Model Complexity and Choice of Model Approaches for Practical Simulations of CO$_2$ Injection, Migration, Leakage, and Long-term Fate

Project Number DE-FE0009563

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Princeton University
Presentation Outline

• Project Goals and Objectives
• Project overview
• Accomplishments
• Summary
Benefit to the Program

• The aim of the project is to develop criteria for the selection of the appropriate level of model complexity for CO$_2$ sequestration modeling at a given site. This will increase the confidence in modeling results, and reduce computational cost when appropriate.

• Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.
Project Overview: Goals and Objectives

• Goal: Develop a suite of models, across a broad spectrum of complexity, and determine when simplified models are appropriate for CO$_2$ sequestration modeling.

• Project objectives:
  – Assemble a suite of models across the range of complexity
  – Compare the performance of models of different complexity when applied to actual sites
  – Develop a set of practical criteria that can guide the choice of model complexity
Project Overview: Project Members

• Core members:
  – Princeton University: M. Celia (PI), K. Bandilla, B. Guo, E. Leister
  – Lawrence Berkeley National Lab: J. Birkholzer (co-PI), A. Cihan, S. Finsterle, Q. Zhou

• Affiliates:
  – University of Bergen: J. Nordbotten, E. Keilegavlen
  – CIPR: S. Gasda
  – University of Stuttgart: R. Helmig
Project Overview:
Technical Status

- Spectrum of model complexity
- New algorithm developments
- Site selection
- Model comparison
- Model complexity and design optimization
Domain

from Birkholzer et al., 2008
Model Complexity

- Fully coupled 3-D
- Simplified 3-D
- Vertical equilibrium

Macrosopic invasion percolation

Simplified vertical equilibrium
New Algorithms

- Fully coupled 3-D
- Simplified 3-D
- Vertical equilibrium
- Dynamic Vertical Drainage
- Invasion Percolation with Viscosity
- Macroscopic invasion percolation
- Simplified vertical equilibrium
Dynamic Vertical Drainage

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<th>simplified 3-D</th>
<th>vertical dynamic</th>
<th>vertical equilibrium</th>
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Invasion Percolation

**Viscous-Dominated**
- Experiment (Lenormand et al., 1988)
  - M=1.80×10^{-5}, Ca=4.95×10^{-7}, Bo=0

**Capillary-Dominated**
- New Growth Model
  - M=1.80×10^{-5}, Ca=5.34×10^{-11}, Bo=0

**Stable**
- M=100.0, Ca=9.83×10^{-4}, Bo=0
Site Selection

- Sleipner (9th layer of Utsira formation)
- Basal Aquifer
- In Salah
- Ketzin (CO2SINK)
- Cranfield (Phase III Early Test)
Sleipner Data
Basal Aquifer Data


Model Comparison

• Compare model results to find criteria for choice of appropriate level of complexity
• Different complexity for different questions:
  – Shape and areal extent of CO$_2$ plume
  – Areal extent of pressure response
  – Migration of fluids out of injection formation
Initial Basal Aquifer Comparison

numerical vertical equilibrium

semi-analytic vertical equilibrium

numerical single-phase

analytic single-phase (Theis)
Optimization

- Provides inverse modeling capabilities for multi-phase simulator TOUGH2 or, via PEST interface, other forward prediction tools
- iTOUGH2 involves a suite of global and local optimization methods

Forward Predictors

1. Analytical Solutions
2. Vertically Integrated Numerical Two-Phase Flow Models
   - Sharp-Interface Models
   - Vertically Integrated Multi-Phase Models
   - CO₂ migration in complex and heterogeneous systems
3. Simulator TOUGH2
   - Multi-phase flow in full 3D systems
Accomplishments to Date

- Established research team and distributed responsibilities.
- Completed review of existing CO₂ sequestration modeling approaches and their application to actual sites.
- Collected and analyzed data for Sleipner and Basal Aquifer.
- Completed study on the impact of model complexity on basin-scale pressure response in the Basal Aquifer.
Accomplishments to Date (cont)

- Developed, implemented and tested vertical drainage dynamics algorithm.
- Developed and implemented algorithm for macroscopic invasion percolation modeling including viscous effects.
Conclusions

- Vertical drainage dynamics algorithm improves the vertical-equilibrium approach and is able to accurately predict CO₂ plume migration under many practical conditions.
- Single-phase sufficient for basin-scale pressure response, but semi-analytic solutions are likely not sufficient.
Future Plans

• Data collection for additional sites
• Improve vertical drainage dynamics algorithm
• Improve viscous invasion percolation algorithm
• Model comparison
• Development of best practices manual
THANK YOU!

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Organization Chart

Project PI
Prof. M. Celia (Princeton)

Project co-PI
Dr. J. Birkholzer (LBNL)

Code Development
M. Celia (Princeton)
K. Bandilla (Princeton)

Field Applications
M. Celia (Princeton)
K. Bandilla (Princeton)

Optimization
J. Birkholzer (LBNL)
A. Cihan (LBNL)
S. Finsterle (LBNL)

Vertical Dynamics
M. Celia (Princeton)
K. Bandilla (Princeton)

Percolation
K. Bandilla (Princeton)
A. Cihan (LBNL)

Model Criteria
M. Celia (Princeton)
J. Birkholzer (LBNL)
K. Bandilla (Princeton)
A. Cihan (LBNL)
S. Finsterle (LBNL)
# Gantt Chart

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light grey: accomplished; dark grey: planned; MS: mile stone
Bibliography