Part I: Field-Based Observations for CO₂ Geological Storage from 6 Years of CO₂ Injection at Aquistore

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Outline

• Fundamental Requirements for CO₂ Storage and MMV
• Introduction to Aquistore Project
• CO₂ Injection
• Time-Lapse Pressure Monitoring Dynamics
• Well Cementing Dynamics
• Surface and Subsurface Gas Measurement
• Well Dynamics
• Salt Precipitation
• Seismic Monitoring
• Dynamic Reservoir Modeling
• Summary
CCUS

Global CO₂ capture capacity at large-scale facilities by source
Fundamental Requirements for CO$_2$ Storage

A geological site suitable for CO$_2$ storage must have:

- sufficient **injectivity** to receive CO$_2$ at the rate at which it is to be supplied
- secure **containment (and conformance)** of the CO$_2$ for the long-term
- sufficient **capacity** to store the delivered CO$_2$ over the lifetime of injection operations

ISO/TC 265

ISO 27914

Document provides recommendations for the safe and effective storage of CO$_2$ in subsurface geologic formations through all phases of a storage project life cycle.
Measurement, Monitoring and Verification (MMV)

• Project operators **shall** develop and implement an MMV program suited to their operation be designed to serve the following objectives:
  • (a) to protect health, safety, and the environment throughout the project life cycle by **detecting early warning signs of significant irregularities or unexpected movement of CO\(_2\) or formation fluid**
    • (i) through **gathering information on the effectiveness of containment of CO\(_2\)** throughout the project life cycle; and
    • (ii) by providing **sufficient evidence that the CO\(_2\) has not moved beyond the storage complex**, including leakage to a shallow subsurface zone or to the atmosphere
  • (b) to **support risk management** throughout the project life cycle
  • (c) to provide adequate information for **decision support** within the project, **communication** with regulatory authorities and with other stakeholders, including the local community or local landowners as appropriate
Planning for MMV at Aquistore...

(1) Plume/Containment Monitoring
(2) Public Assurance
(3) Research Objectives
Aquistore - CO₂ Storage in Saskatchewan

- SaskPower owner and operator of the wells and Aquistore, an independent CO₂ Monitoring and Storage research project managed through PTRC with guidance provided by a Science and Engineering Research Committee.

- Injection commenced April 16, 2015 and a ribbon cutting ceremony May 20, 2015. Over 370,000 tonnes of CO₂ injected to date.

- Testing and comparing proven and novel measurement, monitoring and verification technologies for efficiency and economics.

- CO₂ injection well with confirmed acceptance of up to 2400 tonnes/day and one observation well 150m away from injection well.

- Aquistore has and will continue to contribute significant evidence-based knowledge in support of safe and effective implementation of the geological storage of CO₂ in association with coal-fired power generation and that MMV technologies can be effectively deployed in commercial projects to demonstrate injectivity, conformance and containment performance metrics under complex and dynamic operating conditions.
MMV Program at Aquistore

Site characterization

Baseline Surveys

- Site/Funding Agreements
- Injection Well
- Observation Well
- H₂O Injection Test
- Permanent & Baseline 3D Seismic
- Groundwater, Soil Gas, Passive Seismic
- GPS, Tiltmeters, InSAR, Piezometers
- Crosswell Seismic, Monitor I 3D Seismic
- CO₂ Injection
- Baseline VSP, Monitor II 3D Seismic

Surface-based:
- Regional 3D seismic survey
  - Geological characterization
  - Baseline & time-lapse
- Permanent seismic array
  - Time-lapse imaging
- Electrical/electromagnetic
- Gravity
- Passive seismic (broadband & short period array)
  - InSAR
- GPS
- Tiltmeters
- Groundwater & soil gas monitoring
- Carbon isotope profile

Down-hole:
- Cross-well seismic & VSP
- Cross-well & surface-to-downhole electrical monitoring
- Real-time P & T
- Passive seismic
- Fluid sampling
- Time-lapse logging
- Distributed Acoustic/ Temperature Sensors (DAS/DTS)
- Heater cable
- Gravity

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NSERC/Energi Simulation Industrial Research Consortium on Reservoir Geomechanics
Site Configuration
Geological Setting

- Storage reservoir is 200 m thick and extends from 3130 m to 3350 m depth at the injection well and comprises the Deadwood and Winnipeg formations.

- The Deadwood Formation is sandstone with silty-to-shaley interbeds. It is overlain by the Winnipeg Formation, which includes the Icebox (shale) and Black Island (sandstone).

- The Icebox constitutes a shale caprock and is the primary seal to the reservoir. A secondary storage seal is provided by the Prairie Evaporite Formation which is a ~150 m thick evaporitic unit that resides ~500 m above the reservoir.

- The injection well has been perforated over four intervals: one in the Black Island, two in the upper and one in the lower Deadwood interval.
DTS lines are located along the length of the tubing of injection well, and the casing of the observation well (~spaced every 100 m). DTS lines do NOT cover the targeted CO2 storage interval. NOT capable of profiling the injection flowrate in the 4 perforated zones.
CO₂ Injection
**CO₂ Injection**

Multiple *non-isothermal transient periods* of relatively high injection rates followed by periods of limited injection.

*Thermal map* shows *rapid heating & cooling* of the wellbore with injection. Temperature is monitored along *Inj* and *Obs wells* (DTS).
Dynamic Responses during CO₂ Injection

Density Instability

\( \frac{\partial \rho}{\partial z} < 0 \)

CO₂ column is gravitationally unstable.

Isothermal

Thermal

Cumulative Volumes Calculations
Time Lapse Pressure Transient Dynamics
Time-lapse Pressure Transient Analysis at Aquistore

20-30 good falloff periods from 2015 to 2020 (potential for build-up analysis!?)

Temporal Evolution of Non-Isothermal (..cold) CO$_2$ Injectivity at Aquistore

Injectivity data could be grouped into 3 clusters with distinct injectivity status (~10,000% increase).

No seasonal variation in injectivity
Injectivity correlates negatively with BHT.
Cementing Dynamics
Observation Well – Dynamics during Cementing

4 Casing-Conveyed Pressure Gauges
1. 3137m (Ice Box Shale)
2. 3177m (Black Island)
3. 3235m (Upper Deadwood)
4. 3305m (Lower Deadwood)
Cementing Dynamics

Instrumentation string landed at bottom hole

Reservoir Pressure*

P/T-3135 disconnected

Started, stopped pumping to pressure up stage collar.

Start circulation and conditioning mud for cementing

24 hours

Start of 1st Stage of Cement

End of 1st Stage

P-3302 m
P-3232 m
P-3174 m
P-3135 m

T-3302 m
T-3232 m
T-3174 m
T-3135 m

End conditioning mud for cementing

[Diagram showing pressure and temperature over time with annotations for key events in the cementing process]
Surface and Subsurface Gas Measurement
Gas Measurements: Surface and Subsurface

- **Surface**

- **Subsurface**
  - Sample the gases contained in drilling fluids
  - Compound-specific isotopes of $\delta^{13}C$ in gases show patterns as a function of depth (kerogen, maturity, mixing, alteration, etc)
  - Gas samples (e.g. SCVF, soil gas, etc) can then be fingerprinted

**Interpretation:**

1. Soils on this 49 km$^2$ grid will respire about 70,000 tons/yr CO$_2$ naturally across the seasons. So there is the potential for significant buildup of CO$_2$.
2. The soils in this region are hard, tight, cemented, and compact, and significant accumulation of naturally produced-CO$_2$ in SK is well documented.
3. Soil wetness (low points, wet seasons) enhance CO$_2$ storage by limiting outward diffusion.

**D. Risk, St. F.X. - FluxLab**
Well Integrity Dynamics
Response of Casing Conveyed Sensors to CO$_2$ Injection

Behind Casing Pressure Dynamics > 1MPa

Behind Casing Thermal Dynamics 30°C
Metallurgy and Corrosion - CO₂ Injection Well

Gauge Mandrel for Tubing Conveyed Gauge

Depth (Not-To-Scale)

- DTS
- Casing Conveyed Sensor (3055 m)
- Tubing Conveyed Sensor (3136 m)
- Packer (3141.7 – 3142.0)
- Casing Conveyed Sensor (3162 m)

Turn-Around Sub for DTS
4 ½” Tubing
(114.3mm, 17.26 kg/m, L-80, QB2)
Salt Precipitation Dynamics
Salt Precipitation

Brine Chemistry:
- Highly saline, Na, Ca, Cl dominated
- The water is likely saturated with respect to halite, calcite and anhydrite

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<th>Solution</th>
<th>Precipitates</th>
<th>mmoles/L</th>
<th>g/L</th>
<th>cc/L</th>
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<tr>
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<td>Total</td>
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<td>Br⁻</td>
<td>0.71</td>
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Lower Deadwood 3255m – 3266m

Virtual Flowmeter Log from Downhole Camera Videos

Correcting for
- image distortion
- image overlap
- image orientation

results in:
“stitched images” of
wellbore profile
Seismic Monitoring
Time Lapse Seismic Monitoring

- Effectiveness of permanent array is demonstrated - still operational after 8.5 years.
- Alternative DAS fibre configurations show potential for surface data acquisition.
- No induced seismicity over 5-1/2 years of injection.
- CO\textsubscript{2} plume is contained within the reservoir.
- Constrains vertical distribution of CO\textsubscript{2} in the reservoir.
- Strong influence of reservoir structure is observed.
Experimental DAS Configurations (Fibre Optics)
Dynamic Reservoir Modeling
Different History Matched Realizations of CO\textsubscript{2} Plume

Layer Cake Model  

with Stochastic Properties

with Stochastic Properties + Flexure

Stochastic Properties + Flexure + Seismic

Simulated CO\textsubscript{2} Saturation  
Deadwood D – Top Layer Only

1.4 km  

Saturation-Thickness Average  
Map – All Layers

Gas saturation

- 0 to 0.5
- 0.5 to 0.75
- 0.75 to 1.0
Different History Matched Realizations of CO₂ Plume

- All realizations match reported field data!
- Very similar history matches on injection rate data, but with very different petrophysical property distribution.
- There is a need to constrain the simulation with time-lapse seismic surveys.
Additional Constraint: Observation Well BHP using Bubble Tube

- Loss of casing conveyed gauges in Obs Well meant no BHP data away from injection well
- Convert casing conveyed fluid recovery system (which did not fail) to automated bubble tube system for BHP at Obs Well
MMV and CO₂ Storage

A geological site suitable for the CO₂ storage must have:

- sufficient **injectivity** to receive CO₂ at the rate at which it is to be supplied
- secure **containment (and conformance)** of the CO₂ for the long-term
- sufficient **capacity** to store the delivered CO₂ over the lifetime of injection operations

Know what you’re looking for!

Sometimes it really does make sense to just get started!
Field-Based Observations for CO\textsubscript{2} Geological Storage from 6 Years of Dynamic CO\textsubscript{2} Injection at the Aquistore CO\textsubscript{2} Storage Site

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