

The Coal-Seq Consortium: Advancing the Science of CO₂ Sequestration in Coal Bed and Gas Shale Reservoirs Project Number (DE FE0001560)



Advanced Resources
International, Inc.

George J. Koperna Jr.

Advanced Resources International, Inc.

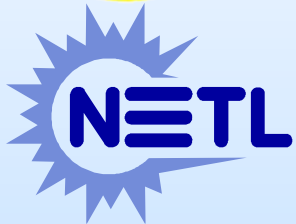
1:50pm, Tuesday, August 12, 2014

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS
August 12-14, 2014



Coal-Seq Consortium

A public-private research partnership to improve the understanding of CO₂ within coal and shale reservoirs.



Presentation Outline

- Program Goal and Benefits Statement
- Project Overview
 - Goal
 - Objectives
- Technical Status
- Accomplishments to Date
- Next Steps and Future Plans
- Appendix

Program Goal and Project Benefits

- Program Goal:
 - *Support industry's ability to predict CO₂ storage capacity in geologic formations to within ± 30 percent.*
- Project Benefits Statement
 - This research seeks to develop a set of robust mathematical models to predict how coal and shale permeability and injectivity change in the presence of CO₂. When complete, this work will more accurately predict permeability/ injectivity in these reservoir types, contributing to the Program goal of more accurately predicting CO₂ storage capacity in geologic formations.

Project Overview: Goal and Task Objectives

Goal:

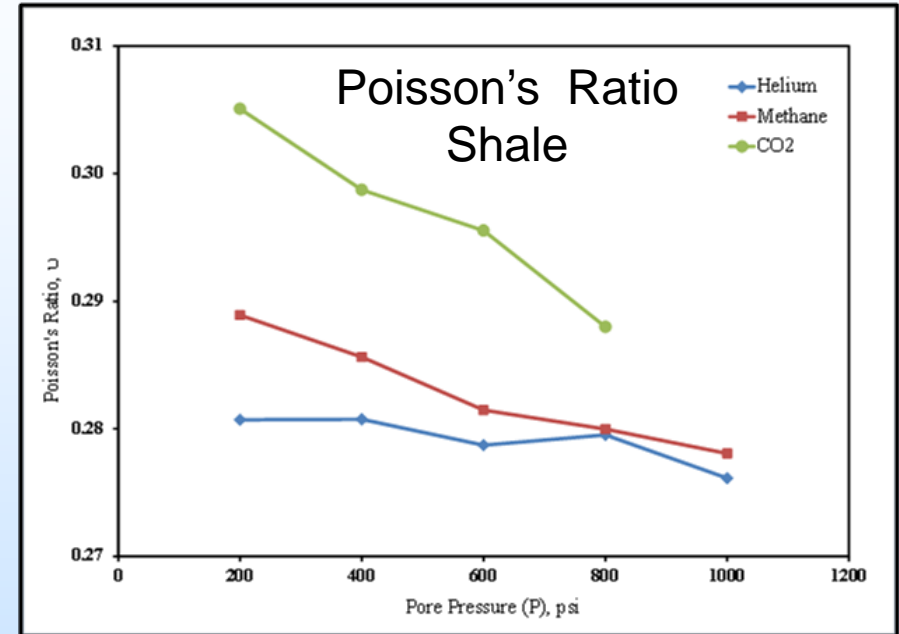
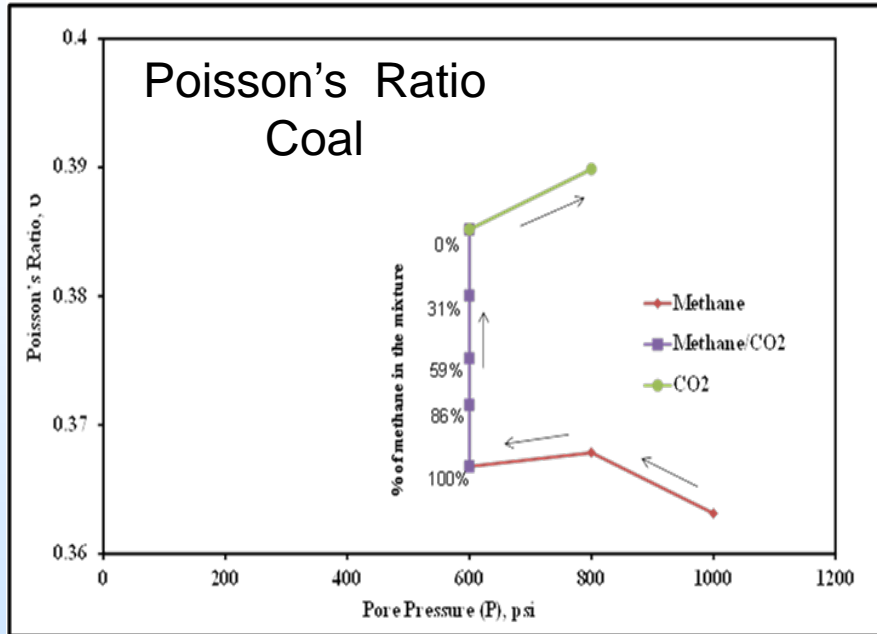
Develop robust mathematical models to accurately predict how coal and shale permeability and injectivity change with CO₂ injection, incorporating the following the Task Objectives:

Objectives:

- **Task 2** – Observe and measure changes in coal and shale mechanical properties with exposure to high pressure CO₂.
- **Task 3** - Investigate cleat and matrix swelling and shrinkage during gas production and CO₂ injection.
- **Task 4** - Model CO₂ injection under in-situ conditions and develop improved algorithms and adsorption models.
- **Task 5** – Advanced simulation of coal permeability changes during CO₂ injection and storage.
- **Task 6** – Reporting results, delivering code and data

Technical Status - Task 2

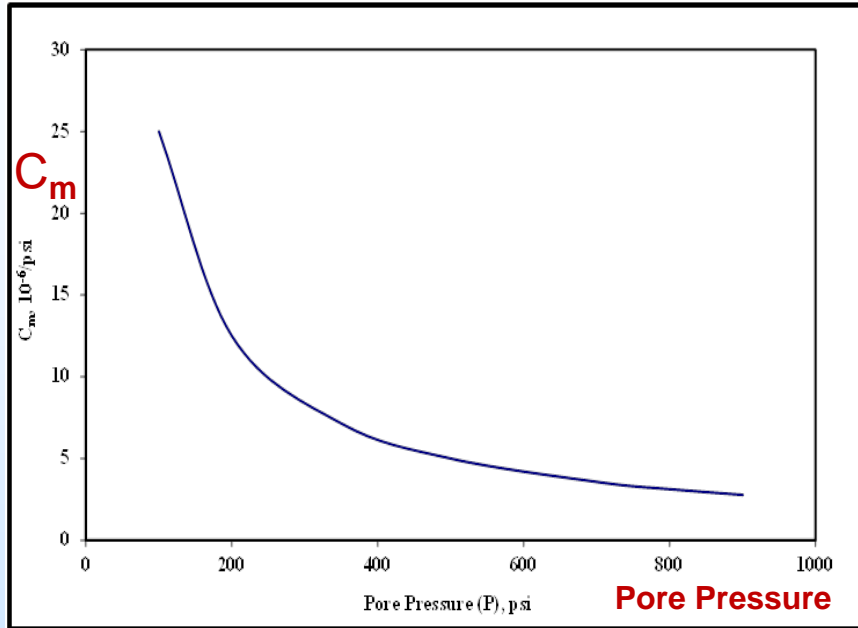
Change in Coal and Shale Properties



- **COAL** - Young's Modulus decreases & Poisson's Ratio increases when methane is displaced with CO₂ indicating that *the sample does get softer*, although **changes are not significant**.
- **SHALE** – Relative to methane, CO₂ weakens shale because the change in Poisson's Ratio with pore pressure is larger for CO₂ than for methane.

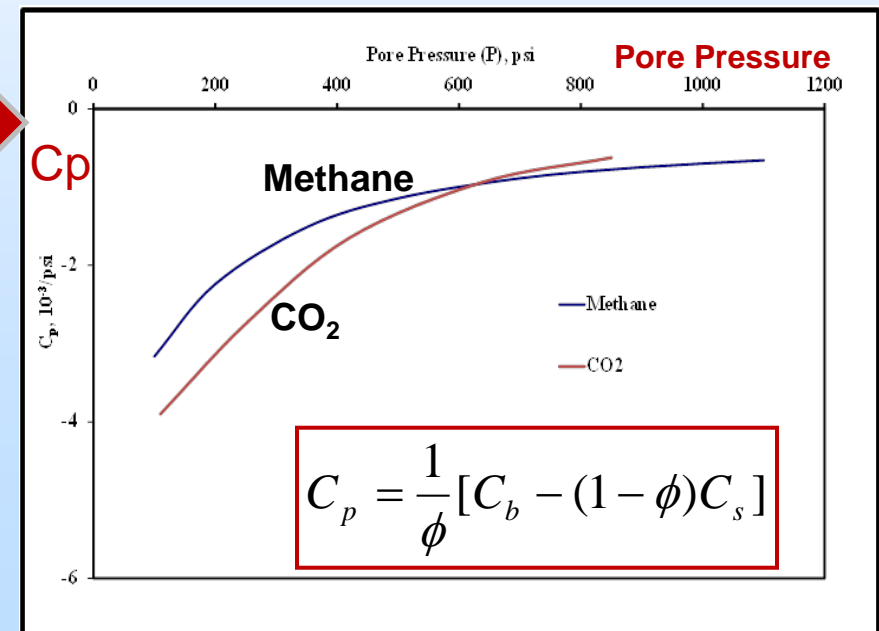
Technical Status – Task 3

Investigate Cleat & Matrix Swelling/ Shrinkage



Compressibility under replicated field conditions is not constant

- Compressibility changes as the pore pressure of the sorbing gas changes in the reservoir.
- Calculated values of C_p (shown) express compressibility changes for the total volume of coal (C_m already included).



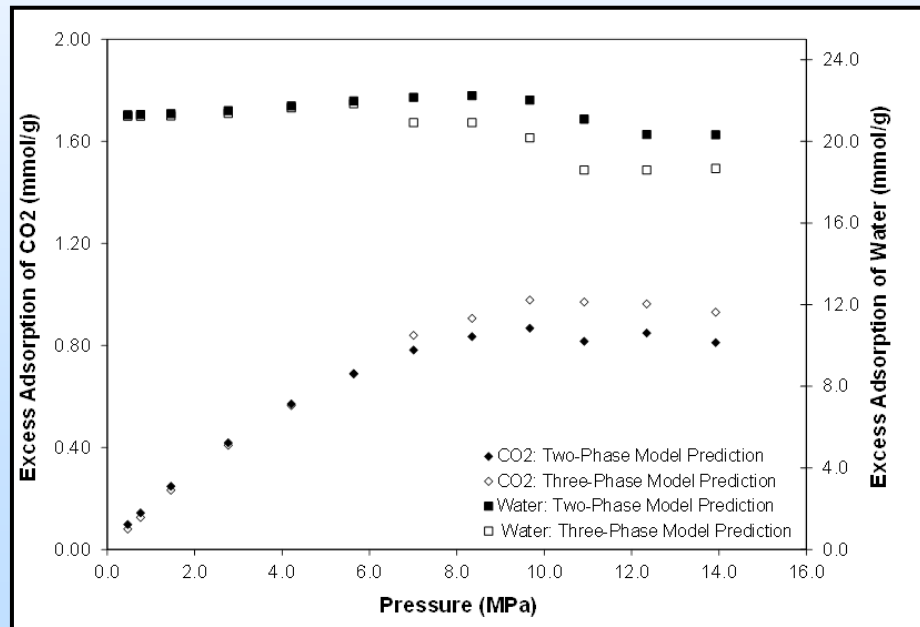
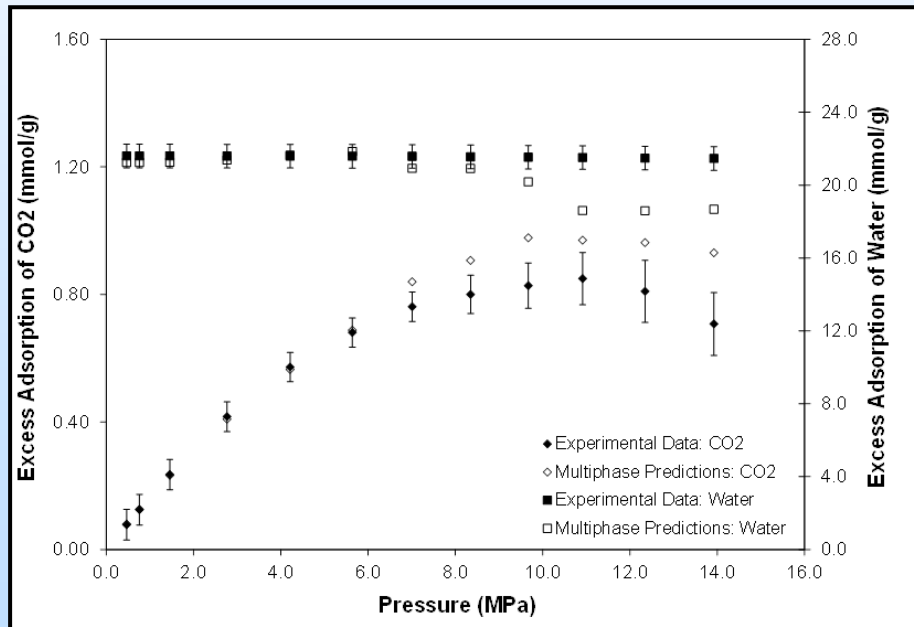
Technical Status - Task 4

Modeling CO₂ Injection under In-Situ Conditions

• Adsorption – Gas/Water Mixtures

- Investigated competitive adsorption behavior of gas/water mixtures on wet coals
- Developed a new Gibbs-energy-driven multiphase (three-phase) algorithm for gas/water mixtures.

Example: Wet Wyodak Coal at 328.2 °K



Multiphase Predictions for CO₂/Water Mixture Adsorption

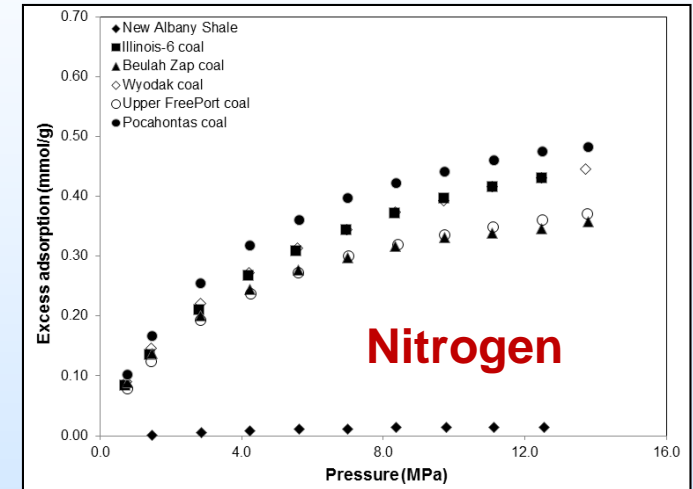
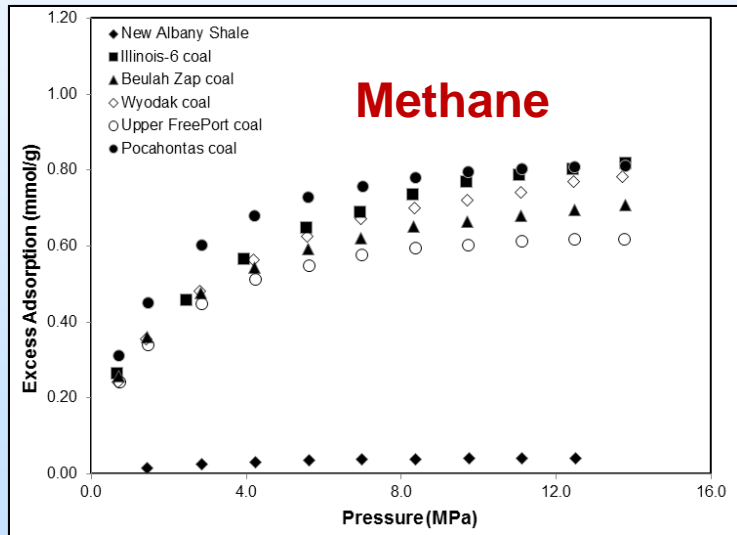
Comparison of Predictions from the Two- and Three-Phase Models for CO₂/Water Mixture Adsorption

Technical Status – Task 4

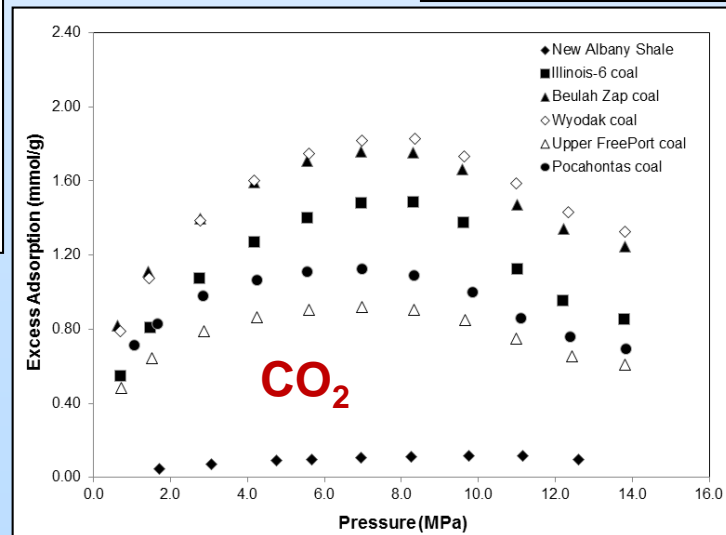
Modeling CO₂ Injection under In-Situ Conditions

- **Adsorption**

- New data for pure-gas adsorption on shale
- Extended coal adsorption models to the case of shale-gas adsorption.



Comparison of Adsorption on New Albany Shale and Argonne Coals at 328.2 °K



Technical Status – Task 4

Modeling CO₂ Injection under In-Situ Conditions

- **Equation-of-State (EOS)**

- A new equation-of-state volume-translation method provides accurate predictions of the saturated and single-phase densities of diverse classes of molecules
- Special emphasis on fluids found in reservoir systems.

$$p = \frac{RT}{v - b} - \frac{a(T)}{v(v + b) + b(v - b)}$$

Original Peng-Robinson EOS

$$V_{VTPR} = V_{PR} + C - \delta_c \left(\frac{0.35}{0.35 + d} \right)$$

Volume Translation Equation

Where:

$$C = \left(\frac{RT_c}{p_c} \right) (c_1 - (0.004 + c_1) \exp(-2d))$$



New Expression

C1 is a constant, fluid dependent parameter

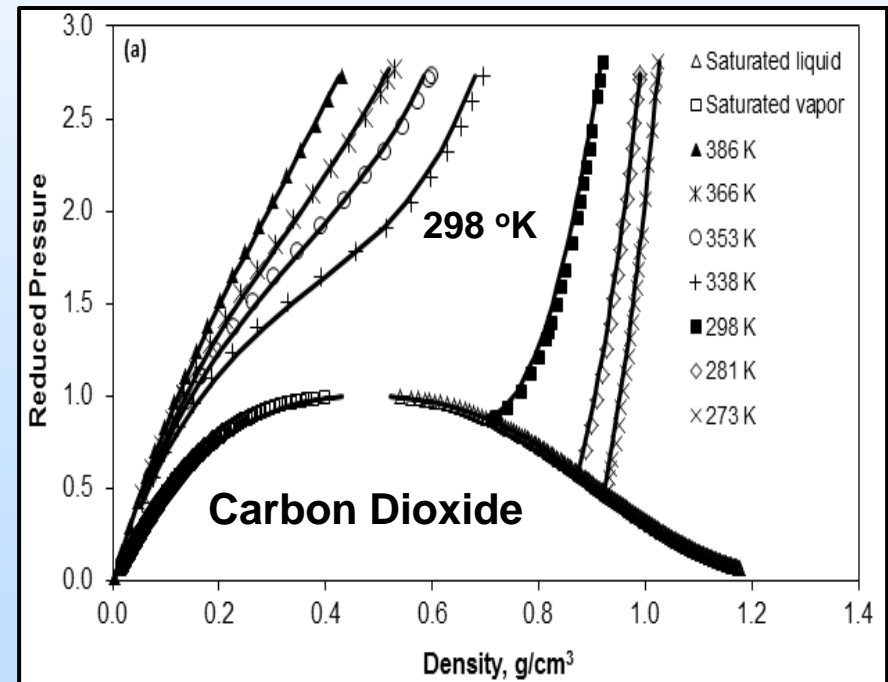
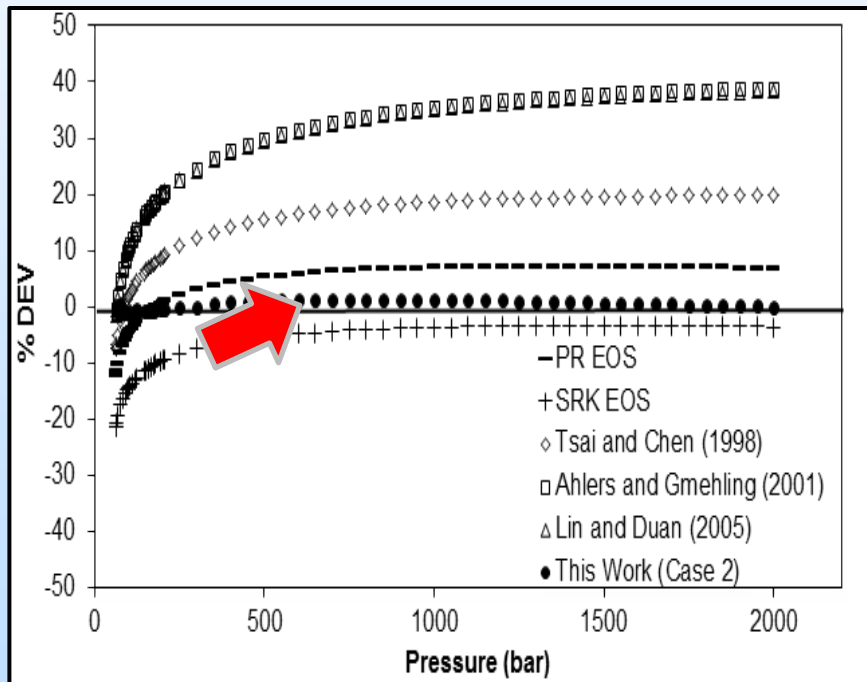
And:

$$d = \frac{1}{RT_c} \left(\frac{\partial p^{PR}}{\partial \rho} \right)_T \quad \delta_c = \left(\frac{RT_c}{p_c} \right) (z_c^{EOS} - z_c^{exp})$$

Technical Status – Task 4

Modeling CO₂ Injection under In-Situ Conditions

- **Equation-of-State (EOS) Predictions using the new Peng-Robinson EOS Volume Translation Method**
 - Predictions for single phase liquid densities & comparison with other models
 - Predictions of phase equilibrium calculations and volumetric properties

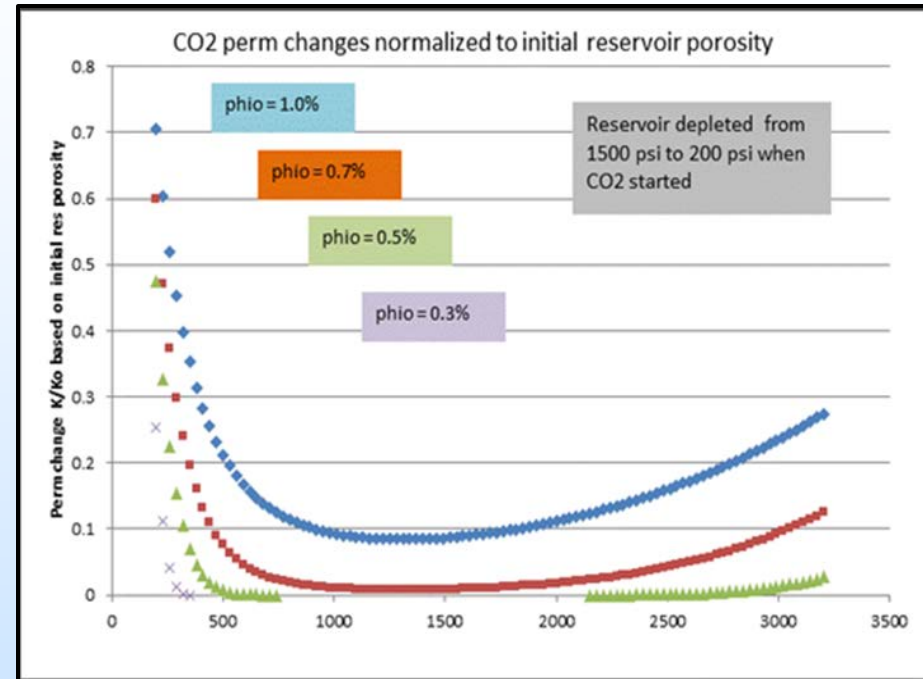


Example: Carbon Dioxide at 298 °K

Technical Status - Task 5

Advanced Modeling of Permeability Changes

- Permeability changes depend on initial cleat porosity and abandonment pressure.
- During CO₂ injection, the stress path moves away from the coal failure envelope due to:
 - replacement of CH₄ by CO₂, (2)
 - further injection of CO₂ to raise reservoir pressure.



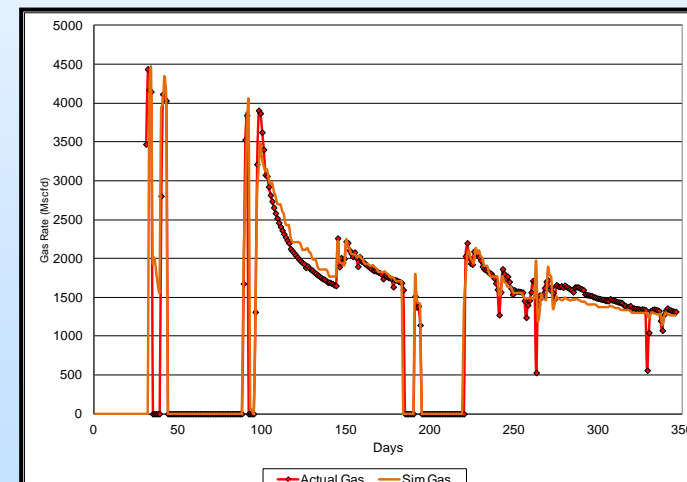
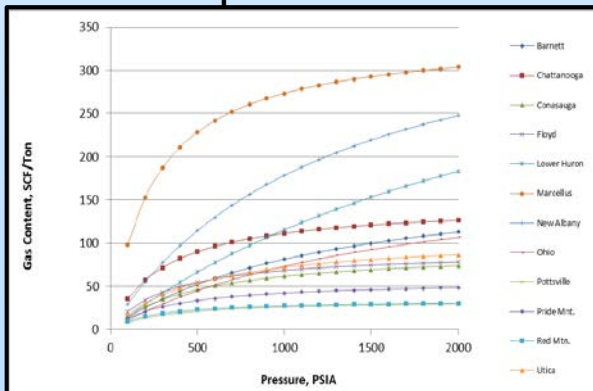
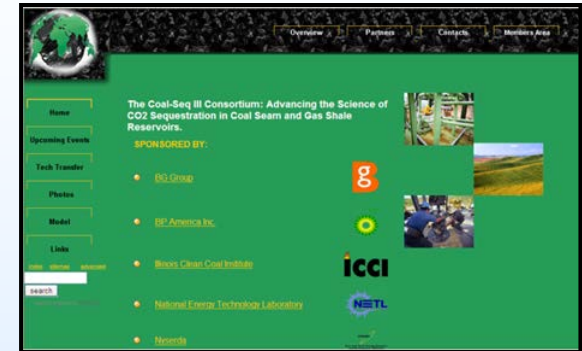
- **Shear failure of coal in a depleted CBM reservoir should not happen during CO₂ injection.**
 - failure of coal might happen before CO₂ injection if the reservoir is depleted to very low pressure (< 200 psi).



Technical Status – Task 6

Technology Transfer

- Flow and storage modeling for shale sequestration
- Testing of code against large-scale projects.
- Basin-oriented review of coal and shale storage potential.
- Coal and Shale Property Database
- Coal-Seq Screening Module
- Coal-Seq Website (www.coal-seq.com)
- Coal-Seq Forums



Accomplishments to Date

- Laboratory tasks 2 through 5 completed and reports final:
 - Changes in Coal Properties with Exposure to CO₂ - (No code required)
 - Cleat and Matrix Shrinkage/Swelling
 - Modeling of CO₂ Injection under Field Replicated Conditions - (Code delivered to DOE)
 - Advanced Modeling of permeability changes during CO₂ sequestration
- Flow and Storage Modeling for Shale Sequestration completed
 - Includes a detailed history match of a Marcellus Shale well
- Coal and Shale Property database assembled
- Two Coal-Seq Forums held

Key Findings/Lessons Learned

Tasks 2 and 3 – Change in Coal and Shale Properties with CO₂ Injection; Cleat and Matrix Swelling/ Shrinkage

- Observed changes in Poisson's ratio and Young's modulus due to injection of CO₂ are too small to support the theory of “coal weakening associated with methane depletion or CO₂ injection”.
- CO₂ injection should be quantity-controlled rather than pressure-controlled to prevent rapid swelling, tensional strain and coal failure in the vicinity of the injection.
- Coal compressibility, expressed by parameters, C_p and C_m , is not constant, but will vary as the pore pressure of the sorbing gas changes in the reservoir.

Key Findings/Lessons Learned

Task 4 – Modeling CO₂ Injection Under In-Situ Conditions

- Formulated a new approach for modeling the competitive adsorption of gas/water mixtures.
- Developed a rigorous model for describing the adsorption-induced swelling of coals.
- Developed a new volume-translation function for saturated and single-phase liquid densities at high-pressures.
- Generalized the Peng-Robinson equation of state for describing the vapor-liquid equilibrium of gas/water mixtures at high-pressures.
- Provided new data and insight to gas adsorption behavior on wet coals by measurement of CO₂ isotherms on wet coals.
- Provided new data for pure-gas adsorption on shale and have extended coal adsorption models to the case of shale-gas adsorption.

Key Findings/Lessons Learned

Task 5 – Advanced Modeling of Coal Permeability Changes

- **Permeability Changes With Methane Depletion**
 - Successful history match of exponential permeability increase up to failure in a San Juan Basin CBM well.
 - General behavior is a flattening of the exponential permeability increase with depletion, **interpreted as a loss of permeability due to fines creation.**
 - If cleat porosity is greater than 0.5%, there appears to be no appreciable permeability increase with depletion.
 - **To model the observed permeability increase with depletion, cleat porosity must be less than 0.2%.**
- **Permeability Changes After Coal Failure**
 - Permeability after failure appears to vary from well-to-well.
 - Modeling permeability changes after failure is important to better forecast long term gas rates and ultimate recovery in San Juan CBM wells.
 - **Shear failure of coal in a depleted CBM reservoir should not happen during CO₂ injection.**
 - However, it might happen before CO₂ injection if the reservoir is depleted to very low pressure (< 200 psi).

Key Findings/Lessons Learned

Task 5 – Advanced Modeling of Coal Permeability Changes

- **Permeability Changes With CO₂ Injection**

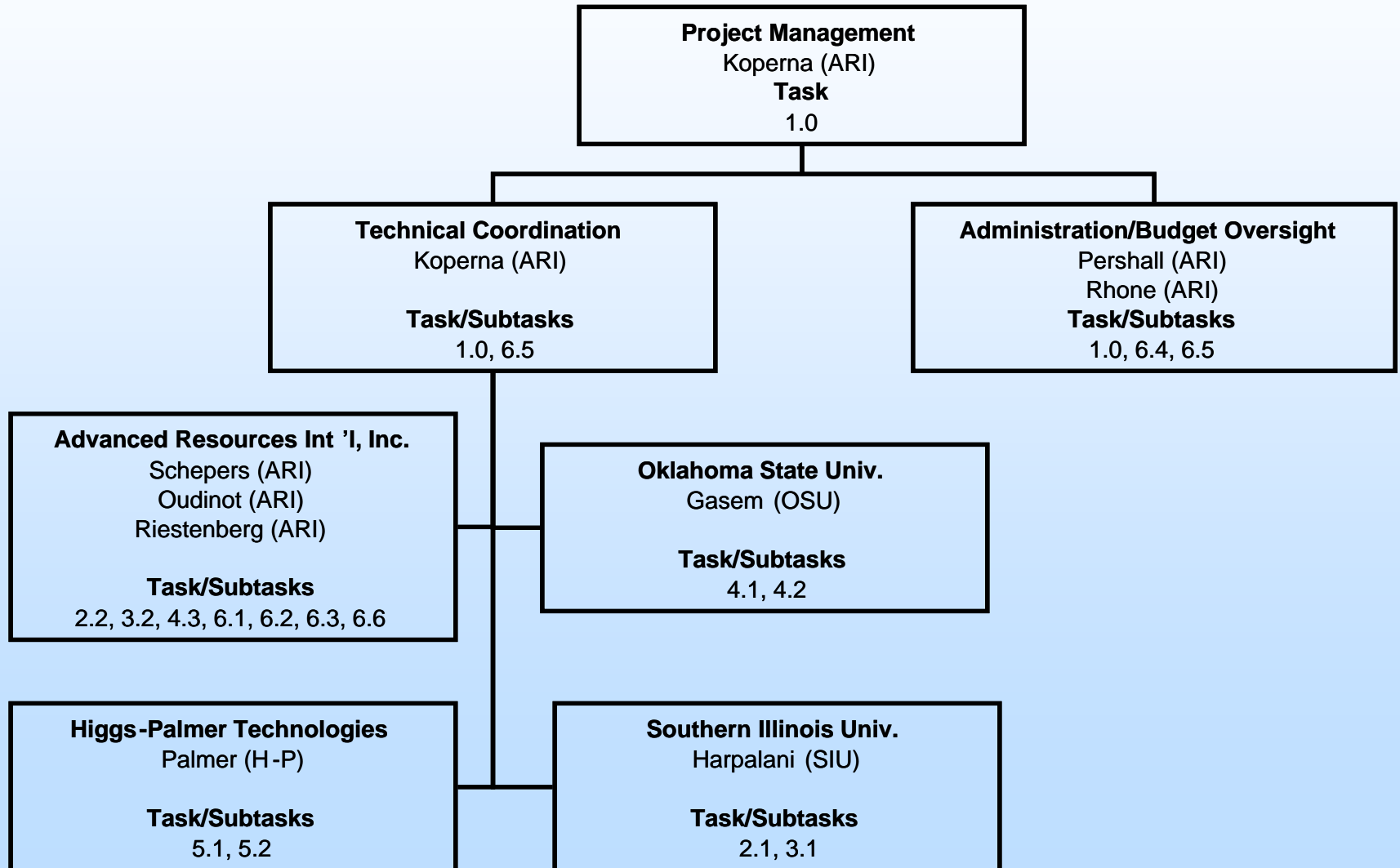
- Tensile failure should occur if during CO₂ injection, reservoir pressure exceeds overburden pressure, creating horizontal cracks along bedding planes.
- This would also increase CO₂ injectivity, unless the tensile failure created coal fines that plugged the fractures.
- At low depletion pressure, CO₂ is injected while raising reservoir pressure. CO₂ replaces methane and matrix swelling exceeds the effect of pressure-induced cleat inflation, significantly reducing coal porosity and permeability. Coal anisotropies suppress cleat inflation.
- **CO₂ injectivity is predicted to be difficult in the San Juan basin due to cleat anisotropy ($g \approx 0.2$), plus very low initial cleat porosity.**
- **Ideal strategy for successful CO₂ injection: Inject CO₂ at the lowest depletion pressure possible, and at a rate slow enough that reservoir pressure barely rises.**

Next Steps and Future Plans

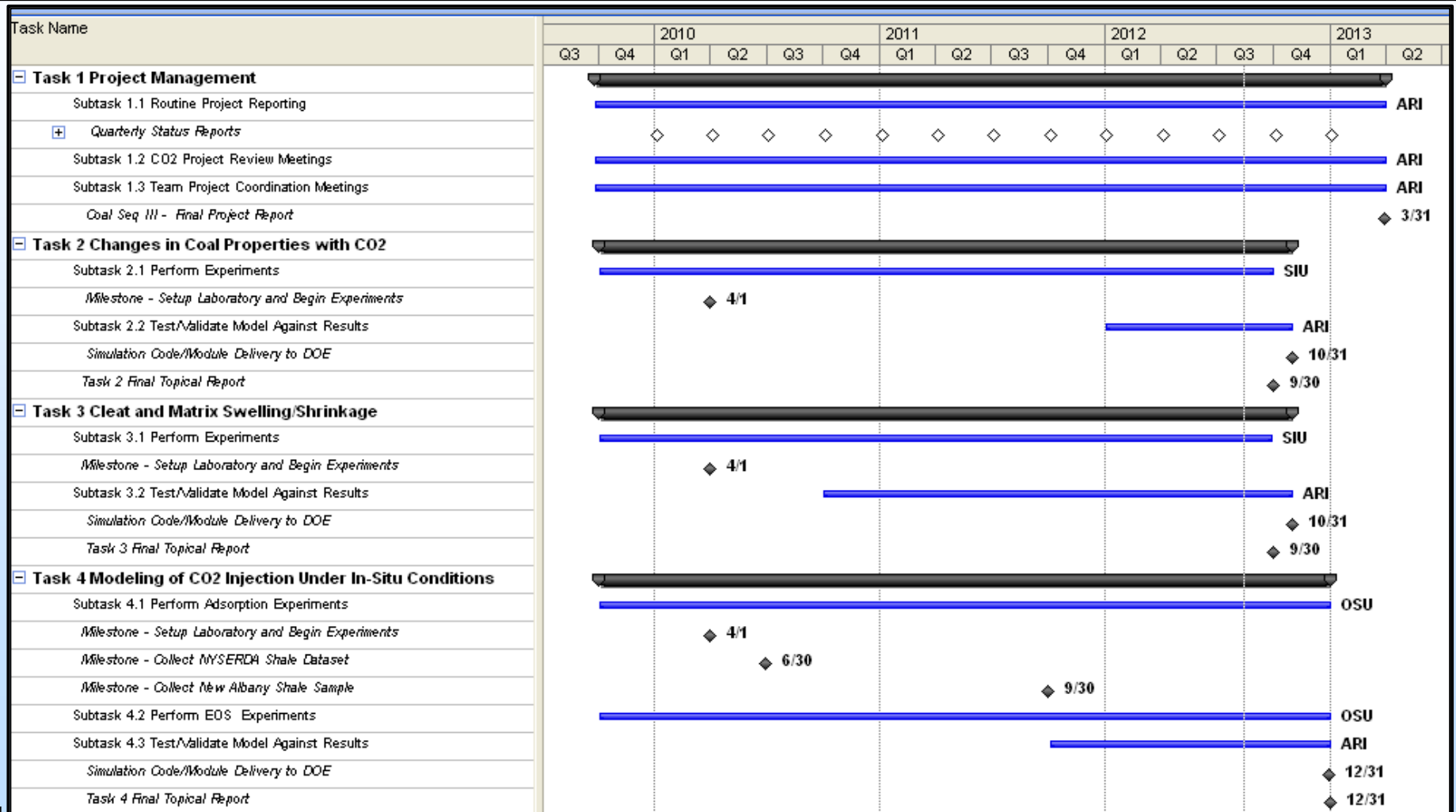
- **Final Steps**

- Testing of Code Against Large Scale Projects
 - Insert simulation modules into a stand-alone simulation code
 - Validate code against field data set (Pump Canyon CO₂/ECBM pilot)
- Basin Oriented Review of Coal and Shale Storage Potential
 - Assess the CO₂ storage potential of San Juan Basin's Fruitland Coal & the Marcellus Shale
- Coal/Shale Property Database
 - Database of porosity and CO₂ and methane isotherms for US coal and shale gas basins
 - Data from public and private sources
 - Database will serve as basis for the Screening Model
- Screening Model
 - Develop a screening model capable of estimating CO₂ storage for gas shale and coal seam reservoirs
 - Will include findings from CoalSeq III (shrinkage/swelling and failure)
 - Will be built in Visual Basic
 - Input parameters will be available to choose from the Coal/shale Property Database
 - Previous simulations will provide CO₂ storage volumes and injection rates

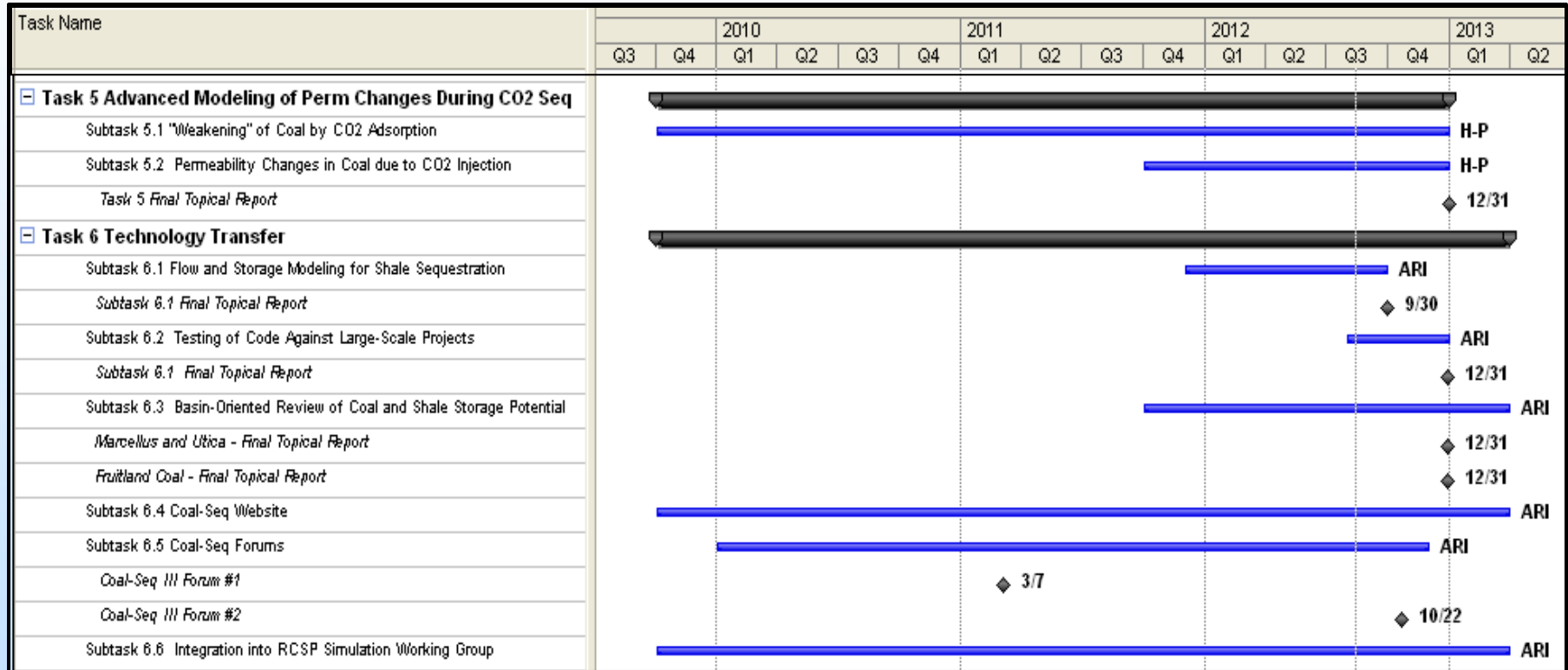
Appendix: Organization Chart



Appendix: Gantt Chart



Appendix: Gantt Chart, cont.



Appendix: Bibliography

- Agelia M. Abudour, Sayeed A. Mohammad, Robert L. Robinson, Jr., Khaled A.M. Gasem. “Volume-translated Peng Robinson Equation of State for Saturated and Single-Phase Liquid densities.” *Fluid Phase Equilibria*, 335, 74-87, 2012.
- 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.
- Sayeed A. Mohammad, Arunkumar Arumugam, Robert L. Robinson, Jr., Khaled A. M. Gasem. “High-Pressure Adsorption of Pure Gases on Coals and Activated Carbon: Measurements and Modeling.” *Energy Fuels*, 26 (1), 536–548, 2012.

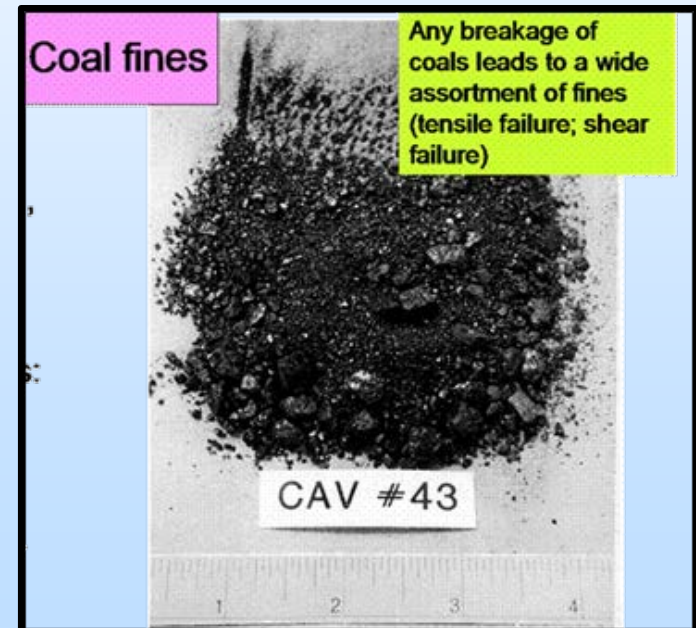
Appendix: Bibliography, cont.

- 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.*
- 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.

Technical Status - Task 5

Advanced Modeling of Permeability Changes

- Two opposing permeability effects can occur near coal shear failure:
 - Permeability can increase due to dilatancy (brittle failure).
 - Permeability can decrease due to changes in coal mechanical properties, or due to creation of coal “fines”.
 - Which permeability change occurs will depend partly on coal rank.
- From analysis of field data, it appears that permeability flattens or decreases after failure occurs at low reservoir pressure.
- Permeability decrease is expected due to fines creation, movement, and plugging, especially in a soft rock such as coal.



Technical Status – Task 5

Advanced Modeling of Permeability Changes

- Coal failure can be predicted through field data
- A new Palmer-Higgs (P-H) model has been developed and is able to predict when failure will occur.

