Overview of Reservoir Simulation and Risk Assessment for WESTCARB’s Kimberlina Phase III Pilot

Curtis M. Oldenburg
Christine Doughty
Lawrence Berkeley National Laboratory

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Outline

Part 1
• Overview of reservoir simulation
  — Geologic model
  — TOUGH2/ECO2N
  — Results
  — Evolution of mobile fraction

Part 2
• Application of the Certification Framework (CF) to K3
  — Characterization (surface, hydrology, geology)
  — Reservoir modeling
  — Likelihood of CO₂ and brine intersecting conduits
  — CO₂ and brine leakage risk
Geologic Model

20 km X 20 km Geologic Model

Source: Jeff Wagoner (LLNL)

Geologic Model of Vedder

EarthVision Model Vedder Formation

East-West Cross-section

North-South Cross-section

Oldenburg & Doughty p. 2
TOUGH2 Model Development

- EarthVision model of Olcese and Vedder
  - 600 layers
  - 50 x 50 lateral cells
  - x: 250 m wide, y: 200 m wide
- TOUGH2 model
  - Vedder - 30 layers (6 EV layers combined to form each TOUGH2 layer)
  - Closed boundaries above and below Vedder
  - Constant-pressure boundaries at x extrema, closed at y extrema
  - Lateral grid spacing varies
    - 5 m at injection well
    - 55 m over region where CO₂ plume expected to go
    - Increasing to 2.5 km far from injection well
  - Earthvision facies assigned to TOUGH2 cells
  - Model is a tilted plane – good approximation to the nearly uniform dip observed in the EarthVision model. Dip angle is 7 degrees
### Model Parameters

<table>
<thead>
<tr>
<th>Facies</th>
<th>Porosity</th>
<th>Horizontal Permeability</th>
<th>Vertical Permeability</th>
<th>Residual Liquid Saturation</th>
<th>Maximum Residual Gas Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>28%</td>
<td>200 md</td>
<td>20 md</td>
<td>0.2</td>
<td>0.28</td>
</tr>
<tr>
<td>Shale</td>
<td>15%</td>
<td>0.1 md</td>
<td>0.01 md</td>
<td>0.3</td>
<td>0.29</td>
</tr>
</tbody>
</table>

- Residual gas saturation
  - zero during drainage
  - non-zero during imbibition, depends on saturation history

### CO₂ Injection in Vedder

- Inject 250,000 t per year for 4 years
- Inject over entire thickness of Vedder (158 m thick)
- At injection location, about 50/50 sand/shale, so net sand thickness is about 79 m
- $P = 220$ bars, $T = 81^°C$, density of CO₂ = 632 kg/m³
Saturation in Cross-Section

Plume at 20 years is approx. the same as at 200 years.
Hysteretic relative permeability

=> Permeability of each phase depends on its saturation change history.

Relative permeability of CO₂ is higher at given saturation if the region is being flooded with CO₂ (draining water).

When CO₂ migrates away, water comes back in (wetting), relative permeability of CO₂ is lower at a given saturation leading ultimately to residual gas trapping.

Source: Chris Doughty (LBNL)
### Part 2: Risk Assessment for WESTCARB’s Kimberlina Phase III Pilot

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/University</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curt Oldenburg</td>
<td>LBNL</td>
</tr>
<tr>
<td>Preston Jordan</td>
<td>UT Austin</td>
</tr>
<tr>
<td>Chris Doughty</td>
<td>LLNL</td>
</tr>
<tr>
<td>Steve Bryant</td>
<td>LLNL</td>
</tr>
<tr>
<td>Navanit Kumar</td>
<td>UT Austin</td>
</tr>
<tr>
<td>Jeff Wagoner</td>
<td>LLNL</td>
</tr>
<tr>
<td>Mary Jane Coombs</td>
<td>UCOP</td>
</tr>
<tr>
<td>JP Nicot</td>
<td>Texas Bureau of Economic Geology</td>
</tr>
</tbody>
</table>

#### Kimberlina Phase III Pilot (K3)

- **Status of Sedimentary Basins in California**
  - Excluded
  - Included for further investigation

- **Other Layers**
  - Natural Gas Field
  - Oil Field
  - County Boundary
  - Power plants
  - Refineries
  - Cement and Lime
  - Gas Processing Plants

250,000 t CO₂/yr for four years
K3 Injection in a Nutshell

- CO₂ sourced from ~50 MW oxy-combustion power plant
- Inject 250,000 t CO₂ per year for 4 years at power plant site
- Inject over entire thickness of Vedder (160 m thick)
- At injection location, about 50/50 sand/shale => net sand thickness is about 80 m
- Top of Vedder is at a depth of 2300 m
- Vedder P = 220 bars, T = 80°C, density of CO₂ = 630 kg/m³
- Cap rock is Freeman-Jewett shale (100 m thick)
- Overlying this is the Olcese sand (200 m thick)
- Cap rocks to Olcese are Round Mountain/Fruitvale, McLure, and Macoma (all shale aquitards) totaling 700 m of thickness
Preliminary FEP Analysis

- Quintessa online FEP database
  - Features = characteristics such as geometry and flow properties
  - Events = abrupt changes in Features or Processes such as earthquakes
  - Processes = dynamics such as fluid flow or phase change
- 143 FEPs in Quintessa database
- We sorted FEPs into three groups
  - Group 3 = not relevant (78)
  - Group 2 = low probability or low impact or not in scope of K3RA (44)
  - Group 1 = very relevant (21)
- Screening done assuming K3 pilot parameters—not long-term GCS
- All Group 1 FEPs turned out to be either Features or Processes (no Events)

Group 1 FEPs

<table>
<thead>
<tr>
<th>FEP</th>
<th>Category, Class, or FEP Description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2.6</td>
<td>Rock failure</td>
<td>This topic is somewhat out of scope but a prototype should have characteristics allowing for quick and effective remedial action. The largest number of dikes would require that the permeability conditions, including the fluid pressure drawn down. Similarly, the small amount of CO2 might not make it relatively easy to produce the (back) body of a pressure gradient.</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Physical properties of CO2</td>
<td>Injection depth is shown. Temperature and pressure are extrapolated (see FEM 4.1.9 and 4.1.10). The well-known and defendable code TOUGH2 is used (see Section 5.1).</td>
</tr>
<tr>
<td>3.1.2</td>
<td>CO2 phase behavior</td>
<td>See FEP 3.1.1</td>
</tr>
<tr>
<td>3.1.3</td>
<td>CO2 mobility and pressure formation</td>
<td>See FEP 3.1.1</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Effect of pressurization of reservoir on reservoir</td>
<td>Addressed in TOUGH2 modeling (see Section 5.1). Maximum additional pressure due to section 3 brine (Figure 3.5), which is few percent of the total fluid pressure and unable to be pressure gradient.</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Mechanical processes and conditions</td>
<td>Fault reactivation, fracture creation until addressed in Section 5.1</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Adsorption of free CO2</td>
<td>Addressed by TOUGH2 modeling (Section 5.1)</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Buoyancy-driven flow</td>
<td>Addressed by TOUGH2 modeling (Section 5.1)</td>
</tr>
<tr>
<td>3.3.3</td>
<td>CO2 release processes</td>
<td>CO2 release processes and impacts of the surface or subsurface are treated in CF (Section 5.1).</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Reservoir type</td>
<td>Testing into a saline aquifer - see TOUGH2 results (Section 5.1)</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Reservoir geometry</td>
<td>Specific geometric properties have been included into the TOUGH2 model (Section 5.1)</td>
</tr>
<tr>
<td>4.1.6</td>
<td>Caprock or sealing formation</td>
<td>Depicted in Figure 3.2.1, Primary and secondary seals. Permeability and capillary entry pressure not known</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Pore architecture</td>
<td>Permeability and porosity are discussed in Section 5.1</td>
</tr>
<tr>
<td>4.1.10</td>
<td>Mixed properties</td>
<td>Depicted in Section 3.2.4</td>
</tr>
<tr>
<td>4.1.11</td>
<td>Fracture and features</td>
<td>Depicted in Section 3.2.3</td>
</tr>
<tr>
<td>4.1.12</td>
<td>Undeveloped features</td>
<td>Despite the lack of local data, there has been well-studied because of the scarcity of initial gas deposits. Uncertainty properties structures are unlikely to be present. Fluid distribution is addressed in Section 2.2.9</td>
</tr>
<tr>
<td>4.1.15</td>
<td>Petrophysical properties</td>
<td>Depicted in Section 5.1 porosity, permeability, relative permeability curves, residual saturation - data enhanced/extracted from other wells and from expert knowledge</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Fluid properties</td>
<td>CO2 properties are addressed in FEP 3.1.1 and 3.1.2. Molten brine properties are used in TOUGH2 simulations</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Loss of containment</td>
<td>Addressed in CF and on sections on seals (Section 6)</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Corrosion of pipe/penetration</td>
<td>piping corrosion properties of L/A, May be design of piping given in Section 2.3.2. Elevated pressure issues may not be sufficient for more saline water to reach swelling aquifer - see Appendix C</td>
</tr>
</tbody>
</table>
Some Group 2 FEPs

- Seismicity—relatively non-seismic area of CA
- Drilling activities—mostly for water much shallower than Vedder
- CO₂ composition—very pure CO₂ stream from CES plant
- Overpressuring—pressure buildup mostly during 4 years of injection
- Displacement of saline fluids—low-volume injection
- Induced seismicity— injection rate and injectivity compatible with small pressure buildup

CF in a Nutshell

- Leakage
- Impact
- USDW Compartment
- Storage Region

Oldenburg & Doughty p.12
CF Compartments

- ECA Compartment
- NSE Compartment
- HS Compartment
- USDW Compartment
- HMR Compartment

Conduits (wells and faults)

Storage Region

CF Conduits and Compartments

- ECA
- HS
- NSE
- USDW

Wells

Faults and Fractures

Source

CO₂

Potable water

Sealing Formation
CF Logic

Oldenburg & Doughty  p.14

CF Approach

- Hazard
  - CO₂ injection as a perturbation to the system
- Risk arises from
  - Potential for CO₂ and brine leakage
  - Potential for impacts due to leakage
- First step is to define the storage region
- Second step is to identify where impacts may occur
- Third step is to identify and characterize potential leakage conduits (wells and faults)
- Fourth step is to model CO₂ plume and pressure
- Fifth step is to evaluate potential for leakage and the associated impacts => calculate risk
1. Define Storage Region

First step is to define the storage region
- Vedder Formation from injection well to 10 km (6 mi) radius

2. Define Vulnerable Entities

- Topographic relief is minimal.
- Agriculture is primary land use (almond orchards).
- Site is adjacent to U.S. Route 99 and railroad.
- There are a few residences, closest one being 1 km to SW, but generally very sparsely populated.
- Calm conditions, inversion, tule fog in winter.

Bakersfield climate
Geologic Characterization

20 km X 20 km Geologic Model

USDW and Hydrostratigraphy

Oldenburg & Doughty p.16
3a. O&G Wells in 20 km x 20 km Area

Third step is to characterize potential conduits
— wells

Red => well penetrates top of Vedder

Blue => well terminates shallower than Vedder

Black => no depth data

3b. Oil Fields and Faults Near K3 Site

Third step is to characterize potential conduits
— Faults (green)
Faults

- There are no faults mapped at the K3 site
- Fundamentally, some concept of fault density is needed to develop a probability of the plume intersecting a fault.
- Faults occur over a wide range of scales => fault density concept requires specification of size of fault.
- In addition, relation between fault orientation and plume shape is important.
- Lacking site-specific fault data, we measured fault statistical properties determined at surrounding oil fields and assumed the same distributions apply at the K3 site.

Example Fault Data

- 956 fault segments were measured

Structure Maps in DOGGR, 1998, CA Oil and Gas Fields, V.1
Near-Kimberlina Fault Orientation

Fault Density

\[ F = B d^{-C_d} \]
\[ \log(F) = a - b \log d \]

- \( F \) is the length of fault in an area with greater than a given displacement \( (d) \)

(\textit{Watterson et al., 1996}, for instance)
Near-Kimberlina Fault Density

Near-Kimberlina Fault Density (cont’d)
Potential Intersections

- Emission Credits and Atmosphere
- Health and Safety
- Near-Surface Environment
- Underground Sources of Drinking Water
- Hydrocarbon and Mineral Resources
- CO₂ source

4. Model CO₂ and Pressure

Oldenburg & Doughty p.21
5. Evaluate Leakage Risk

- Sizes of perturbations
  - CO₂ plume
  - Pressure pulse
- Well and Fault intersection probability
  - CO₂ plume
  - Pressure perturbation
- Well and Fault flow potential
  - Permeability
  - Driving force
- Potential for impacts to compartments
- Overall CLR* and BLR**

*CLR = CO₂ Leakage Risk
**BLR = Brine Leakage Risk

Sizes of Perturbations

CO₂ Plume

Plume is large relative to property lines, small relative to distance to wells and well spacing.

Pressure Perturbation

Pressure pulse is short-lived (<5 years)
CO₂ Plume Conduit Intersection

**Wells**
- Water wells are too shallow to intersect plume.
- Deep wells are sparse.
- CO₂ plume not predicted to intersect deep wells.

**Faults**

**Caveats**
- Could be unknown wells.
- Plume prediction could be wrong.

Probability that CO₂ plume will encounter a fault that fully offsets the seal.

CO₂ Well and Fault Flow Potential

**Wells**
- Blowouts 1/15,000 over 20 yrs (Jordan and Benson, 2008).
- Most wells are filled with drilling mud or cement or have cement plugs.

**Faults**
- Shale-gouge ratio (SGR) suggests seal-offsetting faults will be low-k features.

**Caveats**
- Some wells could be open.

**Caveats**
- There are no data on faults at the K3 site.
- There is no oil or gas at the K3 site.
- Fault permeability is notoriously uncertain.
### Pressure Pulse Intersection

<table>
<thead>
<tr>
<th>Wells</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Multiple wells will be intersected by pressure pulse.</td>
<td>• Multiple faults will be intersected by pressure pulse.</td>
</tr>
<tr>
<td>• Deep wells are sparse.</td>
<td></td>
</tr>
</tbody>
</table>

**Caveats**

<table>
<thead>
<tr>
<th>Wells</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Could be unknown wells.</td>
<td>• Could be unknown faults.</td>
</tr>
<tr>
<td>• Pressure prediction could be wrong.</td>
<td>• Pressure prediction could be wrong.</td>
</tr>
</tbody>
</table>

### Brine Well and Fault Flow Potential

<table>
<thead>
<tr>
<th>Wells</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Blowouts 1/15,000 over 20 yrs (Jordan and Benson, 2008).</td>
<td>• Elevated pressure does not necessarily lead to significant upflow.</td>
</tr>
<tr>
<td>• Most wells are filled with drilling mud or cement or have cement plugs.</td>
<td>• Low k by SGR</td>
</tr>
<tr>
<td>• Elevated pressure does not necessarily lead to significant upflow.</td>
<td>• Density stratified system</td>
</tr>
<tr>
<td></td>
<td>• Low k</td>
</tr>
<tr>
<td></td>
<td>• Density stratified system</td>
</tr>
</tbody>
</table>

**Caveats**

<table>
<thead>
<tr>
<th>Wells</th>
<th>Faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Well properties are uncertain.</td>
<td>• Fault permeability is notoriously uncertain.</td>
</tr>
</tbody>
</table>
Impacts

- The impacts of potential leakage will be relatively small in this sparsely populated region (e.g., CO₂ discharging at the ground surface).

- Emphasis on likelihood of occurrence of low-impact events arises because it is hard to justify expending large resources on modeling low-probability, low-impact events.

- Conservative likelihood estimates are consistent with the sparse subsurface data available for the site.

Summary

- We have used the CF approach (along with FEP analysis) to analyze CO₂ and brine leakage risk at the K3 site.

- We made use of 3D geologic model, and inventory of wells and associated data near the site.

- Lack of data on faulting inspired a novel approach to calculating the probability of encountering faults in a statistical sense.

- Numerical simulations with TOUGH2 and CMG-GEM provide defensible predictions of CO₂ plume migration.

- Based on these data, simulations, and analyses we find the leakage risk for the K3 pilot project to be de minimis.

- Additional data gathering, validation of the novel approaches used here, and modeling should be undertaken as the pilot project proceeds.
Acknowledgments

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