The Role of Risk Assessment in Designing MMV Programs

November 9, 2007
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Outline

1. Identifying Risks: Ranking Systems
2. *Performance & Risk Management drives MMV*
3. Measurements for Injectivity, Capacity, and Containment
4. Modeling – The Central MMV Tool
September Sea Ice Extent, 1982-2007
5-year intervals

National Snow and Ice Data Center, Boulder, CO

Total extent = 4.3 million sq km
CO₂ Storage Project Lifecycle

Operation Phase - 10 - 50 years

Pre-Operation
1 - 2 years

MMV Activities:
Baseline Establishment

Characterization

Design

Construction

Preparation

Injection

Decommissioning

Surveillance

Performance & Risk Management

CarbonWorkflow® Process

Post-Operation
100+ years

Transfer of Liability

Certification
Outline

- Identifying Risks: Ranking Systems
- Performance & Risk Management drives MMV
- Measurements for Injectivity, Capacity, and Containment
- Modeling – The Central MMV Tool
F. E. P. Data Entry

Wildenborg 2007
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Compartments & Conduits

Example Cross-Section

A

CO₂ Source
Wells
Faults and Fractures
Sealing Formation

HMR

ECA

HSE

USDW

Water source
CO₂ injection well
Deacidification well
Injection well
Water-well

Emission Credits & Atmosphere

Health, Safety, Environment

Underground Source of Drinking Water

Hydrocarbon & Mineral Resources

CO₂ Source / Storage Reservoir

the Certification Framework (CF) project
Oldenburg, Bryant, and Nicot, 2007
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### Event description

**ID**  
2.9 Drilling a “dry hole”

<table>
<thead>
<tr>
<th>Description</th>
<th>Drilling reveals that injectivity is not acceptable where well is planned; project is not viable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timescale</td>
<td>Should be indicated during site characterization or well drilling</td>
</tr>
<tr>
<td>Potentially Involved Parties</td>
<td>Site characterization team, well construction team, operator</td>
</tr>
<tr>
<td>Preventive Action</td>
<td>Careful site selection</td>
</tr>
<tr>
<td>Mitigation Response</td>
<td>Drill to new horizon, if still no viable options, plug first well, drill another or move to a new location and drill new well</td>
</tr>
<tr>
<td>Residual Risk</td>
<td>If dry hole not well plugged, could become leakage pathway in the future</td>
</tr>
<tr>
<td>Warning Signals</td>
<td>Core samples, seismic survey and other site characterization tests of porosity and permeability, extent of reservoir</td>
</tr>
<tr>
<td>Interdependence / Risk Coupling</td>
<td>None</td>
</tr>
<tr>
<td>Priority Ranking</td>
<td>2</td>
</tr>
<tr>
<td>Mitigation Cost</td>
<td>2</td>
</tr>
<tr>
<td>Comments</td>
<td>At least at this early stage of the CCS industry, everyone will be “careful”. There is always residual risk because it is not possible to “fully” characterize the earth.</td>
</tr>
</tbody>
</table>

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**World Resources Institute 2007**  
*by permission*
## Prioritized sources of hazard

An alternative prioritization could be proposed for other cases (e.g., Texas GOM)

<table>
<thead>
<tr>
<th>Atmospheric release hazards</th>
<th>Groundwater degradation hazard</th>
<th>Crustal deformation hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well leakage</td>
<td>Well leakage</td>
<td>Well failure</td>
</tr>
<tr>
<td>Fault leakage</td>
<td>Fault leakage</td>
<td>Fault slip/leakage</td>
</tr>
<tr>
<td>Caprock leakage</td>
<td>Caprock leakage</td>
<td>Caprock failure</td>
</tr>
<tr>
<td>Pipeline/ops leakage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Pink = highest priority
- Orange = high priority
- Yellow = moderate priority

Prioritization uses expert knowledge and can be advised by science and experience

Friedmann 2007

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### Qualitative Risk Prevention & Mitigation Matrix

<table>
<thead>
<tr>
<th>SEVERITY</th>
<th>Light</th>
<th>Serious</th>
<th>Major</th>
<th>Catastrophic</th>
<th>Multi-Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIKELIHOOD</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
<td>-4</td>
<td>-5</td>
</tr>
</tbody>
</table>

#### Control Measures
- **RED** (INTOLERABLE): Do not take this risk
- **YELLOW** (UNDESIRABLE): Demonstrate ALARP before proceeding
- **GREEN** (ACCEPTABLE): Proceed carefully, with continuous improvement
- **BLUE** (NEGLIGIBLE): Safe to proceed
- **BLACK** (NON-OPERABLE): Evacuate the zone and or area/country

#### Prevention
- Not applicable for qualitative risk assessment.

#### Likelihood
- **Improbable**: 1
- **Unlikely**: 2
- **Possible**: 3
- **Likely**: 4
- **Probable**: 5

#### Mitigation
- **CONTROL MEASURES**
  - **RED**: Non-operable
  - **YELLOW**: Intolerable
  - **GREEN**: Acceptable
  - **BLUE**: Negligible
  - **BLACK**: Non-operable

#### Severe Risk
- **WHITE ARROW**: Indicates decreasing risk from light to catastrophic.

#### Risk Levels
- **INTOLERABLE**: Do not take this risk.
- **UNDISCOVERABLE**: Demonstrate ALARP before proceeding.
- **ACCEPTABLE**: Proceed carefully, with continuous improvement.
- **NEGLIGIBLE**: Safe to proceed.
- **NON-OPERABLE**: Evacuate the zone and or area/country.

#### Risk Mitigation
- Use a matrix to assess and manage risks.

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White arrow indicates decreasing risk.
Outline

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- Modeling – The Central MMV Tool
Performance & Risk Management System

Performance & Risk Assessment

Injectivity, Capacity, Containment

FUNCTIONS * STAKES

Costs and Credits, Environment, Health & Safety, Image

Measurement for Characterization

Modeling

Project Design

Construction Technologies & Interventions

Monitoring Measurements

feedback

RESPONSE
Focused Monitoring Deployment

- Microbiology
- Airborne Flux
- Satellite Imaging
- Cement CO2 work
- Distributed Flowmeters
- Dynamic Modelling
- Water chemistry
- Geochemistry
- Surface Flux
- Wellhead sampling
- Logging
- Soil gas
- Annulus Sampling
- Geomechanics
- Tracers
- Micro-Seismic
- 4D VSP
- Permanent 4D Seismic

Espie 2007
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# Monitoring Targets and Monitoring Methods

## Monitoring Targets

- CO\(_2\) conc. and fluxes at ground level
- CO\(_2\) conc. in the vadose zone and soil
- Groundwater quality
- Leakage up faults and fractures
- Early warning of caprock failure
- CO\(_2\) plume location
- Solubility and mineral trapping

## Monitoring Methods

<table>
<thead>
<tr>
<th>Monitoring Methods</th>
<th>Injectivity</th>
<th>Capacity</th>
<th>Containment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow metering, Office or other differential</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrared CO(_2) detectors</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole logs (casing, cement, fluids)</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Pressure msmt: Well, reservoir, annulus, aquifer</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Gravity measurements</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>EM (electrical, electromagnetic) surveys</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Seismic: 3-D time-lapse surveys</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Seismic: Microseismicity monitoring</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Seismic: VSP, walkaway, cross-well</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tiltmeters</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Satellite and/or airborne data</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Samples: Fluid, optional tracers</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vegetation changes observed on ground</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Samples: Soil gas</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Samples: Air, via eddy-flux towers or grab</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Method applicable to target*

Modified after Vu Hoang, Vivalda, and Verliac, 2007
Monitoring Selection Tool

- **2D surface seismic**
- **Airborne EM**
- **Boomer/Sparker profiling**
- **Cross-hole EM**
- **Downhole pressure/temperature**
- **Eddy covariance**
- **Fluid geochemistry**
- **Ground penetrating radar**
- **IR diode lasers**
- **Land ERT**
- **Microseismic monitoring**
- **Multicomponent surface seismic**
- **Permanent borehole EM**
- **Sidescan sonar**
- **Surface gas flux**
- **Tiltmeters**
- **Vertical seismic profiling (VSP)**

### Monitoring Aims

<table>
<thead>
<tr>
<th>Aim Score</th>
<th>Definition</th>
<th>Explanation</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not applicable</td>
<td>The technique cannot be used for the selected aim.</td>
<td>Green</td>
</tr>
<tr>
<td>1</td>
<td>Possibly applicable</td>
<td>The technique may be appropriate for the selected aim but is probably of marginal utility. It is unlikely to be a preferred option but may be useful in combination with other methods. Site-specific conditions or specialised scientific requirements however may call for deployment of the technique.</td>
<td>Green</td>
</tr>
<tr>
<td>2</td>
<td>Probably applicable</td>
<td>The technique is likely to be suitable for the storage application, though there are probably other more effective techniques that should also be considered. The technique could be included in a monitoring protocol to provide additional information for a monitoring aim, supplementing other, higher-ranked techniques. Site-specific conditions or specialised scientific requirements however may call for deployment of the technique.</td>
<td>Amber</td>
</tr>
<tr>
<td>3</td>
<td>Definitely applicable</td>
<td>The technique would normally be included to meet a particular monitoring aim and its exclusion may reduce the potential for the aim to be achieved. However, site-specific conditions may degrade the efficacy of the technique, or even preclude its deployment.</td>
<td>Amber</td>
</tr>
<tr>
<td>4</td>
<td>Strongly recommended</td>
<td>The technique would normally be regarded as a key element in meeting a particular monitoring aim and its exclusion would reduce the potential for the aim to be achieved. However, site-specific conditions may degrade the efficacy of the technique, or even preclude its deployment.</td>
<td>Red</td>
</tr>
</tbody>
</table>

For more details, visit [http://www.co2captureandstorage.info/co2tool_v2.1beta/co2tool_panel.php](http://www.co2captureandstorage.info/co2tool_v2.1beta/co2tool_panel.php)
Outline

• Identifying Risks: Ranking Systems
• *Performance & Risk Management drives MMV*
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Injectivity

- Permeability
  - Core
  - Logs
  - Formation testers
  - Well tests

- Injection induced near-wellbore effects
  - Dry-out
  - Salt precipitation – Carbonate dissolution

- Mitigation
  - Injection well design and number
  - Hydraulic fracturing
Capacity: Characterization and Monitoring

- High-Resolution Seismic, VSP’s, and Sonic

- Borehole imagers

- Formation Evaluation

- Mineralogy
Capacity: Measurements for CO₂ Saturation

X-Well EM Surveys
CO₂ Saturation

Inject well
Reservoir
30 m thick
Interwell Spacing 60 m
Monitoring well

CO₂ Rich-phase
75 Ωm

Water 4.5 Ωm

A priori information improves interpretation

Without Boundary Knowledge
With Boundary Knowledge

50Ωm
10Ωm
5Ωm

Neutron Capture Logging (Σ)
CO₂ Saturation near wellbore
CO₂ breakthrough at a monitoring well
Frio brine experiment in Texas:

Adapted from Luling et al, SPE 5A-55
Sakurai et al, SPWLA
Capacity & Containment: Microseismics

Microseismicity events are micro-cracks occurring in the formation due to pressure increase. Listening to these cracks is a powerful monitoring technique.

- Detection, 3D Location, and Classification of Microseismicity Events
- Control of Pumping Rate to Avoid Fracturing the Cap Rock
- Detection of Fault Reactivation
Containment: Measurements for Well Integrity

Joint analysis of data from these tools:
- Multi-finger caliper
- Electromagnetic
- Ultrasonic
- Sonic

To characterize:
- Casing corrosion
  - Internal / external
  - Corrosion type
- Cement quality
  - Bonding at interfaces
  - Cement properties
- Near-wellbore formation damage
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  1. Site conceptual model
  2. Static geologic-geophysical model
  3. Dynamic geophysical model
  4. Measurements
  5. Do Over
Building a Static Model – Structure & Properties

Model should include overburden
CO₂ Injection Dynamic Modeling

Current status: Improved fluid-fluid / fluid-rock interactions
- Accurate description of mutual solubilities
- Dry-out / Salting out effect
- Salt precipitation
- Coal swelling and shrinkage

- Upscaling
- ECLIPSE – E300
- Calibration on monitoring measurements (History match)
- 3D Full Compositional Flow Simulator
- Geomechanics Simulator
- Thermodynamics
- Geochemistry
- Thermal Modeling
Injectivity – Modeling Near-Wellbore Effects

Refined wellbore radial model for injectivity studies

- Is Injection possible?
- Injection rate estimation respecting BHP
- Critical outputs for Injectivity:
  - Injection rate
  - BHP
  - Salt precipitation profile
  - Dry-out radius
Capacity – Volumetrics & Trapping

- Capacity estimation
  - Dissolved CO$_2$
  - Trapped CO$_2$ (immobile)
  - Free CO$_2$ (mobile)

- Plume Monitoring
- Hydrodynamic Trapping
- Flow Gradient impact
Containment – Reservoir Geomechanics

- Coupled simulation
  - Reservoir simulator
    - Update permeability
  - Mechanical simulator
    - $\delta p, \delta T, \delta S$

Eclipse-GM (E300)
VISAGE - VIP
RECAP

- Risk identification and prioritization methods: several ways to slice the universe of risk
- CO₂ Project Functions: Injectivity, Capacity, Containment
- Monitoring techniques exist for each function
- Modeling is key to the “V” of MMV