Strategies for Optimization of Pore Volume Utilization for CO$_2$ Storage

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Purpose

- Assess the fraction of pore-space that can be used for storage of CO$_2$
- Identify reservoir engineering strategies to maximize the capacity and security of storage reservoirs
Some Factors Controlling the Capacity of Storage Reservoirs

- Multiphase Flow Effects ($C_i$)
- Gravity Effects ($C_g$)
- Heterogeneity Effects ($C_h$)
- Structural Effects ($C_s$)
Approach

Umbrella Point Model

Well Penetration
End Injection Period

- Dissolved
- Mobile
- Immobile
- Total
### Variables Investigated and Assessed

<table>
<thead>
<tr>
<th>Well penetration</th>
<th>Capacity Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper one-quarter</td>
<td>&gt; 10% decrease</td>
</tr>
<tr>
<td>Upper one-half</td>
<td></td>
</tr>
<tr>
<td>Full</td>
<td></td>
</tr>
<tr>
<td>Lower one-half (base case)</td>
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<td>Lower one-quarter</td>
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<th>Horizontal well</th>
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<tr>
<td>At top</td>
<td></td>
</tr>
<tr>
<td>At mid-depth</td>
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Stochastic Model Construction

- **Input:** Schematic representation for three depositional settings

- **Output:** multiple realizations for each depositional setting

- TProGS preserves extent, orientation, and juxtaposition of facies

*Model Developed with Cooperation of TBEG*
Geological Model Specifications

- 1 km by 1 km by 100 m thick
- Top and bottom boundaries closed
- Lateral boundaries constant pressure (open)
- Permeability and porosity distribution represents a fluvial-deltaic geology, created stochastically
- Grid resolution
  - Lateral 50 m
  - Vertical 1 to 11 m (depends on lithology, 3 grid layers per geologic layer)
# Model Properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>Porosity</th>
<th>Horizontal Permeability (md)</th>
<th>Vertical Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier Core</td>
<td>0.32</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>Sand Channel</td>
<td>0.30</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Splay 2</td>
<td>0.30</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Washover</td>
<td>0.29</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Splay 1</td>
<td>0.28</td>
<td>150</td>
<td>30</td>
</tr>
<tr>
<td>Shale</td>
<td>0.10</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

- \( P_0 = 188 \text{ bars}, \ T_0 = 78^\circ \text{C}, \ \text{Salinity} 100,000 \ \text{ppm} \)
- Characteristic curves
  - \( S_{lr} = 0.30, \ S_{g_{max}} = 0.25 \)
Processes Modeled with TOUGH2

- Two-phase system
  - Native brine is wetting phase
  - Injected supercritical CO$_2$ is non-wetting phase
- Fluid flow modeled with multi-phase extension of Darcy’s law
- Hysteretic relative permeability and capillary pressure functions describe interaction between phases
- CO$_2$ partially dissolves in brine according to Henry’s Law
- Isothermal simulations

*Hysteritic Capillary Pressure and Relative Permeability Curves Used by TOUGH2*
Base Case

• Single vertical injection well located in middle of model
• Penetrates the entire formation thickness
• Constant injection rate of 1800 T/day (0.66 Mt/year) for 20 years
• Rest for 30 years
Full Penetration (Base Case)
Lower Half Penetration

1 yr

2 yrs

5 yrs

10 yrs

20 yrs

21 yrs

25 yrs

30 yrs

50 yrs
Upper Half Penetration

1 yr

2 yrs

5 yrs

10 yrs

20 yrs

21 yrs

25 yrs

30 yrs

50 yrs
Well Far from Shale Gap
Well Near Shale Gap
Horizontal Well at Top

1 yr

2 yrs

5 yrs

10 yrs

20 yrs

21 yrs

25 yrs

30 yrs

50 yrs
Horizontal Well at Mid-Depth
Low-Permeability Sand
High-Permeability Sand
Pulsed Injection

1 yr

2 yrs

5 yrs

10 yrs

20 yrs

21 yrs

25 yrs

30 yrs

50 yrs
Multiple Wells

1 yr

2 yrs

5 yrs

10 yrs

20 yrs

21 yrs

25 yrs

30 yrs

50 yrs
Mass Balance
(fractional display used for bar graphs)
Well Penetration

Well Penetration End Inception Period

Well Penetration End Rest Period
Horizontal Well

Horizontal Well
End Injection Period

Horizontal Well
End Rest Period
Sand Permeability

End Injection Period
- Dissolved
- Mobile
- Immobile
- Total

End Rest Period
- Dissolved
- Mobile
- Immobile
- Total
Pulsed Injection

Time-Dependent Injection
End Injection Period

Time-Dependent Injection
End Rest Period
Multiple Wells

**Multiple Wells End Injection Period**

**Multiple Wells End Rest Period**

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Overall Comparison (End of Injection)

- **Dissolved**
- **Mobile**
- **Immobile**
- **Total**

- **All Parameters**
  - End Injection Period

- **Upper Quarter**
- **Upper Half**
- **Full penetration**
- **Lower Half**
- **Lower Quarter**
- **Near shale gap**
- **Far from shale gap**
- **Hor Well Top**
- **Hor Well Mid-depth**
- **Hor Well Bottom**
- **Perm Low**
- **Perm High**
- **1 yr on/off**
- **Multiple wells**

Graph showing comparisons of dissolved, mobile, immobile, and total parameters for various geological and well conditions.
Overall Comparison (End of Rest Period)
# Capacity Optimization

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**Capacity Impact**

- **> 10% decrease**
- **Base Case**
- **> 10% increase**
Capacity After Rest Period

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<th>Total Stored</th>
<th>End Rest Period</th>
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- Upper Quarter
- Upper Half
- Full penetration
- Lower Half
- Lower Quarter
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- Perm High
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Average = 9%
Fraction of CO$_2$ Immobilized and Dissolved 30 Years After Injection Stops

Average = 94%

Immobile and Dissolved Fraction End Rest Period
Conclusions

• Storage capacity
  – Base case ~ 8% of maximum capacity
  – Lower permeability ~ 22% of maximum capacity
  – Higher permeability ~ 4% of maximum capacity

• Capacity optimization
  – Inject at the bottom of the storage formation
  – Avoid known short circuits to the top of the storage formation
  – Horizontal wells can improve pore volume utilization
  – Intermittent injection may improve capacity

• Rate of immobilization and dissolution
  – Average of 94% immobilization in 30 years after injection stops

• Caveats
  – Conclusions are specific to the model system studied here

• Capacity and storage security can be optimized
  – More work is needed in this promising area