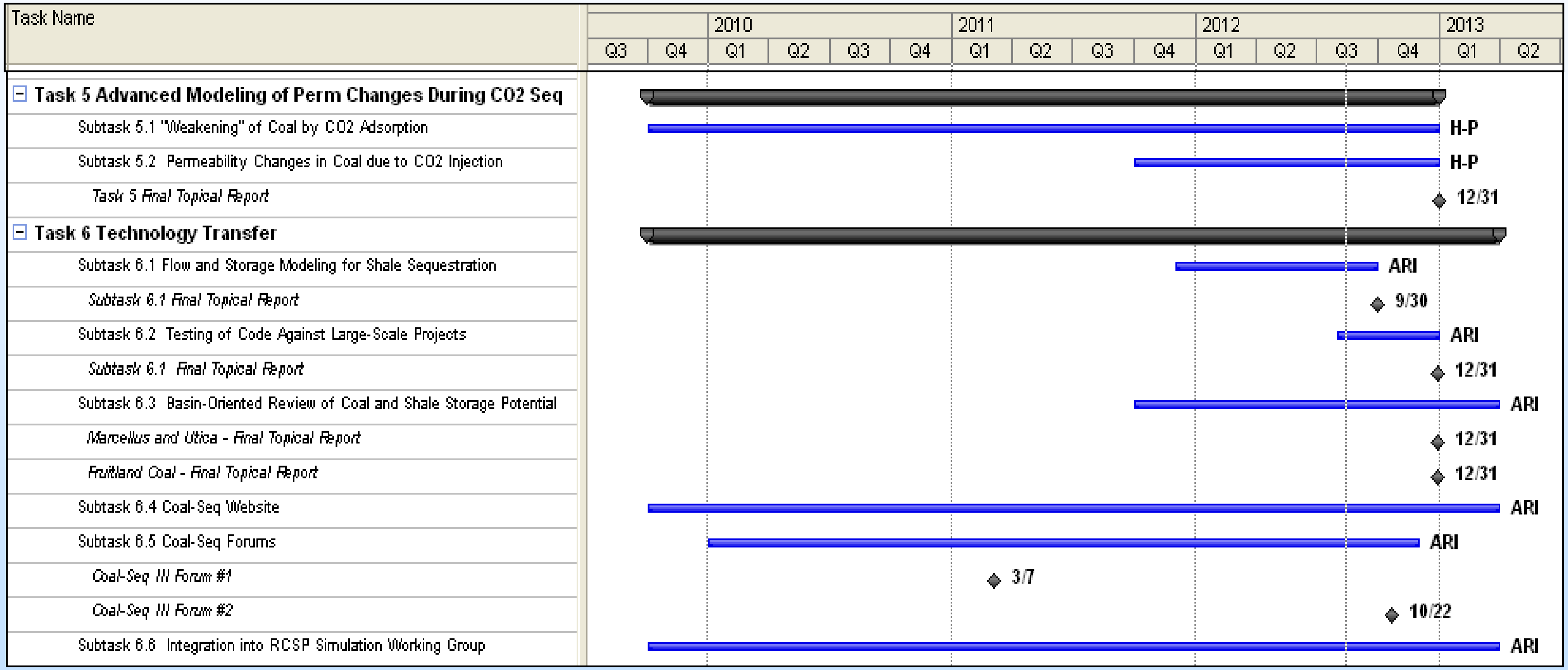
Task 4 Modeling of CO2 Injection Under In-Situ Conditions
Subtask 4.1 Perform Adsorption Experiments
OSU
Milestone - Setup Laboratory and Begin Experiments
4/1
Milestone - Collect NYSERDA Shale Dataset
6/30
Milestone - Collect New Albany Shale Sample
9/30
Subtask 4.2 Perform EOS Experiments
OSU
Subtask 4.3 Test/Validate Model Against Results
ARI
Simulation Code/Module Delivery to DOE
12/31
Task 4 Final Topical Report
12/31

Gantt Chart



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Q3
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Q1
Q2
Task 5 Advanced Modeling of Perm Changes During CO2 Seq
Subtask 5.1 "Weakening" of Coal by CO2 Adsorption
H-P
Subtask 5.2 Permeability Changes in Coal due to CO2 Injection
H-P
Task 5 Final Topical Report
12/31
Task 6 Technology Transfer
Subtask 6.1 Flow and Storage Modeling for Shale Sequestration
ARI
Subtask 6.1 Final Topical Report
9/30
Subtask 6.2 Testing of Code Against Large-Scale Projects
ARI
Subtask 6.1 Final Topical Report
12/31
Subtask 6.3 Basin-Oriented Review of Coal and Shale Storage Potential
ARI
Marcellus and Utica - Final Topical Report
12/31
Fruitland Coal - Final Topical Report
12/31
Subtask 6.4 Coal-Seq Website
ARI
Subtask 6.5 Coal-Seq Forums
ARI
Coal-Seq III Forum #1
3/7
Coal-Seq III Forum #2
10/22
Subtask 6.6 Integration into RCSP Simulation Working Group
ARI

Peer-Reviewed Bibliography

- Sayeed A. Mohammad, Khaled A. M. Gasem. "Multiphase Analysis for High-Pressure Adsorption of CO2/Water Mixtures on Wet Coals." Energy Fuels, 26 (6), 3470-3480, 2012.
- Sayeed A. Mohammad, Mahmud Sudibandriyo, James E. Fitzgerald, X. Liang, Robert L. Robinson, Jr., Khaled A. M. Gasem. "Measurements and Modeling of Excess Adsorption of Pure and Mixed Gases on Wet Coals." Energy Fuels, 26 (5), 2899–2910, 2012.
- Sayeed A. Mohammad, Khaled A. M. Gasem. "Modeling the Competitive Adsorption of CO2 and Water at High Pressures on Wet Coals." Energy Fuels, 26 (1), 557–568, 2012.
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- Agelia M. Abudour, Sayeed A. Mohammad, Khaled A.M. Gasem. "Modeling High-Pressure Phase Equilibria of Coalbed Gases/Water Mixtures with the Peng–Robinson Equation of State." Fluid Phase Equilibria, 319, 77-89, 2012.
- Pongtorn Chareonsuppanimit, Sayeed A. Mohammad, Robert L. Robinson Jr., and Khaled A. M. Gasem. "High-Pressure Adsorption of Gases on Shales: Measurements and Modeling." International Journal of Coal Geology, 95, 34-46, 2012.

Peer-Reviewed Bibliography (Con't)

– Mahmud Sudibandriyo, Sayeed A. Mohammad, Robert L. Robinson, Jr., Khaled A. M. Gasem. "Ono-Kondo Model for High-Pressure Mixed-Gas Adsorption on Activated Carbons and Coals." Energy Fuels, 25 (7), 3355–3367, 2011.

– Mahmud Sudibandriyo, Sayeed A. Mohammad, Robert L. Robinson, Jr., Khaled A. M. Gasem. "Ono-Kondo Lattice Model for High-Pressure Adsorption: Pure Gases." Fluid Phase Equilibria, 299 (2), 238-251, 2010.