Interpretation of multi-level downhole pressure measurements during a field test of subsurface storage of carbon dioxide in the CO2CRC’s Otway site, SE Australia

Jonathan Ennis-King, Tara LaForce and Charles Jenkins
CO2CRC/CSIRO

IEAGHG Monitoring and Modelling Workshop
Edinburgh, UK, July 6-8, 2016
Outline

• Context of Otway Project Stage 2C
• Data collected
• Interpretation of pressure response
  • Fluid density and interface tracking
  • Earth tide response
  • Pressure diffusion and leak detection
Stage 2C Project Outline

- Injected 15,000 tonnes of CO$_2$-rich gas between December 2015 and April 2016, in three lots of 5000 tonnes, with about 10 days between each injection.
- The primary goal was detection of the plume using geophysical techniques.
- Secondary opportunity to examine the above-zone and in-zone pressure response to changes in injection rate.
- Some harmonic injection on a 4-day cycle during second and third phases.
## Schematic of pressure monitoring

<table>
<thead>
<tr>
<th>Zone</th>
<th>Permeability</th>
<th>Porosity</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above-zone</td>
<td>$K_3 = 491$ mD, $\phi_3 = 0.27$, $L_3 = 10.0$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low permeability</td>
<td>$K_2 = 0.023$ mD, $\phi_2 = 0.20$, $L_2 = 44.8$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection zone</td>
<td>$K_1 = 355$ mD, $\phi_1 = 0.26$, $L_1 = 14.9$ m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rate and pressure data from Stage 2C

Rate (t/d)

In-zone (MPa)

Above-zone (MPa)
Utility of multiple gauges

• Protects against failure or poor quality
• Pressure differences between a vertically separated pair of gauges relate to average fluid density
• Calibrate for period when only formation brine is present in that interval
• From computed fluid densities, can track gas-water interface assuming it is sharp
In-zone inferred CO$_2$/brine interface during Stage 2C

120 point median filter, sampled to 10 minutes

Inferred depth of CO$_2$/brine interface (m)

Days since start of November 2015
Inferred density at Stage2B level during Stage 2C injection

1 hour median filter on pressure data

Inferred fluid density between gauges (kg/m³)

- G3-G4 (8.07m)
- G3-G8 (9.95m)
- G6-G4 (5.38m)
- G7-G8 (7.26m)

Days since start of November 2015
Stage2B level temperature during Stage 2C injection
Harmonic effects in above-zone data?

- Remove barometric effects (need atmospheric pressure data)
- Remove earth tide effects – compute the synthetic forcing signal and fit compressibility
- Fit overall pressure increase with suitable functions (polynomials)
- Look for periodic signal at frequency of rate variation (4 days)
Fitting of barometric and earth tide signals
Frequency analysis of residual pressure response

Harmonic injection frequency

Cycles per day
Possible mechanisms for above-zone response

- Pressure diffusion through intervening layers
- Leakage within the wellbore e.g. packers
- Leakage through a distant high-perm pathway
- Geomechanical coupling
- Slow changes to above-zone aquifer conditions e.g. nearby injection/production etc

Both Cranfield and Ketzin field projects showed an above-zone pressure response.

*Is there a ‘fingerprint’ that distinguishes the mechanisms?*
Analysis of response function

- Standard mathematical approach is to derive the response $G(t)$ to a sharp pulse at $t=0$ (Green’s function)
- Then the total response to variable rate $Q(t)$ is
  \[ \int_{0}^{t} G(t - \tau)Q(\tau)d\tau \]
- For simulations, examine the response to a short but finite pulse of injection (rate needs to be within the linear regime)
Theory for pressure diffusion

Neumann and Witherspoon 1969 (single phase)

For a short injection pulse of length $t_d$, and a low permeability baffle, pressure is

$$
\frac{\mu_w Q_w}{4 \pi k_3 L_3} \tilde{t}_d f(\tilde{t}; p, q, c)
$$

where $p = \frac{k_1 L_1}{k_3 L_3} = 1.07$, $q = \frac{\varphi_3 k_1}{\varphi_1 k_3} = 0.75$,

$c = \frac{\varphi_1 L_1 c_1}{\varphi_2 L_2 c_2} = 0.43$, $\tilde{t} = \frac{k_2 t}{\mu_w \varphi_2 (L_2)^2 c_t}$, time scale 81 days
Theory for wellbore leakage

Avci 1994 (single phase)

For a leak path at distance R with flow resistance \( \Omega \), the response time depends on pressure transmission along the two reservoirs, so the time scale is

\[
\frac{\mu_w \varphi_1 (R)^2 c_t_1}{k_1} + \frac{\mu_w \varphi_3 (R)^2 c_t_3}{k_3}
\]

For \( R=100 \text{m} \), the time scale is \(~ 2 \text{ hours} \), so well separated from pressure diffusion time scale.
Above-zone response to 0.5 day pulse of water injection

- Simulation
- Semi-analytical solution
- $c \times \exp(-1/(4t))/(2t)$
Above-zone pressure response with leak for 0.5 day injection
Implications for above-zone monitoring

- Could regard the 15,000 tonnes injection as either:
  - Proxy for a larger injection, with response scaled up
  - Proxy for a leak from a full-scale injection.

- The pressure diffusion signal has the advantage that it smears out the response in time (persisting after the ‘leak’ has stopped)

- The presence of pressure diffusion from the main injection may complicate leak detection.
Conclusions

• Above-zone pressure monitoring is sensitive to a small-scale injection, and is able to detect large variations in injection rate.
• Single-phase theory gives good predictions for the above-zone response due to pressure diffusion, which has a long time scale set by the average vertical baffle permeability.
• Wellbore leakage has a much shorter characteristic time, set by the reservoir and above-zone permeabilities.
• The presence of multiple signals – barometric, earth tide, pressure diffusion – complicates analysis.
ACKNOWLEDGEMENTS

We would like to acknowledge the funding provided by the Australian government to support this CO2CRC research project.

We also acknowledge funding from ANLEC R&D and the Victorian Government for the Stage 2C project.

Funding for LBNL was provided through the Carbon Storage Program, U.S. DOE, Assistant Secretary for Fossil Energy, Office of Clean Coal and Carbon Management through the NETL.

We thank the National Geosequestration Laboratory (NGL) for providing the seismic sources (INOVA Vibrators) for this project. Funding for NGL was provided by the Australian Federal Government.
Stage 2C project team


CSIRO: T. Dance, V. Shulakova, T. LaForce, J. Ennis-King, L. Paterson

Government, Industry and Research Partners
Thank you