Evaluating CO₂ Storage and Enhanced Recovery Potential of Shale Gas Formations

Robert Dilmore
Research Engineer,
Predictive Geosciences Division
Office of Research & Development
National Energy Technology Laboratory

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Image: Drill site in the Marcellus shale play. “Horizontal Drilling Rig” by Meredithw, licensed under COM:CCBY-SA
A national resource for Fossil Energy R&D, with a mission to create the knowledge base that can enable the safe, sustainable utilization of our abundant, domestic energy resources, in support of the DOE mission:

- Develops solutions to key barriers to implementation of emerging energy technologies.
- Explores transformational new concepts for next generation energy systems.
- Leverages core competencies to address issues of national concern.

Multi-disciplinary, multi-organizational research teams with strategic partnerships to add capability, capacity, and expertise.
Geologic & Environmental Sciences Focus Area

- Unconventional natural gas and oil environmental performance
- CO$_2$ storage – science base, resource assessment
- CO$_2$ storage – risk assessment, monitoring, and mitigation
- Understanding and reducing risks of offshore hydrocarbon development
- Predicting fracture growth and ground motion
- Improved recovery of natural gas and oil
- Methane hydrates recovery potential
- Water-energy nexus issues
Unconventional Resources Research
Focused on evaluating effects of shale gas development
Field Work to Characterize Performance of Unconventional Marcellus Wellpad

An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells are Hydraulically Fractured in Greene County, Pennsylvania

15 September 2014
Improving Science-Base for Materials & Wellbore Integrity

- Studying performance & integrity of key offshore materials for which data in extreme environments are limited
- Including metallic tubulars and borehole cements

Reducing Risks & Impacts Associated with Extreme Offshore Systems

- Developing critical data for predicting in situ conditions required for assessing risk, borehole/drilling design, loss of control conditions in deepwater & ultra-deepwater settings

Improving Safety through Rapid Detection & In Situ Characterization

- Tools & techniques to monitor and quickly detect potential hazards for extreme offshore hydrocarbon
National Risk Assessment Partnership

NRAP leverages DOE’s capabilities to help quantify uncertainties and risks necessary to remove barriers to full-scale CO₂ storage deployment.

Objective: Building toolsets and improving the science base to address key questions about potential impacts related to release of CO₂ or brine from the storage reservoir, and potential ground-motion impacts due to injection of CO₂
National Risk Assessment Partnership

NRAP leverages DOE’s capabilities to quantify risks and related uncertainties to help remove barriers to full-scale CO₂ storage deployment.

Simulating risk performance across the entire carbon storage system; and generating thousands of realizations to quantify uncertainties.
Multi-Scale CT Flow and Imaging User Facility

Measuring flow at in situ P, T, stress, and geochemical conditions

Simulating flow through pore and fracture networks

CT/well log comparison

Medical CT Scanner
-10^{-4} to 10^{-2} m
- Core scale
- Pressure, temperature, and flow controls

Industrial CT Scanner
-10^{-6} to 10^{-3} m
- Pore & core scale
- Pressure & flow controls

Micro CT Scanner
- Resolution 10^{-6} to 10^{-5} m
- Pore scale

Current Collaborations
Experimental observation of cement fracture self-healing
Industrial Carbon Management Initiative

Carbon Capture
Chemical Looping Combustion

Carbon Storage
Depleted Shale Fields

Carbon Utilization
Photocatalytic Conversion

CCUS for Industrial Applications

Industrial assessment and systems analysis
Objective: Develop a robust characterization of site-scale CO₂ storage and EGR potential of gas-bearing shale formations and preliminary assessment of potential economic viability.
**CO₂ Storage in Depleted Shale Gas Formations**

**Scenario:**
- Dry gas window, Marcellus, SW PA,
- Depth of 6,700 ft (~ 2,000 m),
- Gross interval thickness of 120 ft (37 m), 145ºF (63ºC),
- Initial pressure 4,000 psi (27.6 MPa),
- Matrix permeability 0.1 - 1 (μD)

**Sensitivity of CO₂ storage/EGR performance to:**
- Fracture network characteristics
- Matrix CO₂ and CH₄ sorption characteristics
- Injector/producer distance
- Injection pressure
- Stress-dependent matrix permeability

Overview of Technical Approach

- Experimental Characterization
  - Numerical Modeling
    - NG Production
  - Numerical Modeling
    - CO₂ storage in shale
  - Surrogate Reservoir Model Development
  - SRM Application
    - Techno-Economic Assessment

Cover Page: Experimental Characterization of Marcellus Shale Outcrop Samples, and their Interactions with Carbon Dioxide and Methane

6 February 2015

Office of Fossil Energy
NETL-TR-5-1-2015
CO$_2$ and CH$_4$ Sorption capacity as function of %TOC (single-fluid isotherms)

Core-Scale Characterization of Shale Matrix

**Industrial computed tomography scanner**
- ~25 μm resolution
- pre- and post- flooding scans

**Precision Petrophysical Analysis Lab**
- Steady-state flow measurements of effective pore volume and perm.
- Reproduce in-situ net stress

**Effective porosity of shale as function of net stress**

<table>
<thead>
<tr>
<th>Porosity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
</tr>
<tr>
<td>4.0</td>
</tr>
<tr>
<td>3.5</td>
</tr>
</tbody>
</table>

**Effective permeability of shale as function of net stress**

Marcellus Shale, Seneca Falls, NY

Image from: Kashiar Aminian; Discussion of PPAL capability at: SPE/DOE 11765, Symposium on Low Permeability Gas Reservoirs, Denver, CO, March 13-16, 1983
Overview of Technical Approach

Experimental Characterization

Numerical Modeling
- NG Production
- CO₂ storage in shale

Surrogate Reservoir Model Development

SRM Application
- Techno-Economic Assessment
Representing Fracture Networks

- Discrete Transverse Fracture Planes
  
  - Crushed Zone Representation
  
  - Semi-stochastic fracture network and flow modeling

- Discrete Fracture Modeling coupled with conventional reservoir simulation

- Modified dual porosity, multiphase, compositional, multidimensional flow model

- Semi-stochastic fracture network and flow modeling
Reservoir Simulation – Gas Depletion

Discrete Fracture Modeling coupled with conventional reservoir simulation

Modified dual porosity, multiphase, compositional, multidimensional flow model

Semi-stochastic fracture network and flow modeling

Single Lateral Depletion Gas Production and Pressure Field
Modeling CO$_2$ Flow in Fractured Shale
Incorporating matrix swelling/shrinkage effects

FRACGEN stochastically generates fracture networks

NFFLOW models flow in discrete fracture networks

Images from: Sams, N. Overview of NFFLOW & FRACGEN. June 3, 2013
Geo-modeling to Simulation workflow-Marcellus Shale

Well Logs

Structural Modeling

Property Modeling

Natural Fracture Modeling

Hydraulic Fracture -LGR

HF treatment modeling

History matching
### Selecting Well Pad With Representative Geologic and Stimulation Characteristics

#### Hydraulic Fracturing Data Comparison – All Pads vs. Model Pad

<table>
<thead>
<tr>
<th>Parameters</th>
<th>All Pads</th>
<th>Model Pad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stages</td>
<td>8-10</td>
<td>8-10</td>
</tr>
<tr>
<td>Number of cluster/stage</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Stimulated lateral length (ft)</td>
<td>2,500 – 3,500</td>
<td>2,573 – 3,102</td>
</tr>
<tr>
<td>Injected Proppant (lb)</td>
<td>4,000,000 – 6,000,000</td>
<td>3,794,742 – 5,099,860</td>
</tr>
<tr>
<td>Total slurry volume (bbl)</td>
<td>120,000 – 150,000</td>
<td>113,568 – 144,723</td>
</tr>
<tr>
<td>Average injection rate (bpm)</td>
<td>70 – 85</td>
<td>65 – 81.6</td>
</tr>
<tr>
<td>Average injection pressure (psi)</td>
<td>6,000 – 8,000</td>
<td>5,545 – 8,263</td>
</tr>
<tr>
<td>Initial shut in pressure (psi)</td>
<td>3,750 – 4,250</td>
<td>3,200 – 4,654</td>
</tr>
</tbody>
</table>
Well Pad Scale Prediction
Production and Formation Pressure/Saturation Response
# Gas Production Surrogate Reservoir Model

## CH4 Production NN-Input Parameters

<table>
<thead>
<tr>
<th>Static Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location (X,Y)</td>
</tr>
<tr>
<td>Min. Distance to Offset Injector-Producer (Fracture edge)</td>
</tr>
<tr>
<td>Top Cluster Type</td>
</tr>
<tr>
<td>T1-Km(I,K)-Marcellus</td>
</tr>
<tr>
<td>T2(+iBound)-Km(I,K)-Marcellus</td>
</tr>
<tr>
<td>T2(-iBound)-Km(I,K)-Marcellus</td>
</tr>
<tr>
<td>T3(+jBound)-Km(I,K)-Marcellus</td>
</tr>
<tr>
<td>T3(-jBound)-Km(I,K)-Marcellus</td>
</tr>
<tr>
<td>T1-Porosity-Marcellus</td>
</tr>
<tr>
<td>T2(+iBound)-Porosity-Marcellus</td>
</tr>
<tr>
<td>T2(-iBound)-Porosity-Marcellus</td>
</tr>
<tr>
<td>T3(+jBound)-Porosity-Marcellus</td>
</tr>
<tr>
<td>T3(-jBound)-Porosity-Marcellus</td>
</tr>
<tr>
<td>T1-Net Pay-Marcellus</td>
</tr>
<tr>
<td>T2(+iBound)-Net Pay-Marcellus</td>
</tr>
<tr>
<td>T2(-iBound)-Net Pay-Marcellus</td>
</tr>
<tr>
<td>T3(+jBound)-Net Pay-Marcellus</td>
</tr>
<tr>
<td>T3(-jBound)-Net Pay-Marcellus</td>
</tr>
<tr>
<td>CH4-Langmuire Pr</td>
</tr>
<tr>
<td>CH4-Langmuire V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HF Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture Conductivity</td>
</tr>
<tr>
<td>Hydraulic Fracture half length</td>
</tr>
<tr>
<td>T1-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T2(+iBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T2(-iBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T3(+jBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T3(-jBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>Sigma</td>
</tr>
<tr>
<td>Porosity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Natural Fracture Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T2(+iBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T2(-iBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T3(+jBound)-Kf(I,k)-Marcellus</td>
</tr>
<tr>
<td>T3(-jBound)-Kf(I,k)-Marcellus</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dynamic Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Flowing Bottomhole Pressure</td>
</tr>
<tr>
<td>Bottomhole Injection Pressure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Additional Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pattern ID</td>
</tr>
<tr>
<td>Well type</td>
</tr>
</tbody>
</table>

**47 Inputs**
Overview of Technical Approach

- Experimental Characterization
- Numerical Modeling
  - NG Production
  - CO₂ storage in shale
- Surrogate Reservoir Model Development
- SRM Application
  - Techno-Economic Assessment
CO₂ Storage and Enhanced Gas Recovery Scenario

Sensitivity of CO₂ storage/EGR performance to:
- Injector/producer distance
- Injection pressure
- Matrix and fracture perm.
- Matrix and fracture porosity
- Matrix CO₂ and CH₄ sorption characteristics

Overview of Technical Approach

Spatially-Related Data

- Experimental Characterization
- Numerical Modeling
  - NG Production
- Numerical Modeling
  - CO₂ storage in shale
- Surrogate Reservoir Model Development
- SRM Application & Techno-Economic Assessment

Approach to Screening-Level Assessment of Economic Performance of CO₂ Storage and Enhanced Gas Recovery from Depleted Shale Gas Formations: Model Description and Scenario Evaluation

- October 2014
- Preliminary – Do not cite or quote
Linked SRM-Economic Screening Tool

Modeling Approach

Field Properties
- Site location/properties
- Well/Completion details
- TOC

Flood Scenario Definition
- Configuration of well pad (# laterals/adjacency)
- Injection Schedule

Scenario Technical Performance
- CO₂ injectivity over time, bottomhole pressure over time
- Produced gas rate/composition over time

Calculate Mass of CO₂ stored through flood

Dynamic link library

Financial Parameters
- CO₂ storage / NG value
- Electricity cost
- Interest rate
- Debt/equity ratio

Operational Parameters
- Source/sink distance
- Pipeline pressure
- Workover frequency

Economic Screening Model

Scenario Economic Performance

Cumulative Probability

UTC of Storage ($/tonne Stored CO₂)
Key Findings: CO₂ Storage in Shale

• Gas production at economic rates for 30-60 years
• Significantly natural gas depletion and low pressure (<500 psi) in SRV, but limited production from unfractured matrix
• Significant uncertainty OGIP and EUR
• Frac hit will impact rates of primary depletion and recovery
• Storage predominantly as free-phase CO₂ in fractures
• Favorable assumptions about Langmuir characteristics results in only a small increase in storage (sorbed phase)
• Storage ~ 50,000 tonnes per fractured stage
• CO₂ storage is not much greater in injector/producer scenario, and can be less in cases with overlapping SRV
• Cost of CO₂ storage with EGR is expected to be of the same magnitude to saline storage
Thanks for listening!

Shaly limestone Marcellus sample (F2HB) from Facies 2, with several dense bivalve fossils in its interior.