RISK ASSESSMENT FOR CO$_2$ SEQUESTRATION

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INTRODUCTION TO CO₂ SEQUESTRATION

- Effect of anthropogenic CO₂ on global warming
- Carbon mitigation portfolio
  - Improved efficiency vehicles
  - Decarbonization
    - renewable, nuclear
  - Sequestration
- CO₂ sequestration options
  - Ocean
    - large capacity, ecological impact
  - Mineral
    - permanently, energy penalty
  - Geological: mature technology
    - oil/ gas reservoir
    - deep saline formation
    - deep coal seam

http://esd.lbl.gov/GCS/gcs-edu-out.html
RISKS IN CO$_2$ GEOLOGIC STORAGE

- **Risks**
  - Massive release of CO$_2$ to the atmosphere
  - Contamination of local environment: soil, water

- **Risk = Probability * Severity (impact)**

  - Identification of events/scenarios
  - Estimation of likelihood/probability
  - Evaluation of impact/consequences

A. CO$_2$ gas pressure exceeds capillary pressure
B&D. CO$_2$ leaks through faults
C. CO$_2$ escapes through ‘gap’ in caprock
E. CO$_2$ leaks through broken wells
F&G. CO$_2$ leaks through open aquifer

(IPCC, 2005)
**PHYSICAL SYSTEM**

Approx. Depth (m) 300

Radius ~0.1m

- Biosphere
- Aquifer 6
- Aquifer 5
- Aquifer 4
- Aquifer 3
- Aquifer 2
- Aquifer 1
- Aquitard 6
- Aquitard 5
- Aquitard 4
- Aquitard 3
- Aquitard 2
- Caprock
- Low permeability

Simplified geological structure

Upper Formations

Oil Reservoir

Lower Formations

CO₂ Source Pool

Annulus cement

Steel casing

Cement plug
PROCESS DESCRIPTION

- Viability of a sequestration system:
  - Leakage
  - Sequestration

\[
\frac{dM}{dt} = F_i - F_o
\]

- \( M \): CO\(_2\) mass
- \( F_i \): inflow rate = 0
- \( F_o \): outflow rate = leakage + sequestration

- Failed seals of wellbore
- Open fractures and faults
- Dissolution of source pool
- Migration of CO\(_2\) into surrounding formations
- Mineralization
MOVEMENT THROUGH WELLBORE

- Non-penetrating well equation
MOVEMENT THROUGH CAPROCK

- Equation for drainage in tunnels

Wellbore

Caprock

CO₂ source pool

Fluid pressure

Buoyancy
DISSOLUTION OF SOURCE POOL

- Dissolution of source pool to the formations **below** or **above** the source

\[
\text{Steady state dissolution rate} = \text{Diffusion through a semi-infinite plane} + \text{Diffusion through a falling film}
\]
MIGRATION THROUGH FAILED SEALS

- Migration of CO$_2$ to surrounding formations through failed seals on the way of rising up
  - Failure times are unpredictable
    - If the cement annulus fails first...
    - If the cement plug fails first...
  - Physical model
    - Heat conduction from a thin wire
      - Aquifer with advection, dispersion and reaction
      - Aquitard with diffusion and reaction
      - Apply solution for temperature profile
      - Get CO$_2$ concentration in the formation
      - Obtain steady state flux at the wall of the wellbore
        \[
        \lim_{t \to \infty} \left( \frac{\partial C(r, t)}{\partial r} \right)_{r=r_b}
        \]
      - Migration rate = steady state flux * concentration at the wall * thickness
OVERALL MASS BALANCE

- The mass left in the reservoir pool as time goes by:

\[ M = M_0 e^{-\beta t} - \frac{F_D}{\beta} \left[ 1 - e^{-\beta t} \right] - \frac{2\alpha e^{-\beta t}}{\sqrt{\pi \beta}} \int_0^{\sqrt{\beta t}} e^{\xi^2} d\xi \]

Leakage through wellbores and/or faults

Sequestration
Dissolution + Mineralization

\[ \beta = \frac{2\pi N_w K_s r_b \left( 1 + \frac{\rho_s \varphi_s}{\rho_w - \rho_s} \right) + \frac{N_F K_F L_F}{\ln \left( \frac{h_0}{h_F} \right)} \left( 1 + \frac{\rho_s \varphi_F}{\rho_w - \rho_s} \right)}{A_s \rho_s \varepsilon_s S_s} (\rho_w - \rho_s) \]

\[ \alpha = A_s \varepsilon_s S_s C_0 (D\tau)^{1/2} \]

Depends on the failure times of wellbore components
RESULTS FOR ONE SET OF PARAMETERS

- CO₂ mass fractions vs. time
- Left in the reservoir
- Released to the biosphere
- Sequestered in the formations

- CO₂ leakage rate (kg/a) vs. time
- Leakage rate through the wellbore
- Leakage rate to the surface

Loss rate due to migration
- 500 years
- < 5%
MODEL PARAMETERS

• Parameters:
  – Main independent parameters

<table>
<thead>
<tr>
<th>Formation</th>
<th>Brine water</th>
<th>CO₂ phase</th>
<th>Wellbore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth, Thickness, Permeability, Porosity, Tortuosity, Mineralization rate</td>
<td>• Salinity, Pressure, Surface tension of the free phase, Temperature gradient, Darcy velocity, Capillary pressure in reservoir, Dispersion coefficients</td>
<td>• Mass, Composition, Thermo-property, Permeability, Effective saturation</td>
<td>• Cement seal failure times, Casing failure times, Permeability of degraded cement, Effective crack diameter of degraded cement, Surface tension, Wellbore radius</td>
</tr>
</tbody>
</table>

– Main calculated parameters:
  formation fluid density, free phase density, viscosity, solubility, etc.
# Probabilistic Risk Assessment

## Input:
Randomly sampled from probability distribution function of independent parameters

## Monte Carlo Simulation

## Output:
Statistical Analysis

### Generated inputs with independent parameters

<table>
<thead>
<tr>
<th>sample #</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>...</th>
<th>$x_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>Porosity</td>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Model Outputs

<table>
<thead>
<tr>
<th>$y_1$</th>
<th>$y_2$</th>
<th>...</th>
<th>$y_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass left</td>
<td>Mass leaked</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

- [Graph of Surface tension of CO$_2$ in contact with water in wellbore (dyne/cm)]
- [Graph of Average porosity of reservoir formation]
MINIMUM MC SAMPLING SIZE

• 95% confidence interval for the average of the output:

\[ \bar{X} \pm 1.96 \frac{s}{\sqrt{n}} \]

\[ B \quad \iff \quad n = \frac{1.96^2 s^2}{B^2} \]

• Algorithm:

Start → Current population \( \bar{n} \) → \( n > n? \)

Yes → End

No → Add one sample

• Effect of number of input parameters on minimum sampling size
RESULTS FOR MONTE CARLO SIMULATION

Frequency histogram showing fraction released to the biosphere at 5000 years with normal (left) and lognormal (right) inputs
RESULTS FOR MONTE CARLO SIMULATION

Frequency histogram showing various times when 1% of total injected CO$_2$ mass leakage occurs with normal (left) and lognormal (right) inputs.
SAMPLING SIZE VS NUMBER OF PARAMETERS

Number of uncertain parameters

Minimum sampling size

Descending sensitivity order
Ascending sensitivity order
Random sensitivity order
SENSITIVITY ANALYSIS

Spearman's rank correlation between the mass fraction of leakage and normally distributed independent input parameters
SENSITIVITY ANALYSIS

Frequency histogram showing fractions released to the biosphere in 5000 years with different variances of the distribution of relative permeability.
Frequency histogram showing mass fraction released to the biosphere in 5000 years with ten leaky wells under normal (left) and lognormal (right) inputs.
GPU PARALLEL COMPUTING

- Multi-core and many-core

CPU
- 4 cores

GPU
- 240 cores

Dynamic Random Access Memory (DRAM)

Control
CORE
CORE
CORE
Cache

Lecture Notes, David Kirk/NVIDIA and Wen-mei Hwu, 2006-2008
FASTER THAN CONVENTIONAL CPU IMPLEMENTATION

![Graph showing speedup comparison between CPU and GPU implementations. The graph displays the ratio of time taken by one-threaded CPU, four-threaded CPU, and GPU for Monte Carlo simulations.]
CONCLUSIONS

- Developed a CO$_2$ sequestration simulator
  - Based mostly on the ideas of the CQUESTRA model

- Performed deterministic simulation and probabilistic risk assessment
  - Over 90% of the injected CO$_2$ is safely trapped underground after 5000 years in our simulations

- Parallel implementation of Monte Carlo simulation on GPUs
  - 64 times speedups
FUTURE WORK: CO₂ STORAGE IN DEEP SALINE AQUIFER

<table>
<thead>
<tr>
<th>Formation</th>
<th>Deep saline aquifer</th>
<th>Depleted oil/gas reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Post-injection</td>
<td>Mobile</td>
<td>Immobile</td>
</tr>
<tr>
<td>Mobile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immobile</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Trapping mechanisms:
- Structural trapping
- Residual trapping
- Solubility trapping
- Mineral trapping

(Kaldi, 2010)
(IPCC, 2005)
(Juanes et al., 2008)
## FUTURE WORK: CO₂ STORAGE IN DEEP SALINE AQUIFER

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<th>Deep saline aquifer</th>
<th>Depleted oil/gas reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>A layer of target formation</td>
<td>Individual reservoir(s)</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>Discrete</td>
</tr>
<tr>
<td>Leaking scenarios</td>
<td>Leak when encountering broken wells</td>
<td>Leak through intersecting</td>
</tr>
<tr>
<td></td>
<td>Leak when encountering faults</td>
<td>wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leak through faults/fractures</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Injection well**
- **A broken well**
- **A fault**
- **Brine water**
- **Mobile CO₂**
- **Static CO₂ source pool**
Thanks! Questions?