Geologic Carbon Sequestration in the Illinois Basin: Current Activity and Future Possibilities

Edward Mehnert, PhD
Illinois State Geological Survey, Prairie Research Institute, Univ of Illinois at Urbana-Champaign

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Geologic Carbon Sequestration in the Illinois Basin: Current Activity and Future Possibilities

Edward Mehnert, James Damico, Scott Frailey, Hannes Leetaru, Yu-Feng Lin, Roland Okwen
Illinois State Geological Survey, Prairie Research Institute

Nathaniel Adams, Brynne Storsved, Albert Valocchi
Dept of Civil and Environmental Engineering, Univ of Illinois at Urbana-Champaign
Outline

- Background
- CCS projects in IL – current status
- Future for CCS in IL – modeling
• Intergovernmental Panel on Climate Change (IPCC 2007)
  – Global climate has warmed
  – Greenhouse gases (CO₂, CH₄ & N₂O) have increased since 1750
  – Most of the observed increase in global temps since the mid-20th century is very likely due to increases in anthropogenic GHGs
HFCs are hydrofluorcarbons, PFCs are perfluorocarbons, and SF₆ is sulfur hexafluoride.

Background/GCS in Illinois Basin

- Illinois Basin estimates
  - Emissions: 291 million metric tons/year
  - Storage resource
- Why the interest in the Mt. Simon?

<table>
<thead>
<tr>
<th>Resource</th>
<th>Million metric tons</th>
<th>years</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOR</td>
<td>140-440</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Deep Coal</td>
<td>1,600-3,200</td>
<td>5.5-11.0</td>
</tr>
<tr>
<td>Mt. Simon</td>
<td>11,000-150,000</td>
<td>38-515</td>
</tr>
</tbody>
</table>

Background/Geology

- Mt. Simon – open reservoir, laterally extensive, 3 layers
Background/Geology – Thickness of Mt. Simon (2005)

**Thickness in feet**
- Less than 500
- 500 to 1,000
- 1,000 to 1,500
- 1,500 to 2,000
- Greater than 2,000

Thickness data points:

**Map showing the thickness of Mt. Simon Sandstone in the Illinois Basin.**
Background/Geology – TDS of Mt. Simon Brine (2005)
Background/Geology – TDS of Mt. Simon Brine (2005)
Mt. Simon water wells
[well open to Mt. Simon & other aquifers]
Source: S. Meyer, ISWS
CCS Projects in IL

- FutureGen2 in Morgan County (green hexagon)
- IBDP CCS1
- ICCS
- USDOE funded research center
CCS Projects in IL

- FutureGen 2 in Morgan County (green hexagon)
- Managed by FutureGen Alliance
- Retrofit powerplant to oxy-combustion with CO$_2$ storage in Mt. Simon
- Powerplant near Meredosia
- Injection well NE of Jacksonville
- USDOE pulls out of $1.65B FutureGen2.0 carbon capture and sequestration demonstration project in Meredosia, IL (ENR, Feb 16, 2015 p 6-7)
- “Project had not achieved sufficient progress”
Injection well completed 5/4/09
TD= 7,230 ft, into Precambrian rock
>1,500 ft of Mt. Simon sandstone
  – 600 ft has porosity >10%, some >25%
  – Sidewall cores shows k > 500 md
500 ft of Eau Claire (cap rock)
CO$_2$ injection started Nov 2011
1 million tonnes injected thru Nov 2014
CCS Projects in IL/ ICCS

• Currently being drilled, completed in Mt. Simon
• Approx. 1 mile NE of CCS1
• Will be used to store 1 million tonnes/yr for 3 years
Future for CCS/ Sequestration Effects

Possible concerns
- \( \text{CO}_2 \) leakage
- Brine displacement

Source: Birkholzer et al. (2009) IJGGC, 3, 181-194
Future for CCS/ Modeling Approach

• Introduction –
  – If CO$_2$ is sequestered on a commercial scale in the Mt. Simon *in the future*, what will happen to the native groundwater?
  – Will the CO$_2$ be stored permanently?
  – Will GCS affect the integrity of the injection zone or caprock?
  – Will other Mt. Simon users/stakeholders be affected?

• Purpose –
  – Develop modeling tools & expertise to answer these questions for the Mt. Simon Sandstone
  – Evaluate on a basin-scale
  – Develop a series of solutions, not a single solution
Future for CCS/ CO$_2$ Properties

IBDP CCS1:
Depth= 2,135 m or 7,000 ft
P= 3,200 psi or 218 atm or 22.1 MPa
T= 125 F or 51.7 C

CO$_2$ has liquid-like density and gas-like viscosity.

At 800 m
P= 1136 psi
T= 27.4 C
Future for CCS/ CO₂ & Methane Properties

IBDP CCS1:
Depth= 2,135 m or 7,000 ft
P= 3,200 psi or 218 atm or 22.1 MPa
T= 125 F or 51.7 C

CO₂ has liquid-like density and gas-like viscosity.

CO₂ has a critical point at 74 atm (1000 psi) at a temperature of 31.1 °C.

Methane has a critical point at a pressure of 120 atm (1720 psi) and a temperature of 82.3 °C.

Ethane has a critical point at a pressure of 100 atm (1450 psi) and a temperature of 58.1 °C.

At 800 m
P= 1136 psi
T= 27.4 C
## Future for CCS/ CO₂ & Methane Properties

<table>
<thead>
<tr>
<th>Gas</th>
<th>Viscosity (Pa*sec)</th>
<th>Density (kg/m³)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>5.5056e-04</td>
<td>996.53</td>
<td>liquid</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>6.8674e-05</td>
<td>784.29</td>
<td>SC</td>
</tr>
<tr>
<td>Methane</td>
<td>1.8437e-05</td>
<td>135.93</td>
<td>SC</td>
</tr>
</tbody>
</table>

### Notes:
1) All values for 50°C and 20 MPa (2,900 psi)
2) Source: NIST chemistry webBook

Future for CCS/ Modeling

• Two-phase flow
  – Capillary
  – Gravimetric
  – Viscous forces

• GCS trapping mechanisms
  – Structural or stratigraphic trapping
  – Residual saturation trapping
  – Solubility trapping
  – Mineral trapping (not modeled)

Source: IPCC (2005)
Future for CCS/Modeling

- Using TOUGH2-MP (LBL code)
- Large model with 20 injection wells
  - >1.2 million elements, which vary in size
  - Mt. Simon has 4 to 24 vertical layers
  - Eau Claire has 3 layers
  - Precambrian has 1 layer
- Boundary Conditions
  - Fixed pressure (sides & top)
  - No flow on bottom
## Future for CCS/ Modeling

### Scenario Descriptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Type</th>
<th>Description</th>
<th>Wells</th>
<th>Notes</th>
</tr>
</thead>
</table>
| ILB01a   | IBDP | Inject 100 million tonnes per year | 20    | Baseline scenario
2 injection zones with K= 1x10^{-12} m² or 1,000 mD
Results: Zhou et al. (2010) |
| ILB01b   | None | 100 MT/year | 20    | Reduced Kv for 9 layers in Mt. Simon, now Kv = Kh |
| ILB02a   | Static | 50 MT/year | 20    | 1 injection zone (upper zone retained)
K, injection zones = 5x10^{-14} m² or 50 mD |
| ILB02b   | Static | 50 MT/year | 20    | Revised distant elements using available data & professional judgment.
T & S data from ISWS bedrock aquifer model
(Meyer et al. 2009)
Results: Mehnert et al. (2013), Roy et al. (2014) |
| ILB03a   | Flow | 100 MT/year | 40    | Revised geologic data, vertical layering, T, brine TDS, K & porosity based on IBDP dynamic data
K, injection zones = 3.2x10^{-13} m² or 326 mD
New gridding to allow 40 wells
Results: Mehnert et al. (2014) |


## Future for CCS/ Modeling

### Scenario Descriptions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Injection Rate</th>
<th>Wells</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILB01a</td>
<td>IBDP data: None, Inject 100 million tonnes per year</td>
<td>20</td>
<td>Baseline scenario, 2 injection zones with $K = 1 \times 10^{-12}$ m$^2$ or 1,000 mD</td>
<td>Zhou et al. (2010)</td>
</tr>
<tr>
<td>ILB01b</td>
<td>None</td>
<td>100 MT/year</td>
<td>20</td>
<td>Reduced $K_v$ for 9 layers in Mt. Simon, now $K_v = K_h$</td>
</tr>
<tr>
<td>ILB02a</td>
<td>Static</td>
<td>50 MT/year</td>
<td>20</td>
<td>1 injection zone (upper zone retained), $K$, injection zones = $5 \times 10^{-14}$ m$^2$ or 50 mD</td>
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Future for CCS/ Modeling: ILB02b

- $\Delta P$ after 50 yrs & for top of the Mt. Simon (injection zone)
- $\Delta P = P(50 \text{ years}) - P(0 \text{ years})$, 1 MPa = 145 psi

![Diagram of ILB02b ΔP, MPa](image1)

![Diagram of ILB02b ΔP, MPa](image2)
Future for CCS/Modeling: ILB02b

- Predicted gas saturation (top) and pressure change (bottom) between 2 wells.
- N-S cross-section between wells 14 & 15: caprock, injection zone (Mt. Simon) and Precambrian
- Max change = 13.3 MPa (1,929 psi) at T = 50 yrs (1 MPa = 145 psi)
• New input data have become available:
  – Temperature gradient with depth
    • old T gradient = 9.2°C/km
    • new T gradient = 18.9°C/km (Mean, US oil reservoirs= 36°C/km)
    • CO₂ density, solubility and viscosity are f(T)
Future for CCS/ Modeling: 3rd generation—new input data

- TDS data developed with USEPA grant
  - Brine density is \( f(TDS) \)
  - \( \text{CO}_2 \) solubility is \( f(TDS) \)
Future for CCS/Modeling: 3rd generation – new input data

- Revised geologic data for Mt. Simon thickness
Future for CCS/Modeling: new 3D grid
Mt. Simon core: injection zone & baffle (6,863 ft)

Source: Freiburg et al., 2014. ISGS Circular 583
Geologic models: ILB02a (core data) & ILB03a (flow data)
Geologic models: ILB02a (core data) & ILB03a (flow data)

Model includes (top down):
Eau Claire – 4 layers
Mt. Simon – 24 layers
Pre-Mt. Simon – 1 layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\lambda$</th>
<th>$S_{lr}$</th>
<th>$S_{ls}$</th>
<th>$S_{gr}$</th>
<th>$\lambda$</th>
<th>$S_{lr}$</th>
<th>$P_0$ (Pa)</th>
<th>$P_{max}$ (Pa)</th>
<th>$S_{ls}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eau Claire</td>
<td>0.412</td>
<td>0.40</td>
<td>1.0</td>
<td>0.30</td>
<td>0.412</td>
<td>0.03</td>
<td>5.0e+6</td>
<td>1.0e+9</td>
<td>0.999</td>
</tr>
<tr>
<td>Mt. Simon minimum</td>
<td>0.412</td>
<td>0.30</td>
<td>1.0</td>
<td>0.25</td>
<td>0.412</td>
<td>0.00</td>
<td>6.49e+3</td>
<td>5.0e+5</td>
<td>0.999</td>
</tr>
<tr>
<td>Mt. Simon maximum</td>
<td>0.900</td>
<td>0.30</td>
<td>1.0</td>
<td>0.25</td>
<td>0.412</td>
<td>0.00</td>
<td>2.12e+4</td>
<td>5.0e+5</td>
<td>0.999</td>
</tr>
<tr>
<td>Pre-Mt. Simon</td>
<td>0.412</td>
<td>0.40</td>
<td>1.0</td>
<td>0.30</td>
<td>0.412</td>
<td>0.03</td>
<td>1.0e+7</td>
<td>1.0e+9</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Relative Permeability:

\[ k_{rl} = \sqrt{S^* \{1 - (1 - [S^*]^{1/\lambda})^{\lambda}\}^2} \]
\[ k_{rl} = 1 \] if $S_l < S_{ls}$  \[ [1a] \]
\[ k_{rl} = 1 - k_{rl} \] if $S_l \geq S_{ls}$  \[ [1b] \]

Capillary Pressure:

\[ P_{cap} = -P_0 \left(\left[S^*\right]^{-1/\lambda} - 1\right)^{1-\lambda} \]

where $S^* = (S_l - S_{lr})/(S_{ls} - S_{lr})$, $\hat{S} = (S_l - S_{lr})/(1 - S_{lr} - S_{gr})$
Modeling Results/ ILB03

- CO₂ distribution at $t = 10, 50, 100 \& 5,000$ years (inject for 50 yrs)
- Plan view (top) & N-S cross-section thru well 19 (black box)

### Times

- $T = 10$
- 50
- 100
- 5,000 years
Modeling Results/ ILB03 CO₂ saturation by layer

- layer 0 = pre-MS, layer 1&2 = MS injection zones, layer 11 = highest layer with CO₂
- CO₂ moves into layers 1, 2, & 3 early, up to >0.9 sat, drops to 0.25 sat after 1,000 yrs

Residual saturation = 56% in layers 1-3
Modeling Results/ ILB03

- **CO$_2$ mass balance**
  - Dissolved CO$_2$ is high, drops to 10% and slowly increases to 15%
Modeling Results/ ILB03 pressure change

- layer 2 = MS injection zone, layer 24 = uppermost MS layer

30 km
Modeling Conclusions

• Modeling results show:
  – Significant effect that the geologic model (thicknesses, porosity & permeability) can have on injection rate and resulting pressures.
  – Well interference for the pressure front
  – Limited transport of CO$_2$ from injection wells (radially & vertically)
  – CO$_2$ dissolution is slow (thousands of years)
  – After 5,000 years, CO$_2$ distribution: 15% dissolved, 56% trapped via residual saturation and 29% mobile.
Modeling future directions

Improve predictive ability of GCS simulators
Plume shape and timing
In US, Class VI regulations require accurate plume locations to determine AOR
• GSCO2: Geological Sequestration of Carbon Dioxide
  – Lead by UIUC/ISGS
  – funded by USDOE, Office of Basic Energy Sciences
  – Started in August 2014
  – www.GSCO2.org

• Research Goals
  – Predicting the location and distribution of the injected CO₂ within the storage reservoir
  – Identifying the mechanism of injection-induced microseismicity and controlling and predicting its occurrence
This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number OCI-1053575.

This research is partially supported with funds from a USEPA STAR grant. Project manager: Barbara Klieforth

Lawrence Berkeley Lab– Quanlin Zhou, Jens Birkholzer & Kenni Zhang contributed to the development of the model discussed.

Natural gas storage companies have provided much useful data.
Questions?

Ed Mehnert, ISGS
demehnert@illinois.edu
217-244-2765

Midwest Geological Sequestration Consortium
www.sequestration.org
EFRC: www.GSCO2.org

Photo credits: Daniel Byers
New Energy Frontiers Research Center

GSC02 | Center for Geologic Storage of CO₂

Multiphysics Flow and Transport
Couple basic and applied researchers

Team Leader
Charles Werth, Ph.D.
University of Texas - Austin

Team Coordinator
Edward Mehnert, PhD.
University of Illinois - Champaign

Pore-Scale Modeling/Upscaling
Albert Valocchi, Ph.D.
University of Illinois - Champaign

Molecular Dynamic Simulations: Fluid Properties and Phase Equilibria
Muhammad Sahimi, Ph.D.
University of Southern California

Microfluidics and Wettability
Charles Werth, Ph.D.
University of Texas - Austin
Kenneth Christensen, Ph.D.
University of Notre Dame

Absorption and Adsorption in Porous Media
Theodore Tsotsis, Ph.D.
University of Southern California

Site Scale Modeling
Edward Mehnert, Ph.D.
University of Illinois - Champaign

Geochemical Experiments
Angela Goodman, Ph.D.
National Energy Technology Laboratory
Drainage Experiments: Raw Particle Image Velocimetry

(Christensen, UND)

Experimental conditions
80 bar, 40°C
$Q = 0.005$ ml/min
Bulk velocity = 0.4 mm/s
$Ca = 3.4 \times 10^{-7}$
$M = 0.03$
$Re_{water} \simeq 0.1$
$Re_{CO_2} \simeq 1$

Kazemifar et al., Advances in Water Resources, (submitted)
Modeling future directions

- Improve link between GCS and groundwater flow models
- Prototype link built for PC versions of ISWS Bedrock Aquifer model & ISGS GCS basin-scale model (N. Adams)
- Python codes used to automate data transfer
MVA Monitoring Matrix

**IBDP Environmental Monitoring Framework**

<table>
<thead>
<tr>
<th>Near Surface</th>
<th>Deep Subsurface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmos.</strong></td>
<td><strong>Above seal</strong></td>
</tr>
<tr>
<td>Eddy covariance</td>
<td>Injection zone</td>
</tr>
<tr>
<td>Soil and vadose zone</td>
<td></td>
</tr>
<tr>
<td>Soil flux</td>
<td></td>
</tr>
<tr>
<td>Aerial imagery</td>
<td>Geophysical surveys</td>
</tr>
<tr>
<td>Soil gas</td>
<td>Geophysical surveys</td>
</tr>
<tr>
<td>MVA surveys</td>
<td>MVA sampling</td>
</tr>
<tr>
<td>P/T monitoring</td>
<td>P/T monitoring</td>
</tr>
<tr>
<td>Shallow groundwater</td>
<td></td>
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</tbody>
</table>