Snøhvit CO$_2$ storage project: Understanding the role of injection induced mechanical deformation

Joshua White, Laura Chiaramonte, Whitney Trainor-Guitton

Project Number: FWP-FEW0174 Task 4

Lawrence Livermore National Laboratory
Carbon Storage R&D Review Meeting, Pittsburgh, August 12-14, 2014
Program Goal No. 4

- “Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.”

Benefit Statement

- An understanding of hydromechanical interactions is essential for effective monitoring and prediction of reservoir performance. This is especially true for storage systems expected to experience higher overpressure.

- This project has developed new analysis methodologies for:
  - probabilistic assessment of fault reactivation potential and in situ stress sensitivity
  - dynamic well-test analyses using multi-rate gauge data
Snøhvit

Structural diagram of Hammerfest Basin at Middle Jurassic level (approx. age of producing reservoir). Blue lines outline the gas fields [from Spencer et al., 2008].
Snøhvit

Depth map at top of Fuglen Fm. (below) and stratigraphic section (right) [from Wennberg et al., 2008]

- Producing natural gas with 5-8% CO₂ content, which needs to be reduced before liquefaction.
- Separated CO₂ was originally re-injected into Tubåen Fm. at approx. 2400-2600m depth.
- Injection began in 2008, but in 2010 Statoil announced storage capacity in Tubåen was lower than expected. Operators recompleted well and have continued injection in the shallower Stø formation.
Focus areas where modeling can help monitoring and project management:

1. **Decision-based Modeling**
   - Using modeling to inform instrument design and deployment schemes

2. **Data Integration and Data Assimilation**
   - Merge diverse monitoring data sets into unified interpretations
   - Deterministic or stochastic inversion of monitoring data

3. **Uncertainty Quantification and Risk Assessment**
   - Quantify how uncertainty impacts performance and risk
Snøhvit Case Study 1
Using modeling to address uncertainty in stress measurements

[Chiaramonte et al. 2014]
A key project concern was whether excess fluid pressure could reactivate faults and create leakage paths.

**Figure**: Model prediction of excess pressure (MPa) necessary to initiate fault slip with the base case scenario parameters, which corresponds to a SS/NF environment with N-S $S_{H_{max}}$ direction.
Sensitivity analyses reveal that critical uncertainty is SHmax orientation, but overall leakage risk is low.

**Figure:** SHmax azimuth dominates critical pressure sensitivity

- Suggests highest-value target for future characterization efforts
Snøhvit Case Study 2
Welltest analysis and continuous inversion of gauge data

Figure: 4D difference amplitude maps, 2003-2009, lower perforation.
Pressure response indicative of a partially compartmentalized system

BHP estimated from permanent pressure/temperature sensors at 1782 mTVDss, hourly data.
Well tests commonly used to look for flow barriers and other indications of reservoir structure.

Figure 1.21. One sealing fault. Pressure profile at time $t_4$. The fault is reached, and it is seen at the well. Hemi-radial flow.

Figure 1.22. One sealing fault. Drainage radius. This pressure regime corresponds to time $t_2$ on Figure 1.22: the boundary has been reached and the pressure profile is distorted in the reservoir, but the image curve has not changed the well flowing pressure. As the flow time increases, the radius of investigation of the theoretical infinite reservoir curve continues to expand, and the image curve reaches the well (time $t_3$ on Figure 1.22 and Figure 1.20). The well bottom hole pressure starts to deviate from the infinite reservoir response, and drops faster. Ultimately, when the well has been flowing long enough, the two profiles tend to merge (after time $t_4$ on Figure 1.22) and the hemi-radial flow regime is reached: the flow lines converge to the well with a half-circle geometry.

Specialized analysis During the hemi-radial flow regime, the pressure changes with the logarithm of the elapsed time but the slope of the semi-log straight line is double ($2m$) that of the infinite acting radial flow (van Everdingen and Hurst, 1949, Homer, 1951).

$t_1$: the fault is not reached, radial flow
$t_2$: the fault is reached
$t_3$: the fault is seen at the well, transition
$t_4$: hemi-radial flow

[Figure from Bourdet, 2002]
Falloff analysis showed clear indications of flow barriers

- Results suggested flow barriers at 110, 110, and 3000m

![Graph showing falloff analysis with clear indications of flow barriers](image)

**Figure:** Falloff analyses using permanent gauge (2009) and PLT data (2011).

(Hansen et al. 2012)
Falloff testing has proven value, but requires shutting in the well for significant periods.

- **Motivating question:** Can we derive similar information from ongoing injection data, without shutting in for long periods?
Generalized superposition well-test method

- Multi-rate injections are difficult to analyze.

- Can use superposition principle to transform a multi-rate injection into an “equivalent” single-rate test.

- Solve for a characteristic buildup curve, as a constrained least-squares problem.

\[ p(t) = q \cdot p_C(t) \]

**Single rate:**

\[ p(t) = \sum_{i} (q_{i+1} - q_i) \cdot p_C(t - t_i) \]

**Multi-rate:**
Automatic calibration to Snøhvit data (~5 seconds)
Superposition tool can potentially be used in two modes:

1. **Reservoir characterization mode**
   - Calibrate to gauge data, extract equivalent falloff test
   - Apply standard well-test analysis techniques to results

2. **Pressure forecasting mode**
   - Calibrate to gauge data, project forward in time
   - Quickly explore alternative injection scenarios
Fast-running pressure forecasting

- measurement
- forecast / precast
- calibration period

Pressure, bar vs. time, days

Equivalent buildup test
Fast-running pressure forecasting

- Measurement
- Forecast / Precast
- Calibration period

Pressure, bar vs Time, days

Equivalent buildup test

0 100 200 300 400 500 600 700 800 900 1000 1100
300 310 320 330 340 350 360 370 380 390 400
Fast-running pressure forecasting

![Graph showing pressure over time with measurement, forecast/precast, and calibration period sections.](image-url)
Fast-running pressure forecasting

- Measurement
- Forecast / Precast
- Calibration period

Pressure, bar vs. Time, days

Equivalent buildup test
Fast-running pressure forecasting

![Graph showing pressure over time with measurement, forecast/precast, and calibration period labels.](image)

- Measurement
- Forecast/precast
- Calibration period

Equivalent buildup test

Pressure, bar vs. time, days
Fast-running pressure forecasting

![Graph showing pressure over time with measurement, forecast/precast, and calibration period phases.](image-url)
Retrospective analysis of a brine pre-production scenario
Summary

① This project has explored two useful analysis techniques:
   - Probabilistic assessment of fault reactivation potential and in situ stress sensitivity
   - Dynamic well-test analyses using multi-rate gauge data

② Directions for future work:
   - Full poromechanical simulations of fault reactivation and leakage.
   - Relaxing current assumptions in the welltest analysis methodology to provide a more general tool.
Acknowledgements

- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Data and co-funding were provided by the DOE Carbon Sequestration Program and Statoil.

Contact

- **Laura Chiaramonte**
  Baker Hughes
  laura.chiaramonte@bakerhughes.com

- **Josh White**
  Lawrence Livermore National Laboratory
  jawhite@llnl.gov
Appendix
Org Chart

Fuel Cycle Innovations (Roger Aines)

Carbon Management (Susan Carroll)

LLNL Carbon Sequestration Program
- Task 1. Active Reservoir Management
- Task 2. In Salah
- Task 4. Snovit
- Task 5. Carbonates

Technical Staff
- Boucier, Buscheck Aines
- Ezzedine, Hao, White
- Chiaramonte, White, Hao, Wagoner, Walsh
- Carroll, Hao, Mason, Smith

Expertise
- Subsurface Hydrology
- Computational Geomechanics
- Experimental and Theoretical Geochemistry
- Seismology
- Structural Geology
### Gantt Chart

<table>
<thead>
<tr>
<th>Task</th>
<th>FY2012</th>
<th>FY2013</th>
<th>FY2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Pre-study</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2 Site characterization &amp; geomodel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.3 Flow and transport modeling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.4 Geomechanical modeling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forecasting fault failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caprock deformation &amp; fracture</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- All technical tasks have been completed.

- In the final reporting stage:
  - Several journal manuscripts currently in review or preparation.
Bibliography


3. Numerous conference papers and abstracts.