Storage: Deep Monitoring and Verification

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Why Monitor? – Manage Risk

Risk =

“(Impact of Undesirable Occurrence) x
(The Probability of its Occurrence)”

But it is not that simple……
Risk Perception

Public vs. Experts

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**Public**

Feels - The Dread Factor

Public: Risk Size = ("Known" factor) * ("Dread" factor)

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**Experts**

Calculate

Experts: Risk Size = (Probability) * (Loss)

Expert risk studies are rarely effective for convincing the public that a proposed project is safe.

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Figure 2-1: Differences between Public and Expert Risk Perception –
The public consistently rates some risks higher than risk experts (Slovic et al., 1979).
Risks can be Managed – we do it all the time

- Evaluate & Understand
- Model & Simulate
- Measure & Monitor
- Mitigate
- Experiment and Demonstrate

(I bet they tried it with a dummy first ... 
... and it might be a fake!)
Finding the Right Storage Site

What do we need?

**Capacity:**
The amount of CO₂ that can be safely stored

**Injectivity:**
The ease with which the CO₂ can be injected

**Containment:**
The ability to store CO₂ safely and permanently

**Other:**
- Environment
- Infrastructure
- Regulation
- Public opinion
- Finance

...the best risk reduction approach is to choose the right site in the first place
Deep Monitoring is part of a package
Deep CO\textsubscript{2} Monitoring – 3 Objectives

1: Watch stored CO\textsubscript{2}

2: Watch possible leakage paths

3: Monitor the environment

Operational Monitoring

- Freshwater aquifer
- CO\textsubscript{2} injection well
- Monitoring well
- Abandoned well
- Monitoring well

Well Integrity

- Sealed fault

Containment

- Boundaries
Drawing from the Oilfield: Static and Dynamic Modeling Workflow

- **Surface imaging Mapping**
- **Log interpretation and correlation**
- **Fault and Fracture modelling**
- **3-D flow simulation Geochemistry Geomechanics**
- **3D Geological model**
- **Reservoir and Aquifer property population**
- **Data input**

**ECLIPSE**
Zooming in on the Subsurface
The Need for Technology: High Resolution versus Conventional
Designing a Monitoring Plan

Reduce Risk & Optimize Performance:
Added value for the operator

Minimize Costs:
For each technique,
For the overall plan over time

Abide by laws & Regulations:
EU CCS, EU ETS, state law

Site & technical constraints:
Deployment restrictions,
Measurement sensitivity
Monitoring challenges

Range of scales
- Time - from the very short to the very long
- Space - from the very small to the very large

You can’t directly measure what you want to…
- Spatial distribution and concentration of CO₂
- Sealing boundaries, capacity, permeability.

You can’t measure where you want to…
- Confined to the surface or wells

…BUT you measure what you CAN and construct models
- Consistent with available information
- Improve with time
- With some predictive power (within limits)
Questions for Designing a Monitoring System

- What do I want to monitor?
- What property change can I monitor?
- What variation am I considering?

- What measurement technique to use?
- What should be my sensor specifications?

- Where should I place my sensor?
- For how long?
- How can I deploy it?
- How can I interrogate it?

- How can I interpret the measurement?
- CO₂ movements, leaks…
- P, CO₂ Saturation, Resistivity

- Accuracy / Precision

- Surface, Obs. Well
- (Permanent, Logging…)

- Operation phase, surveillance
Tracking CO₂ Evolution – what we can see

In-well measurements
Surface-to-well measurements
Well-to-well measurements
Microseismic (Onshore)
CSEM (Offshore only)
InSAR
Gravity (Onshore only)
4D Seismic

Size = relative cost

Vertical Resolution, m
Areal Reservoir Coverage →
### What Can we Monitor?

**In boreholes**

- **CO₂ Saturation** *(neutron, density, resistivity, sonic)*
- Sampling, downhole fluid analysis
- Cased Hole Formation Resistivity
- Pressure & Temperature
- Well Integrity *(Cement, Corrosion)*
- Electrical resistivity tomography *(ERT)*
- Microseismic
- X-well seismic
- X-well EM
- Distributed Temperature Sensing
- Tiltmeters

**From the surface**

- 2D, 3D Seismic
- Microseismic
- **Gravimetry** *(to back up time-lapse seismic)*
- Echosounding, Seafloor samples
- Noble Gas Tracers
- MT *(natural source plane wave electrical method)*
- CSEM
- InSAR *(Satellite Radar Imaging)*
CO₂ Saturation Measurement - Ketzin

CO₂ Saturation ~ 60% in upper sand section (yellow).
Little presence of CO₂ in lower sand
No CO₂ above 625 m

Contrast between formation water and CO₂ properties can be detected by neutron capture cross-section, hydrogen index, density, resistivity and sonic velocity to quantify the amount of free-phase CO₂ present in the pore volume.

CO₂ presence over 4 week interval
A primary electromagnetic field is generated from a first well, inducing currents in the formation and a secondary EM field, detected by receivers in the second well. It has a limited resolution but could be used to track the CO₂ plume, possibly in conjunction with seismic methods.
Global Measurements

**Time-lapse Seismic**

Elevations determined from Synthetic Aperture Radar (SAR) images by interferometric methods. Uses two (microwave) antennas, displaced either vertically or horizontally, installed on the same satellite or aircraft platform. One of the antennas transmits the signal, but both receive it, resulting in two images being created.

**Gravimetry**

Sensitive to formation density. CO₂ replacing water can be detected due to contrast between CO₂ and water. Gravimeters are placed at the surface or downhole.

**InSAR**

Sleipner 4D: Courtesy of Statoil

**Magnetotelluric (MT)**

Measures the natural low-frequency electromagnetic field of the Earth.
Seismic amplitudes in 2006

Top Utsira Sand CO₂ – Water contacts
2001
2004
2006

Calculate the expected time-lapse seismic signal (rock physics modelling, based on Gassman’s equation), to decide on 4D seismic.

Some indicative rules of thumb:
- Signal will be stronger in aquifer than in depleted gas reservoirs
- Shallower reservoirs will result in a stronger signal than deep reservoirs
Gravity technology - application

**Time-lapse gravity:**

- CO₂ density is lower than water density, higher than gas density
- Resolution is an order of magnitude lower than seismic resolution
- Surface gravity and borehole gravity

**Courtesy:**
- Arts et al., 2008, First Break
- Gravity monitoring at Sleipner CO₂ injection site
4D Gravimetry and 4D Seismic - Sleipner

Smoothed time-lapse gravity compared with model predictions

- **Observed gravity change**
- **Low temperature reservoir model**
- **High temperature reservoir model**
- **High temperature seismic model**

Note: Accuracy of ~4 microGal

Courtesy of Statoil
How Microseismic Data can be Recorded

Sensor locations

- Live well
- Monitor well
- Behind casing
- Surface seismic
- Buried seismic array

LIVE WELL

MONITOR WELL
Microseismic Visualisation

Microseismicity induced by injection

Phase 1
Phase 2
Phase 3
Remote Sensing Technology - InSAR

We can calculate the expected changes in surface elevation based on pressure changes and a 1D Mechanical Earth Model.

This allows us to decide if a satellite acquisition will provide the required resolution (several mm).
Real Time Monitoring
### Operational Monitoring

- Injection operation control
  - Wellhead pressure
  - Bottom hole Pressure and Temperature
  - Injection rate
  - Microseismicity

### Verification Monitoring

- Well Integrity
  - Annulus pressure
  - Corrosion
  - Cement
  - Soil gas measurements

- Cap Rock / Fault Integrity
  - Microseismicity
  - Pressure interference

### Assurance Monitoring

- Impact: HSE monitoring
  - Potable water quality
  - Soils acidity
  - Atmospheric concentration
  - Surface deformation

- Detection of leaks/migration
  - Sampling & chemical analysis
  - Geophysics techniques
  - Pressure interference
  - Soil gas measurements
  - Vegetation stress
  - Eddy correlation tower

### Quantification of injected CO₂

- Mass flow
- Gas stream composition and phase

### Tracking the CO₂ plume

- Geophysics techniques
- Pressure, Temperature
- Well logs (CO₂ Saturation)
- Sampling
- Geodetic methods

### Quantification of leaks

- Soil gas measurements
- Surface gas measurements
- …
Containment – THE storage issue:
- Failure of sealing cap rock
- Permeable faults and fractures
- Migration along wellbores

Risk reduction through:
- Choosing the right site
- Detailed reservoir characterization
- Comprehensive modelling
- Ongoing monitoring

Risk mitigation through:
- Remediation methodologies
- Risk-based approach to project management

Monitoring:
- Different types of monitoring objectives
- Existing technologies and tools
- More work/research on the integration
- Closely related to Modelling

Conclusion: Monitoring as part of Minimizing Storage Risk
In Summary

Pick the Right Site
- Non-complex, depth, porosity, perm, extent, structure, caprock...
- Some existing wells, but not many
- Access & capability for: 3-D seismic acquisition, logs, core, fluids, background

Use the Right Technology
- Proper density, resolution, noise limits, area of review
- Value equivalent uncertainty reduction
- Has impact on performance & risk

Properly Integrate the Data
- Requires an experienced, skilled, multi-disciplinary team.
- Unified modeling environment
- Shared earth model, easily updatable - “Living”