Enhanced Analytical Simulation Tool for CO₂ Storage Capacity Estimation

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Benefit to the Program/Goals and Objectives

• **Project benefit**
  – Support industry’s ability to predict CO₂ storage capacity in geologic saline formations to within ±30 percent.

• **Major goal**
  – Develop an **Enhanced Analytical Simulation Tool (EASITool)** for simplified reservoir models to predict storage capacity of brine formations.

• **Objectives**
  – Provide fast, reliable and science-based estimate of storage capacity.
  – Integrate analytical/semi-analytical geomechanical models
  – Integrate brine extraction scenarios.
  – Provide sensitivity analysis.
Technical Status

EASiTtoolGUI

1. RESERVOIR PARAMETERS
   - Min
   - Max
   - Pressure [MPa]
   - Temperature [°C]
   - Thickness [m]
   - Salinity [mol/kg]
   - Porosity
   - Permeability [mD]
   - Rock Compressibility [1/MPa]
   - Reservoir Area [km²]
   - Basin Area [km²]
   - Boundary Condition

2. RELATIVE PERMEABILITY (Brooks-Corey)
   - Residual Water Saturation
   - Residual Gas Saturation
   - m
   - n
   - kφ0
   - Kg0
   - α

3. SIMULATION PARAMETERS
   - Simulation Time [years]
   - Injection Well Radius [m]
   - Max Injection Pressure [MPa]
   - Density of Porous Media [kg/m³]
   - Total Stress Ratio (W/H)
   - Poisson’s ratio
   - Coefficient of Thermal Expansion [1/K]
   - Bottom Hole Temperature Drop [K]
   - Young’s Modulus [GPa]
   - Depth [m]
   - Estimated Max Injection Pressure [MPa]
   - Max Injection Rate [ton/day]
   - Max Number of Injectors

4. NPV
   - Drilling Cost [$/well]
   - Operation Cost [$/well/year]
   - Monitoring Cost [$/year]
   - Tax Credit [$/ton]
   - Extractors Drilling Cost [$/well]
   - Extractors Operation Cost [$/well/year]

5. EXTRACTION PARAMETERS
   - Number of Extractors
   - Minimum Extraction Pressure [MPa]
   - Maximum Extraction Rate [ton/day]

6. RESULT CONTROLS
   - Number of injection Wells
   - Export Image and Output Files (Slow)

CO2 Plume Extension

Well Rate (ton/day)

X, km
Y, km

Poremability
Porosity
Rock Comp. Temperature
Swept
Sed.
Salinity
Pressure

Capacity

Run

Simulation Time [sec] 100.
## Technical Status

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<th>Tool/Approach Name</th>
<th>DOE/NETL</th>
<th>CSLF</th>
<th>USGS</th>
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Technical Status

- Tasks 2-4 completed
- NCE
- User feedback, Verification & Application

Diagram:
- Task 2: Development of Pressure Buildup Models
- Task 3: Integration of Rock Geomechanics
- Task 4: Integration of Active Reservoir Management
- Outputs:
  - Reservoir Storage Capacity
  - Number of Required Wells
  - Uncertainty Quantification of the Results
Accomplishments to Date

- Finding the optimized rate to maximize storage capacity
Accomplishments to Date

- Normal fault system

\[ P_{\text{max}} = \frac{1}{2\alpha - \beta_v - \beta_h - (\beta_v - \beta_h) \cos 2\theta + (\beta_v - \beta_h) \sin 2\theta / \mu} \cdot \left[ (1 + K) + (1 - K) \cos 2\theta - (1 - K) \sin 2\theta / \mu \right] \sigma_{v0} - \left[ (\beta_v + \beta_h) + (\beta_v - \beta_h) \cos 2\theta - (\beta_v - \beta_h) \sin 2\theta / \mu \right] P_{pi} - \frac{2\alpha_T E\Delta T}{1 - 2\nu} \]

- Reverse fault system

\[ P_{\text{max}} = \frac{1}{2\alpha - \beta_h - \beta_v - (\beta_h - \beta_v) \cos 2\theta + (\beta_h - \beta_v) \sin 2\theta / \mu} \cdot \left[ (K + 1) + (K - 1) \cos 2\theta - (K - 1) \sin 2\theta / \mu \right] \sigma_{v0} - \left[ (\beta_h + \beta_v) + (\beta_h - \beta_v) \cos 2\theta - (\beta_h - \beta_v) \sin 2\theta / \mu \right] P_{pi} - \frac{2\alpha_T E\Delta T}{1 - 2\nu} \]

- Strike-slip fault system

\[ P_{\text{max}} = \frac{1}{\alpha - \beta_h} \left[ \left( \frac{1 + K_H}{2} + \frac{1 - K_H}{2} \cos 2\theta - \frac{1 - K_H}{2} \sin 2\theta / \mu \right) \sigma_{H0} - \beta_h \cdot P_{pi} - \frac{\alpha_T E\Delta T}{1 - 2\nu} \right] \]

\[ \Delta P_{\text{max}} = P_{\text{max}} - P_{pi} \]

Accomplishments to Date
Accomplishments to Date

Injection time (day)

Normalized injection rate, Q/Q_{max}

Injection rate

Bottom-hole temperature

Temperature (K)

Vertical effective stress, σ'_v (MPa)

Horizontal effective stress, σ'_h (MPa)

1. 50 m above the interface (caprock)
2. 5 m above the interface (caprock)
3. Aquifer-caprock interface
4. 5 m below the interface (aquifer)
5. Middle in the injection aquifer

5. Middle in the injection aquifer
4. 5 m below the interface (aquifer)
3. Aquifer-caprock interface
2. 5 m above the interface (caprock)
1. 50 m above the interface (caprock)

Horizontal effective stress, σ'_h (MPa)

Vertical effective stress, σ'_v (MPa)

σ'_v = q_{slip} \cdot σ'_h

σ'_h = q_{slip} \cdot σ'_v
Accomplishments to Date
Brine Extraction

- Brine extraction improves injectivity (capacity) and reduce the risk of exceeding the fracture pressure.
Accomplishments to Date

- Finding the optimized rate to maximize storage capacity

\[
\begin{align*}
\frac{1}{2} (\ln(t_D) + 0.80908) + S_a &- \frac{1}{2} \frac{\lambda_g}{\lambda_w} E_i \left( - \frac{r_{D1-2}^2}{4 \eta_{D3} t_D} \right) \\
- \frac{1}{2} \frac{\lambda_g}{\lambda_w} E_i \left( - \frac{r_{D2-1}^2}{4 \eta_{D3} t_D} \right) &- \frac{1}{2} \frac{\lambda_g}{\lambda_w} E_i \left( - \frac{r_{D3-2}^2}{4 \eta_{D3} t_D} \right) \\
- \frac{1}{2} \frac{\lambda_g}{\lambda_w} E_i \left( - \frac{r_{D3-1}^2}{4 \eta_{D3} t_D} \right) &+ \frac{1}{2} (\ln(t_D) + 0.80908) + S_a
\end{align*}
\]

\[
\begin{pmatrix}
q_1 \\
-q_2 \\
q_3
\end{pmatrix}
\]

\[
\begin{pmatrix}
2\pi h k_{rg} \\
\mu_g
\end{pmatrix}
\]

\[
\begin{pmatrix}
\mu_g \\
2\pi h k_{rg}
\end{pmatrix}
\]

- Extraction well
- Injection well
Closed Boundary, 4 Extractors
Closed Boundary, 8 Extractors
Closed Boundary, 16 Extractors
Closed Boundary, 16 Extractors
Sensitivity Analysis
Reservoir Area = 219 km$^2$

Basin Area = 219 km$^2$

Basin Area = 500 km$^2$

Basin Area = 1000 km$^2$

Open Boundary
Synergy Opportunities

– EASiTool is an analytical simulation tool for capacity estimation in saline aquifers.

– Input data required for EASiTool is typically available for most of the projects.

– EASiTool results can be compared with the results obtain in other projects via other methods (static, simulation, etc).
Future Plans

• User defined locations for injection and extraction wells
  – Adding multiple reservoirs within the same basin
  – Pressure maps
• Improving the user interface
• Improving sensitivity analysis
• Application of to USGS database (36 Basins)
• Funding to maintain and further develop EASiTool
Summary

- Third version of EASiTool has been released.
- Calculations for maximum injection pressure.
  - Integrates thermal and pore pressure stresses.
- Brine extraction option.
- Constant rate injection option.
- Sensitivity analysis.
- EASiTool is available for download:
  - [http://www.beg.utexas.edu/gccc/EASiTool/](http://www.beg.utexas.edu/gccc/EASiTool/)
Questions/Comments
Appendix

- Organization Chart
- Gantt Chart
- Bibliography
- Extra Slides
# Organization Chart

**Project PI:**

Seyyed A. Hosseini

<table>
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<tr>
<th>Task 1</th>
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<th>Task 3</th>
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Bibliography

- Journals

- Conferences
Analytical model

Vertically averaged gas saturation

Development of dry-out zone leads to increase in relative permeability

Salt

Brine saturated with CO₂

Dissolved CO₂ reduces volumetric flow rate

Pure CO₂

CO₂ saturated with water

Brine free of CO₂

Radial distance from injection well
Accomplishments to Date

• Pore pressure stress coupling
  – Change in total stress ($\Delta \sigma$) is coupled with change in pore pressure ($\Delta P$).
  – We define $\beta_h = \Delta \sigma_h / \Delta P$ and $\beta_v = \Delta \sigma_v / \Delta P$ & typically $\beta_h > \beta_v$.

• Thermal stress
  – Injected CO$_2$ is generally colder than formation brine.
  – Shrinkage of the rock formation (specially near the injection well) by $\sigma^{\Delta T} = 2\alpha_T E \Delta T / (1-2\varphi)$.

• Mohr-Coulomb shear failure criterion
  $$\tau = c + (\sigma_n - \alpha \cdot P_{max}) \mu$$

Accomplishments to Date

1. 50 m above the interface (caprock)
2. 5 m above the interface (caprock)
3. Aquifer-caprock interface
4. 5 m below the interface (aquifer)
5. Middle in the injection aquifer
Accomplishments to Date-10

(a) Vertical effective stress, $\sigma'_v$ (MPa)
(b) Horizontal effective stress, $\sigma'_h$ (MPa)

- 1. 5 m above the interface (caprock)
- 2. Aquifer-caprock interface
- 3. 5 m below the interface (aquifer)
- 4. Middle in the injection aquifer
Accomplishments to Date-9

(a) Change in total stress, $\Delta \sigma_r$ (MPa) vs. Injection time (day)

(b) Change in total stress, $\Delta \sigma_z$ (MPa) vs. Injection time (day)

(c) Change in pore pressure, $\Delta P$ (MPa) vs. Injection time (day)

(d) Temperature (K) vs. Injection time (day)
Verification of EASiTool Models