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The Foundation is an arm of NGWA that is focused on activities related to a broader understanding of ground water.
The 2008 Darcy lecture

Geological Storage as a Carbon Mitigation Option

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Support: The Carbon Mitigation Initiative (CMI) at Princeton University (funding from BP and Ford Motor Company)
Outline

- Overview of the Carbon Problem
- Feasible Solutions
- Geological Storage
- Modeling Strategies for Storage and Leakage
- Applications at Two Field Locations
- Conclusions and Ongoing Work
Overview of the Carbon Problem


>650,000 years
CO$_2$ Emissions

Current Global Emissions: $\sim 30$ Gt CO$_2$/yr $\approx 8$ Gt C/yr
Projected Emissions (2058): $\sim 60$ Gt CO$_2$/yr $\approx 16$ Gt C/yr
“Stabilization Wedges”

Billions of Tons Carbon Dioxide Emitted per Year

Historical emissions

Current path = “ramp”

Flat path

16 GtC/y

1 Wedge = 25 Gt C

Interim Goal

3°C

How to achieve One Wedge

1. Increase **fuel efficiency** of 2 billion cars from 30 mpg to 60 mpg.
2. Replace 1,400 large-scale coal power plants with **natural gas plants**.
3. Add **twice today’s nuclear power**, replacing coal.
4. **Install CCS at 800 large-scale coal power plants.**
5. Drive 2 billion cars on Ethanol, using one-sixth of cropland worldwide.

How to achieve One Wedge

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"We conclude that CO₂ capture and sequestration (CCS) is the critical enabling technology that would reduce CO₂ emissions significantly while also allowing coal to meet the world's pressing energy needs." (The Future of Coal, MIT, 2007)
Carbon Capture and Storage (CCS)

- Current Number of Coal Plants Worldwide: 2,200
- Rate of building in China: 1-2 per week.
- Rate of building in US: <10 per year
- Potential number of wedges from CCS: 3 to 5.
- All projections of carbon reductions include a significant fraction from CCS.
- We need to understand the many aspects of CCS.
Injected Supercritical CO$_2$:

- Slightly miscible with brine \( (\text{solubility limit } \sim 4\%) \)
- Less dense than brine \( (\text{density ratio } 0.25 \text{ to } 0.75) \)
- Less viscous than brine \( (\text{viscosity ratio } 0.2 \text{ to } 0.02) \)
- Water can evaporate into (dry) CO$_2$.

Geochemistry, Geomechanics, Nonisothermal, …
Plume of Injected CO$_2$

- Nonwetting Phase
- Wetting Phase
- Solid Phase

Diagram showing the plume of injected CO$_2$ with labeled phases and variables.

- $Q_{\text{well}}$
- $i(r,t)$
- $h(r,t)$
- CO$_2$
- Brine
- H
Plume of Injected CO$_2$

- Nonwetting Phase
- Wetting Phase
- Solid Phase

$Q_{\text{well}}$

$CO_2$

$i(r,t)$

$h(r,t)$

Brine

$H$

$z$

$r$
Worldwide Density of Oil and Gas Wells

(From IPCC, 2005)
Injection and Leakage

- How to model this system?
- Domain Size: 1,000 km$^2$
- Leakage Pathways: 0.001 m$^2$.
- Flow Properties along well highly uncertain.
- Possible Material Degradation.

(From Duguid, 2006)
Numerical Issues

- **Standard Simulations**
  - Need grid refinement around each well
  - Need vertical resolution for multiple layers
  - Minimum of many millions of grid cells.

- **Computational Options**
  - Upscale parameters in grid blocks with wells (*Gasda and Celia, 2005*)
  - Local grid refinement / Local time stepping (*Gasda, 2007*)
  - Dual-media approach around wells (*Gasda, 2007*)
  - Simplified governing equations (*Nordbotten, Celia, …*)
Possible Simplifications

- Focus on early time ➔ two-phase physics
- Ignore (bulk) Geochemistry and Non-Isothermal Effects ➔ Constant fluid properties in a given layer
- Sharp Interface with Vertical Equilibrium (in each layer)
- Homogeneous, Horizontal Formations
- No leakage in Caprock Formations, except through Wells
Similarity Solution

\[\Gamma \equiv \frac{2\pi\Delta \rho g k \lambda_w H^2}{Q_{in}}\]
\[\tau \equiv \frac{Q_{in} t}{2\pi H \varphi (1 - S_{res})}\]
\[\lambda_1 \equiv \frac{\lambda_c}{\lambda_w}, \quad \lambda_2 \equiv \frac{\lambda_{cw}}{\lambda_W}, \quad \vartheta \equiv \frac{\rho_{cw} - \rho_c}{\rho_w - \rho_{cw}}\]
\[h' \equiv \frac{h}{H}, \quad i' \equiv \frac{i}{H}\]

\[\chi \equiv \frac{r^2}{\tau}\]

(From Nordbotten and Celia, *JFM*, 2006)
When $\Gamma < 0.5$:

\[
h'(\chi) = \frac{h(\chi)}{H} = \frac{1}{\lambda - 1} \left( \sqrt{\frac{2\lambda}{\chi}} - 1 \right)
\]

$\chi_{\text{min}} = \frac{2}{\lambda}$

$\chi_{\text{max}} = 2\lambda$

(From Nordbotten and Celia, *JFM*, 2006)
Similarity Solution: Simplified

\[
\Delta p'(\chi) - F(h') = \begin{cases} 
0, & \chi \geq \Psi \\
-\frac{1}{2\Gamma} \ln\left(\frac{\chi}{\Psi}\right) + \Delta p'(\Psi), & \Psi > \chi > 2\lambda \\
\frac{1}{\Gamma} - \frac{\sqrt{\chi}}{\Gamma \sqrt{2\lambda}} + \Delta p'(2\lambda), & 2\lambda > \chi > 2/\lambda \\
-\frac{1}{2\lambda \Gamma} \ln\left(\frac{\chi \lambda}{2}\right) + \Delta p'(2/\lambda), & 2/\lambda > \chi
\end{cases}
\]

\[
\Psi = \frac{4.5\pi H \phi k (1 - S_B^{res})}{\mu_B c_{eff} Q_{well}}
\]

(Location where \(\Delta p=0\))

(From Nordbotten and Celia, *JFM*, 2006)
(See: Nordbotten and Celia, *CMWR*, 2006)
A Semi-analytical Model

1. Injection Plume, Secondary Plumes and Pressure Fields: Similarity Solution (*Nordbotten and Celia, JFM, 2006*)

2. Leakage Dynamics: Multi-phase Darcy Flow along Leaky Well Segments (*Nordbotten et al., ES&T, 2005, 2008*)

3. Upconing around Leaky Wells (*Nordbotten and Celia, WRR, 2006*)

4. Grid-free solutions: We can now solve 50 years of injection over 2,500 km², 12 layers, and 1,200 wells in about 15 minutes.

\[ Q_{\text{well}} \propto K_{\text{well}} k(S_\alpha)(\frac{p_1 - p_2}{H} - \rho_\alpha g) \]
Example: Possible Injection
Existing Wells
Stratigraphy

Location: 00/10-05-052-2W5

**UPPER CRETACEOUS**
- **EDMONTON GROUP**
  - Group:
  - Formation/Member:
  - Logs:
  - Lithology:
  - Hydrostratigraphy:
    - Sandstone:
    - Shale:
    - Aquifer:
    - Aquitard:

**LOWER CRETACEOUS**
- **MANVILLE GROUP**
  - Group:
  - Formation/Member:
  - Logs:
  - Lithology:
  - Hydrostratigraphy:
    - Sandstone:
    - Shale:
    - Aquifer:
    - Aquitard:

**Lithology**
- Sandstone
- Shale

**Hydrostratigraphy**
- Aquifer
- Aquitard
Domain Size: 50 km x 50 km with 7 permeable layers in the vertical.

Leakage Pathways: >1200 Wells

Monte Carlo Simulations: Well permeabilities are the random inputs (each segment uncorrelated)
Leakage (first layer) after 50 Years

Mean $\sim -2.4 \ [0.4\%]$

Leakage $>1\%$ occurs 25% of the time

$P(>1\%)=25\%$

Risk Assessment and CCS Regulations
Brine Leakage by Layer

Regulations: Where does the brine go?
Overall Modeling Strategy

- Vertical Equilibrium Models at Large Scale (Numerical: VESA; Semi-analytical: ELSA)
- Analytical Solutions for Sub-scale Interactions
- Full Compositional Simulations for Leakage Details
  - Cement Degradation
  - Non-isothermal Effects
- Application: Risk versus depth of injection.
- Application: Basin-wide modeling (500,000 km²).
- Application: Field Measurements along Wells.

From: Celia and Nordbotten, 2008
Concluding Comments

- Technologies exist to solve the carbon problem.
- The scale of the problem is enormous.
- CCS is likely to be an important option, we need to be prepared for large-scale injection projects:
  - Regulatory Issues (EPA Guidelines)
  - Economic Credit and Liability Systems
- Complex processes and systems need to be modeled.
- Simplified, non-traditional models can play an important part.
- Hydrogeology (site characterization, subsurface modeling, risk assessment) must play a central role!
Thank You!

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For more information visit us on the web at [www.ngwa.org](http://www.ngwa.org) or write us at the below address.

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