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

Project Number (DE FE0001560)

George J. Koperna Jr.

Anne Oudinot

Advanced Resources International, Inc.

U.S. Department of Energy

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

August 20-22, 2013

Coal-Seq Consortium

A public-private research partnership to improve the understanding of CO_2 within coal and shale reservoirs.

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NYSERDA
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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 CO_2 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 CO_2. When complete, this work will more accurately predict permeability/ injectivity in these reservoir types, contributing to the Program goal of more accurately predicting CO_2 storage capacity in geologic formations.

Project Overview: Goal and Task Objectives

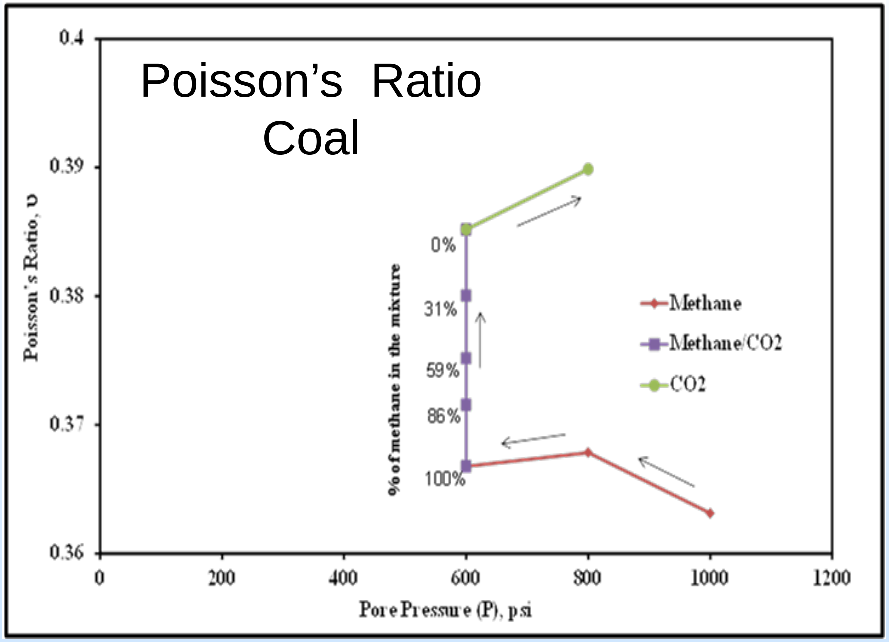
Goal:

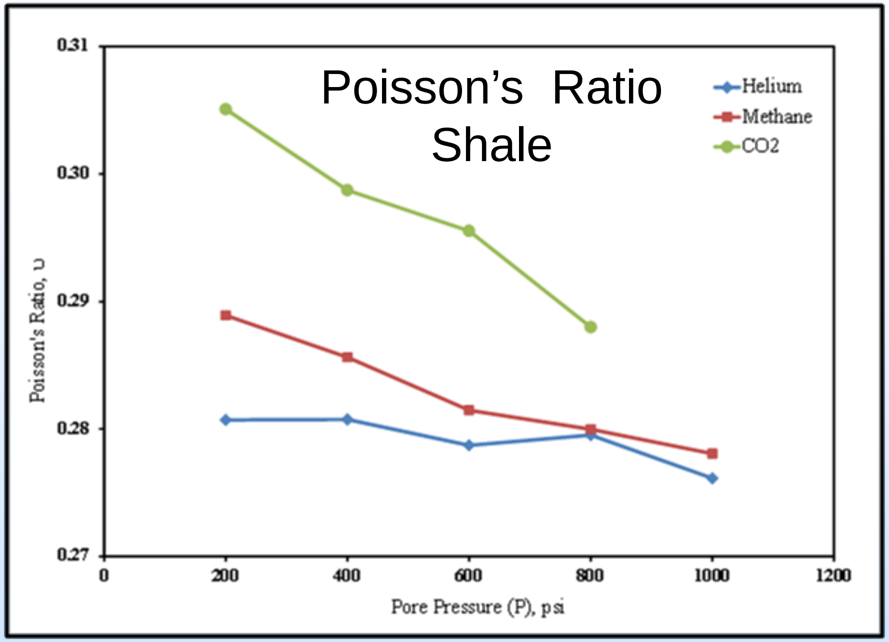
Develop robust mathematical models to accurately predict how coal and shale permeability and injectivity change with CO_2 injection, incorporating the following the Task Objectives:

Objectives:

- **Task 2 –** Observe and measure changes in coal and shale mechanical properties with exposure to high pressure $CO_{2.}$
- **Task 3 -** Investigate cleat and matrix swelling and shrinkage during gas production and CO_2 injection.
- **Task 4 -** Model CO_2 injection under in-situ conditions and develop improved algorithms and adsorption models.
- **Task 5** – Advanced simulation of coal permeability changes during CO_2 injection and storage.

Technical Status - Task 2
Change in Coal and Shale Properties

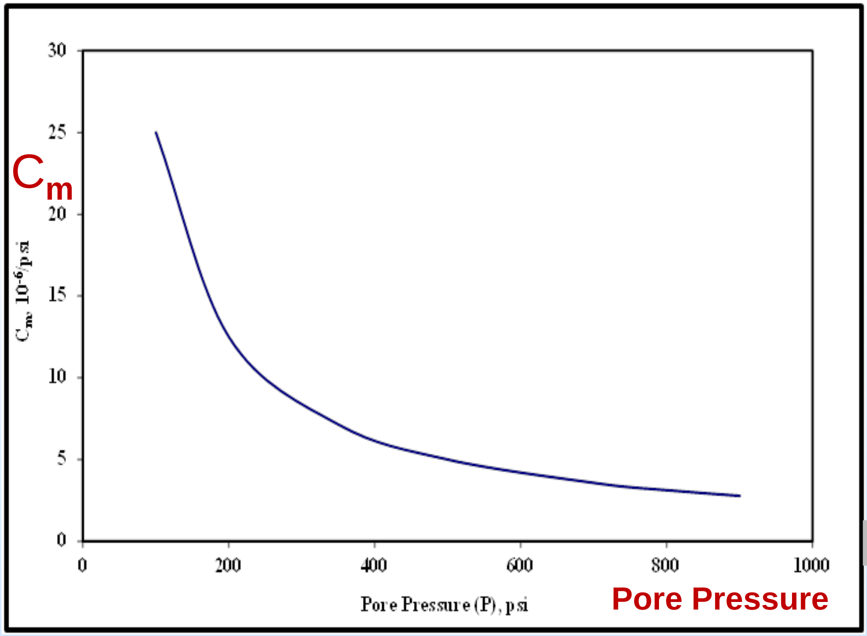

Poisson's Ratio
Coal


Poisson's Ratio
Shale

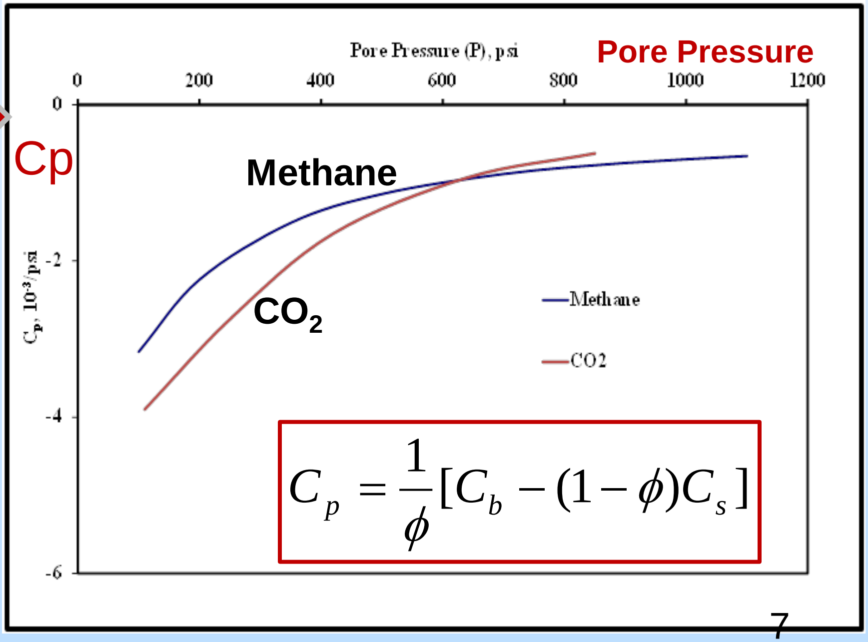
- **COAL** - Young's Modulus decreases & Poisson's Ratio increases when methane is displaced with CO_2 indicating that *the sample does get softer,* although *changes are not significant*.
- **SHALE** – Relative to methane, CO_2 weakens shale because the change in Poisson's Ratio with pore pressure is larger for CO_2 than for methane.

Technical Status – Task 3

Investigate Cleat & Matrix Swelling/ Shrinkage



Compressibility under replicated field conditions



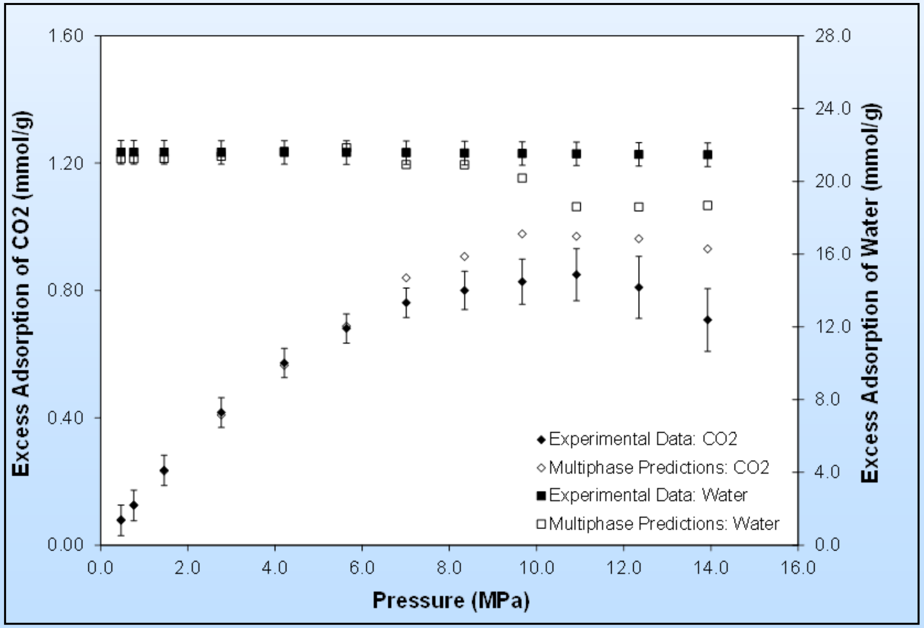
$$\boxed{C_p = \frac{1}{\phi}[C_b - (1-\phi)C_s]}$$

- Coal compressibility 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).

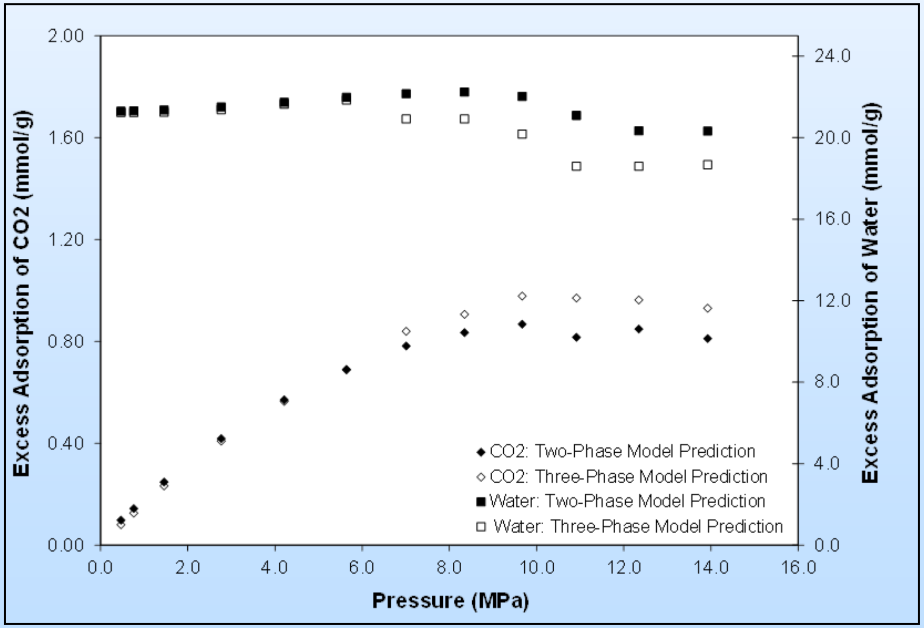
Technical Status - Task 4
Modeling CO_2 Injection under In-Situ Conditions

- **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 ^{o}K



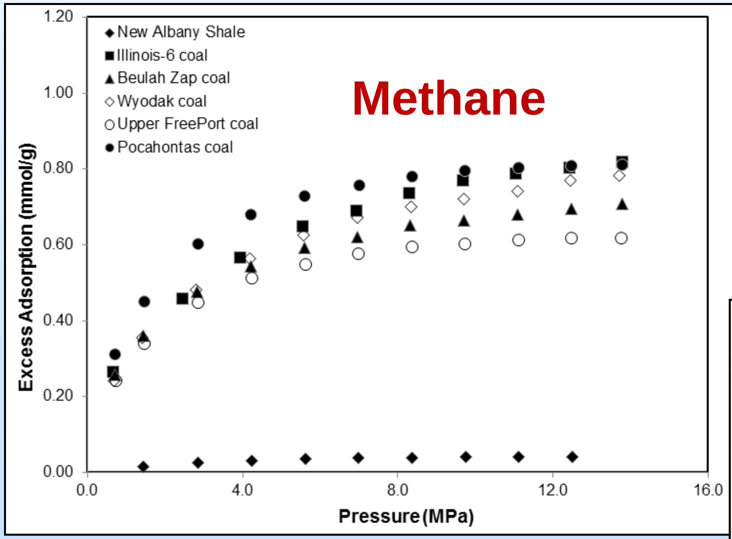
Multiphase Predictions for CO_2/Water Mixture Adsorption

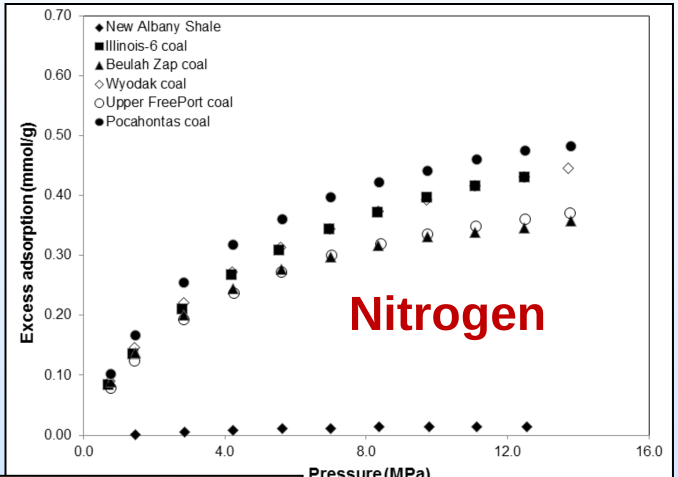


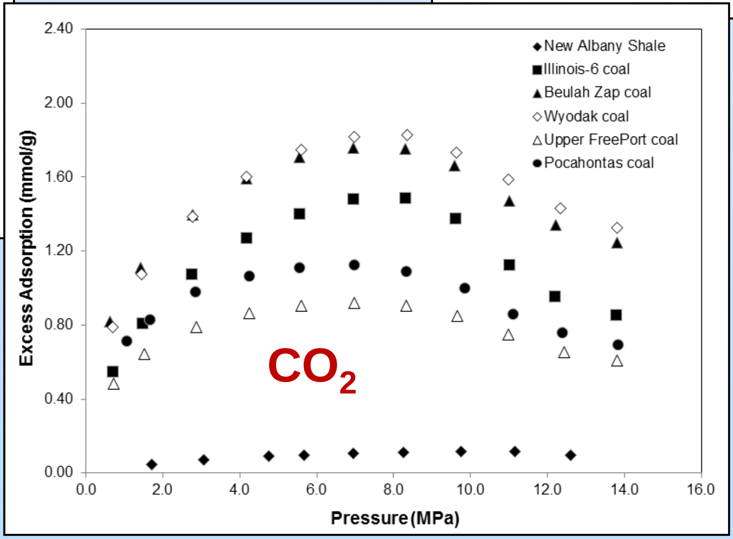
Comparison of Predictions from the Two- and Three-Phase Models for CO_2/Water Mixture Adsorption

Technical Status – Task 4
Modeling CO_2 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 ^{o}K

Technical Status – Task 4
Modeling CO_2 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:

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

New Expression

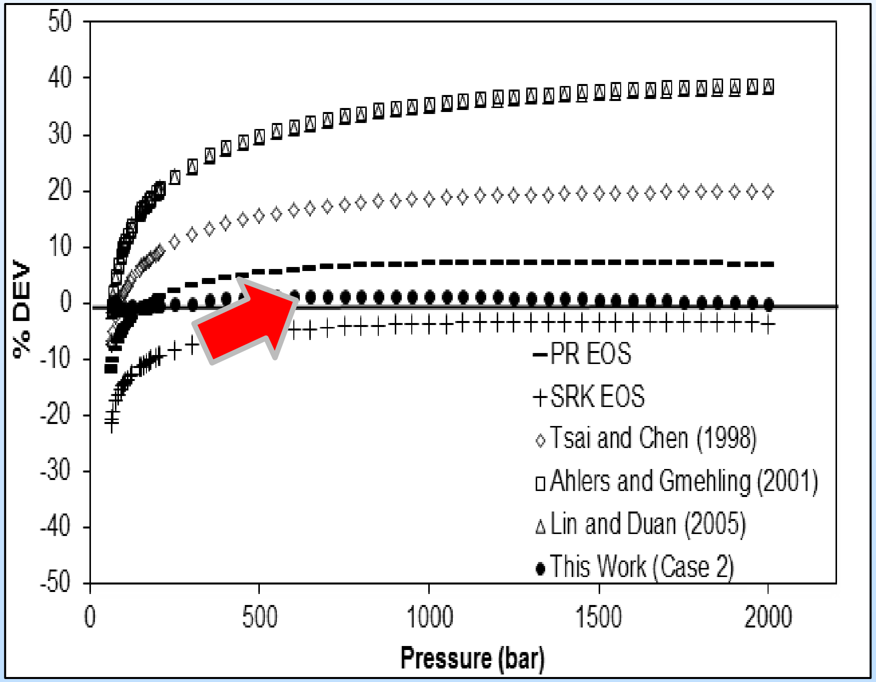
C1 is a constant, fluid dependent parameter

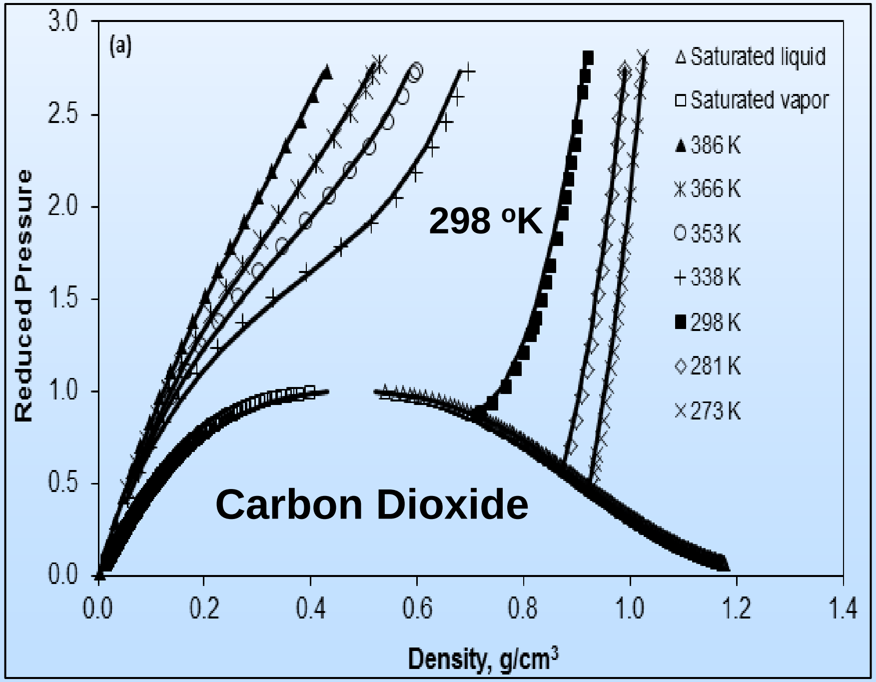
And:

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

Technical Status – Task 4
Modeling CO_2 Injection under In-Situ Conditions

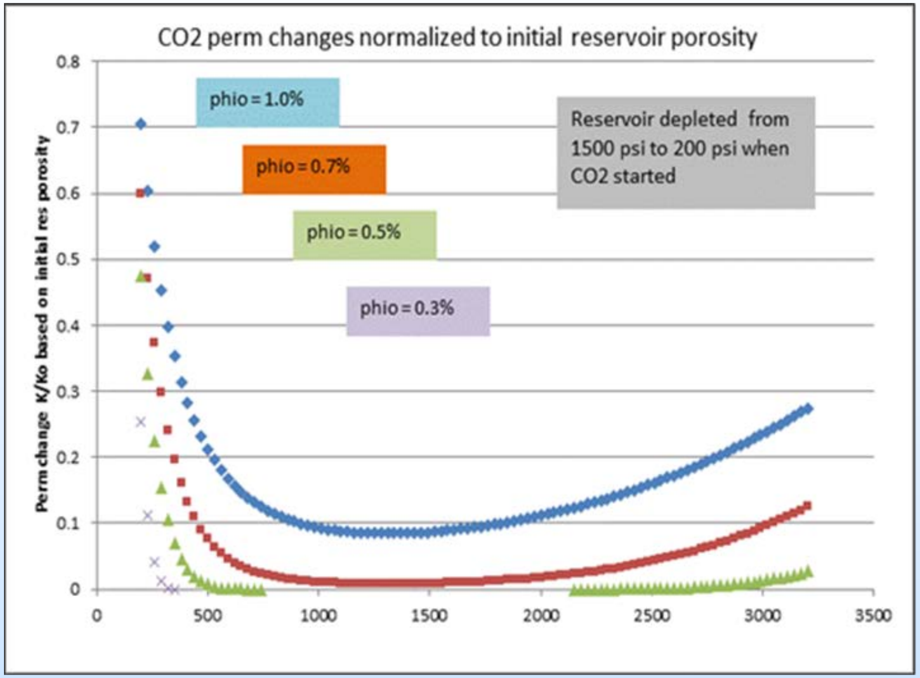
- **Equation-of-State (EOS) Predictions using the new Peng-Robinson EOS Volume Translation Method**
  - Predictions for single phase liquid densities & comparison with other models
  - Predictions of phase equilibrium calculations and volumetric properties





Example: Carbon Dioxide at 298 ºK

Technical Status - Task 5
Advanced Modeling of Permeability Changes



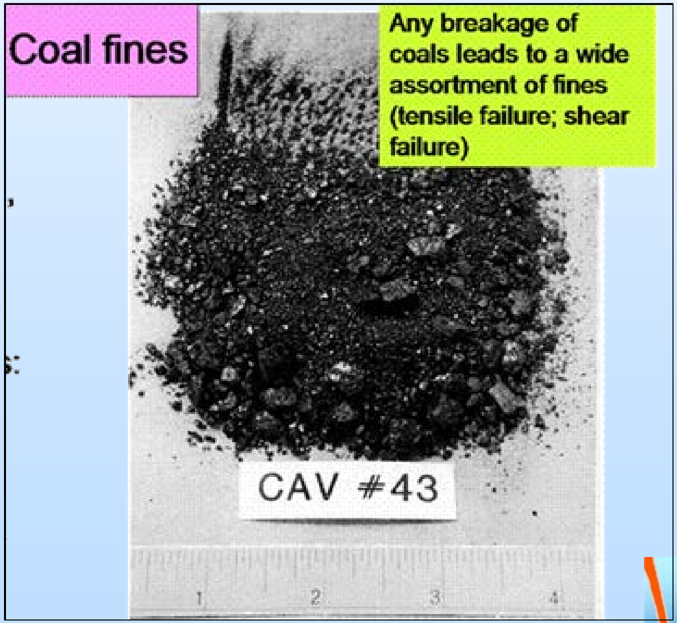
- Permeability changes depend on initial cleat porosity and abandonment pressure.

- During CO_2 injection, the stress path moves away from the coal failure envelope due to:
  - replacement of CH_4 by CO_2, (2)
  - further injection of CO_2 to raise reservoir pressure.

- Shear failure of coal in a depleted CBM reservoir should not happen during CO_2 injection.
  - failure of coal might happen before CO_2 injection if the reservoir is depleted to very low pressure (< 200 psi).

Technical Status - Task 5
Advanced Modeling of Permeability Changes

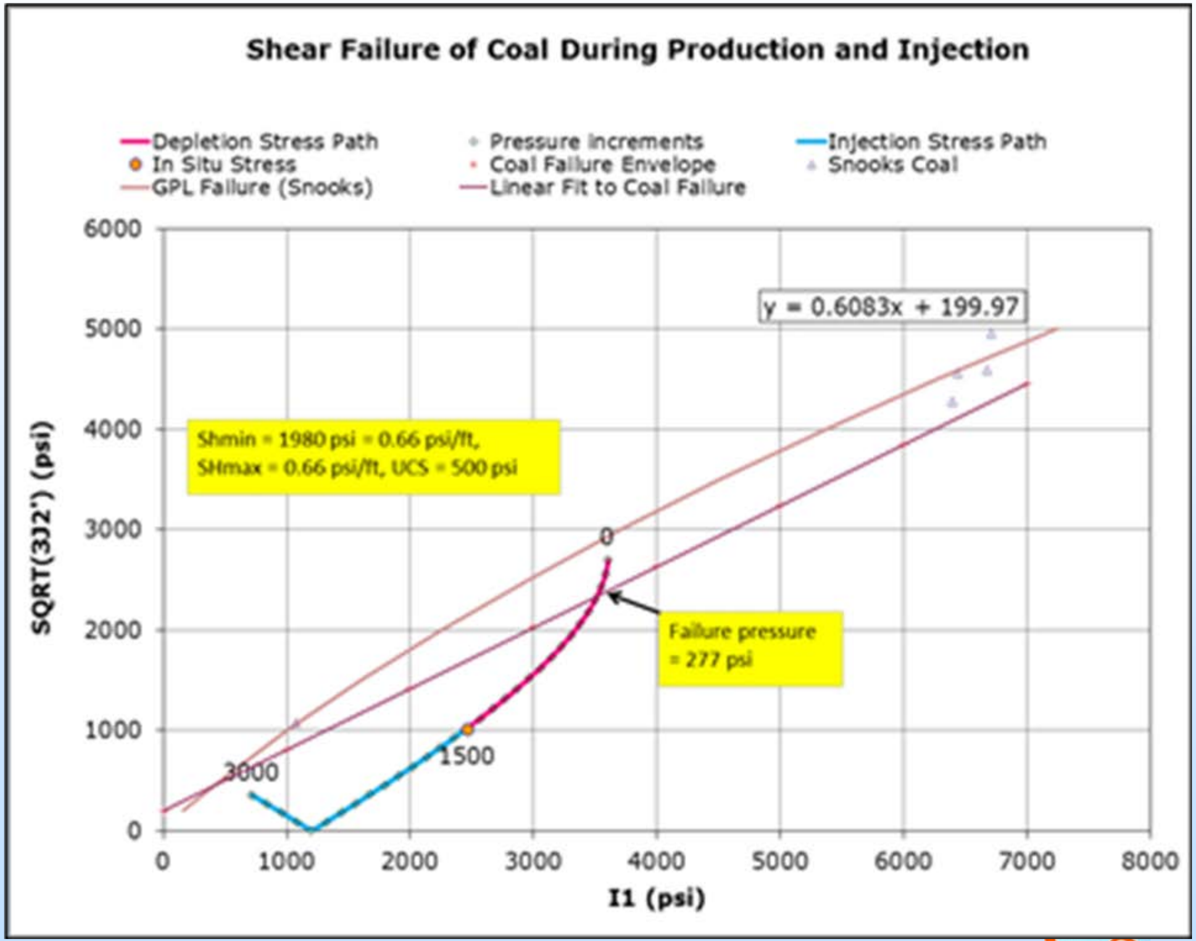
- Two opposing permeability effects can occur near coal shear failure:
  - Permeability can <u>increase</u> due to dilatancy (brittle failure).
  - Permeability can <u>decrease</u> due to changes in coal mechanical properties, or due to creation of coal “fines”.
  - Which permeability change occurs will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



Any breakage of coals leads to a wide assortment of fines (tensile failure; shear failure)

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.

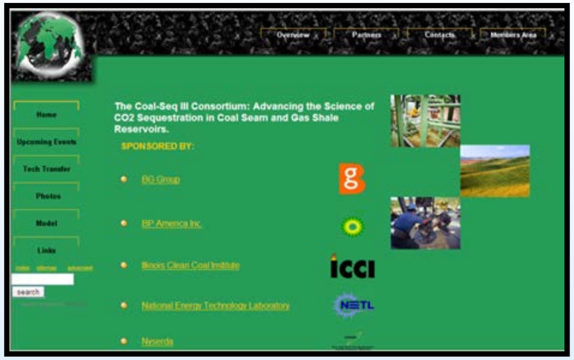

Shear Failure of Coal During Production and Injection

Shmin = 1980 psi = 0.66 psi/ft,
SHmax = 0.66 psi/ft, UCS = 500 psi

Failure pressure
= 277 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-Seq Website (www.coal-seq.com)
- Coal-Seq Forums



The Coal-Seq III Consortium: Advancing the Science of CO2 Sequestration in Coal Seam and Gas Shale Reservoirs.

SPONSORED BY:

- BG Group
- BP America Inc.
- Illinois Clean Coal Institute
- National Energy Technology Laboratory
- Nyserda

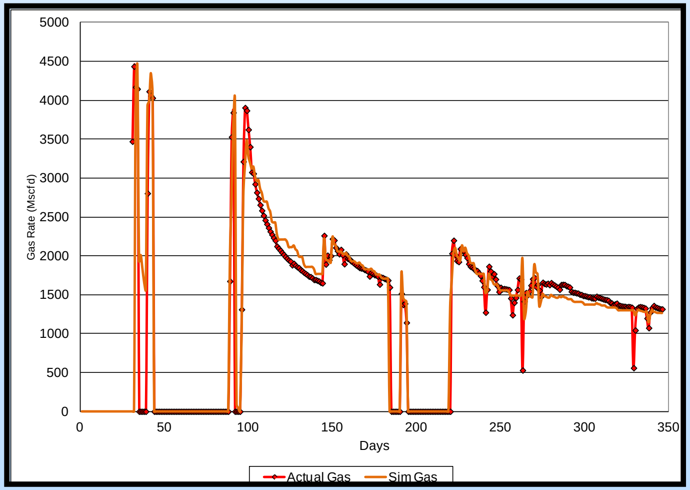
- Coal-Seq Forum VIII, was held in Pittsburgh, PA October 23- 24, 2012

Advanced Resources International, Inc.

Accomplishments to Date

- Tasks 2 to 5 completed.
- Final reports sent to DOE.
- Detailed history match of a Marcellus Shale well.


New Albany Shale



Key Findings/Lessons Learned

Tasks 2 and 3 – Change in Coal and Shale Properties with CO_2 Injection; Cleat and Matrix Swelling/ Shrinkage

- Observed changes in Poisson’s ratio and Young’s modulus due to injection of CO_2 are too small to support the theory of “coal weakening associated with methane depletion or CO_2 injection”.
- CO_2 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 CO_2 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 CO_2 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 CO_2 injection**.
  - However, it might happen before CO_2 injection if the reservoir is depleted to very low pressure (< 200 psi).

Key Findings/Lessons Learned

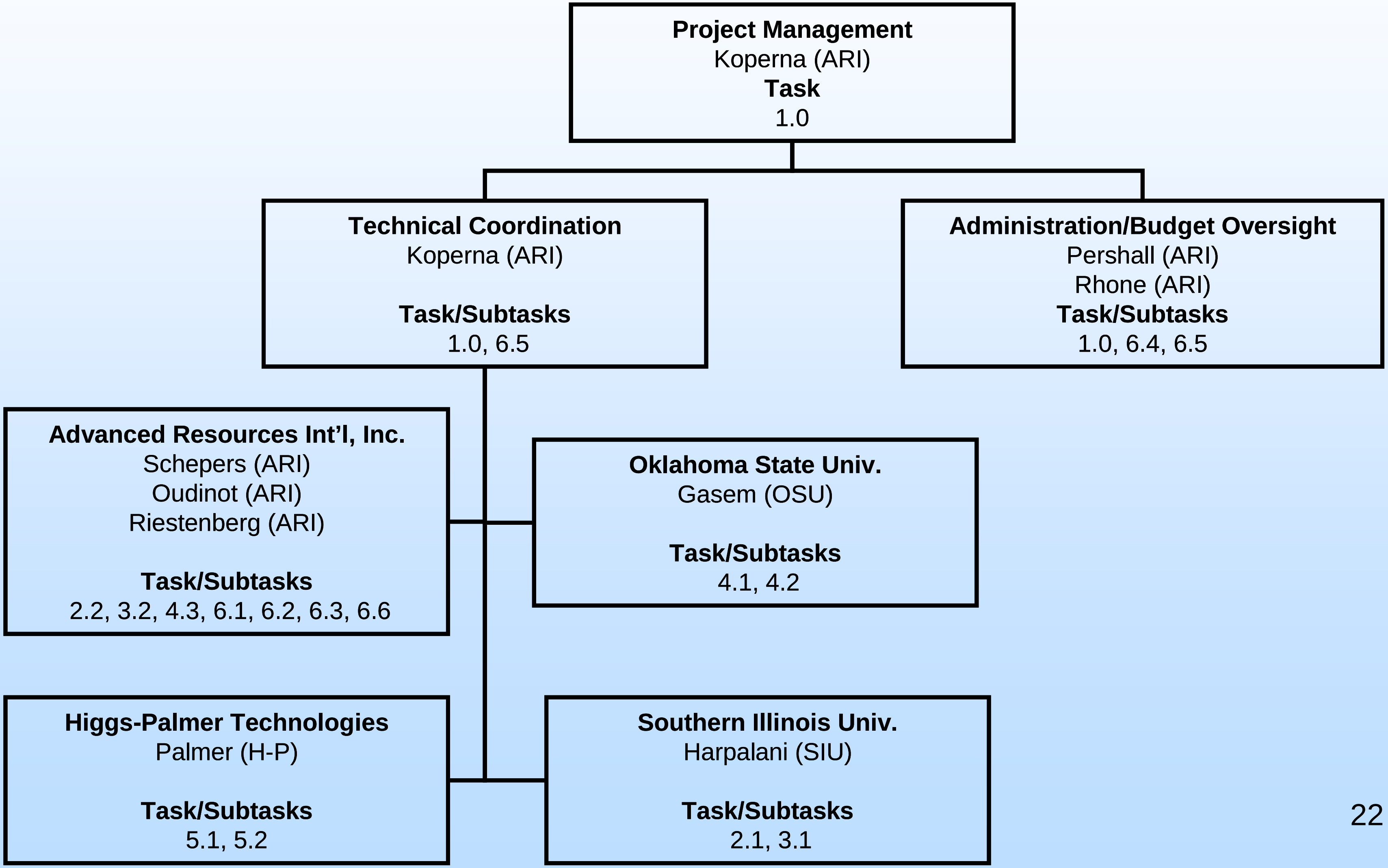
Task 5 – Advanced Modeling of Coal Permeability Changes

- **Permeability Changes With CO_2 Injection**
  - Tensile failure should occur if during CO_2 injection, reservoir pressure exceeds overburden pressure, creating horizontal cracks along bedding planes.
  - This would also increase CO_2 injectivity, unless the tensile failure created coal fines that plugged the fractures.
  - At low depletion pressure, CO_2 is injected while raising reservoir pressure. CO_2 replaces methane and matrix swelling exceeds the effect of pressure-induced cleat inflation, significantly reducing coal porosity and permeability. Coal anisotropies suppress cleat inflation.
  - **CO_2 injectivity is predicted to be difficult in the San Juan basin** due to **cleat anisotropy (g ≈ 0.2), plus very low initial cleat porosity.**
  - Ideal strategy for successful CO_2 injection: **Inject CO_2 at the lowest depletion pressure possible, and at a rate slow enough that reservoir pressure barely rises**.

Next Steps and Future Plans

- **Next Steps**
  - Testing of Code Against Large Scale Projects
    - Insert simulation modules into a stand-alone simulation code
    - Validate code against field data set (Allison Unit CO_2/ECBM pilot or Pump Canyon CO_2/ECBM pilot)
  - Basin Oriented Review of Coal and Shale Storage Potential
    - Assess the CO_2 storage potential of San Juan Basin's Fruitland Coal & the Marcellus Shale
- **Future Plans**
  - Coal/Shale Property Database
    - Database of porosity and CO_2 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 CO_2 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 CO_2 storage volumes and injection rates

Appendix:
Organization Chart



Project Management
Koperna (ARI)
Task
1.0

Technical Coordination
Koperna (ARI)

Task/Subtasks
1.0, 6.5

Administration/Budget Oversight
Pershall (ARI)
Rhone (ARI)
Task/Subtasks
1.0, 6.4, 6.5

Advanced Resources Int’l, Inc.
Schepers (ARI)
Oudinot (ARI)
Riestenberg (ARI)

Task/Subtasks
2.2, 3.2, 4.3, 6.1, 6.2, 6.3, 6.6

Oklahoma State Univ.
Gasem (OSU)

Task/Subtasks
4.1, 4.2

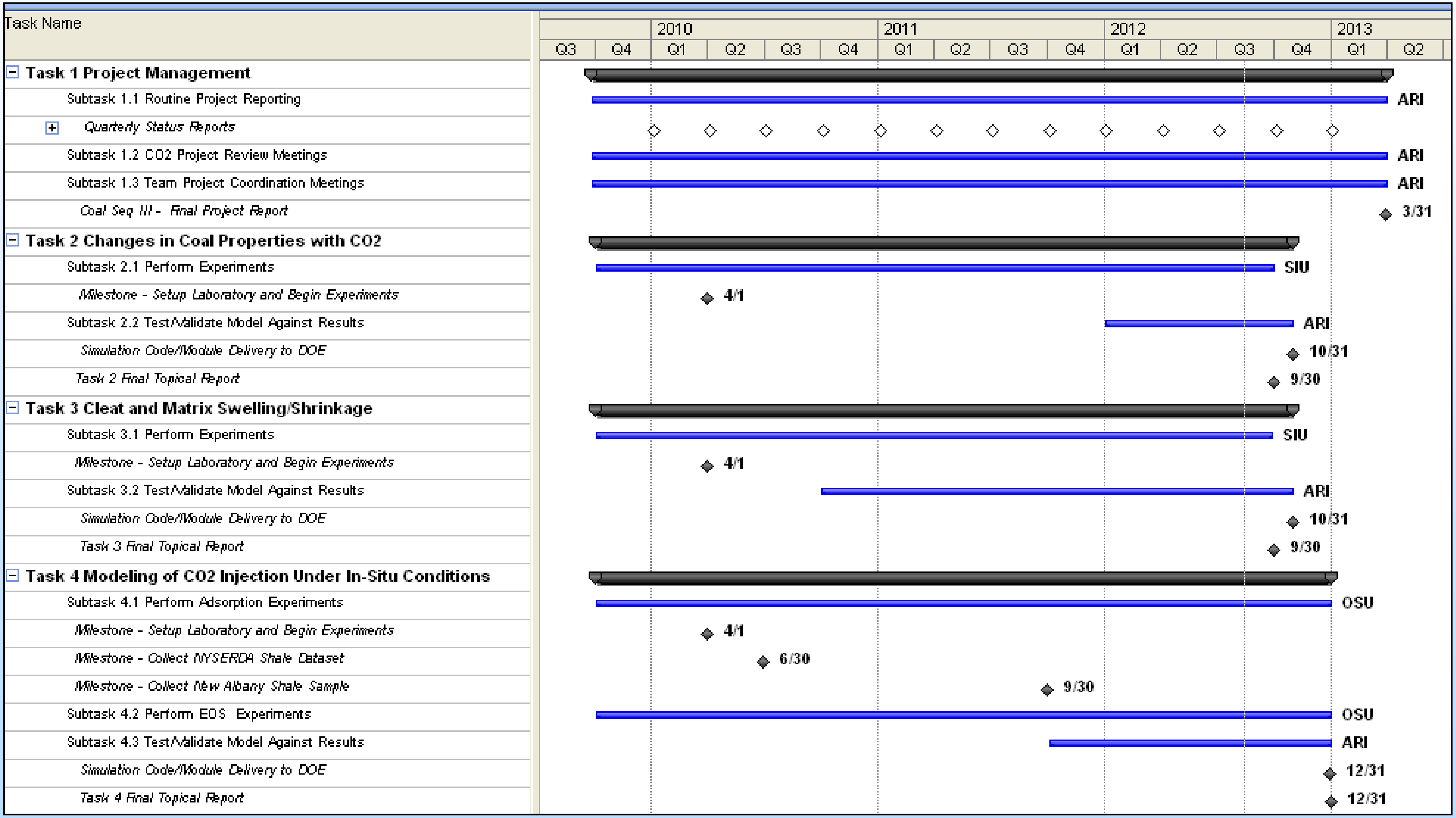
Higgs-Palmer Technologies
Palmer (H-P)

Task/Subtasks
5.1, 5.2

Southern Illinois Univ.
Harpalani (SIU)

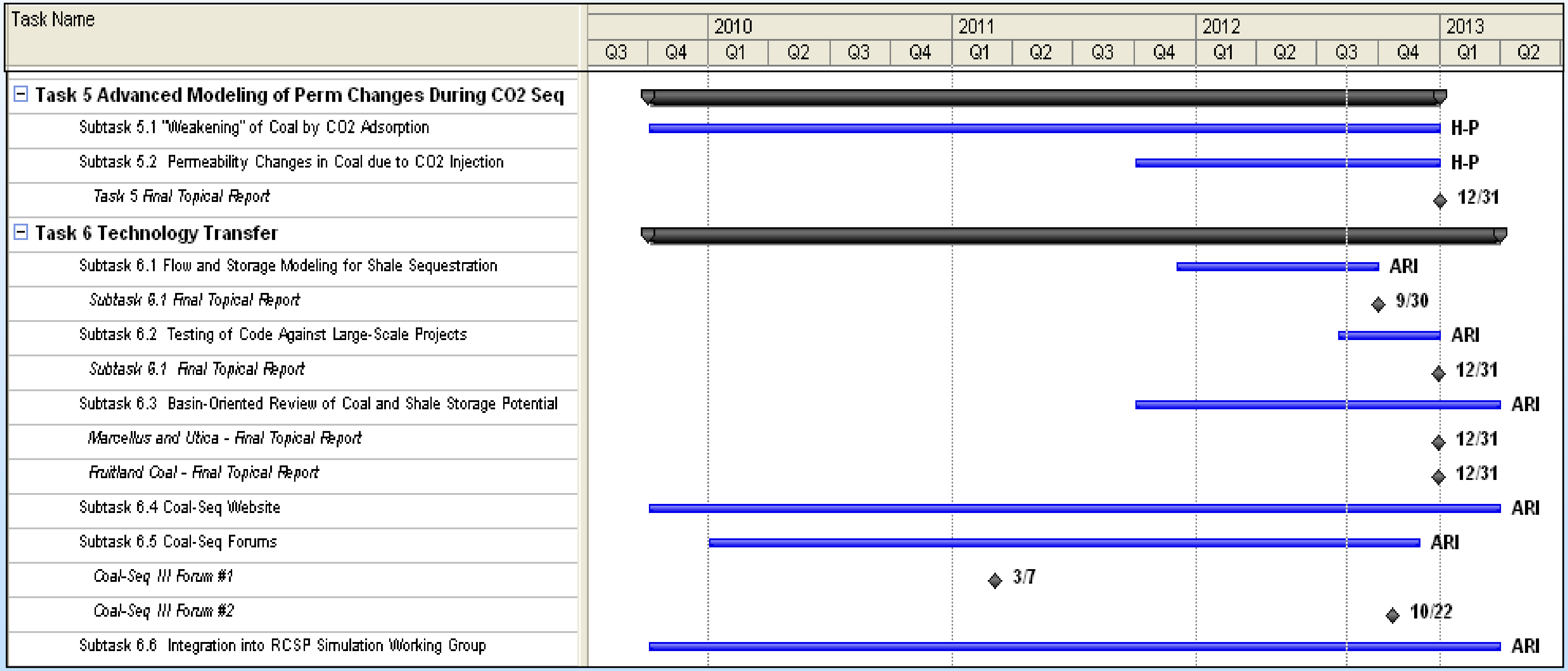
Task/Subtasks
2.1, 3.1

Appendix: Gantt Chart



Task Name	
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	
Subtask 3.1 Perform Experiments	SIU
Milestone - Setup Laboratory and Begin Experiments	4/1
Subtask 3.2 Test/Validate Model Against Results	ARI
Simulation Code/Module Delivery to DOE	10/31
Task 3 Final Topical Report	9/30
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

Appendix: Gantt Chart, cont.



Task Name	
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

Appendix: Bibliography

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- *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.*
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