QUEST and Goldeneye risk assessment

Focusing the monitoring and additional safeguards on key areas

IEA GHG

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Shell is developing significant experience in CCS

Shell involvement in CCS Projects:
- Industrial scale projects in operation
- Industrial scale projects in construction
- Industrial scale projects planned
- Involvement through Cansolv
- Demonstration projects, joint industry partnerships
Quest is a Fully Integrated Saline Aquifer CCS Project

- Quest CCS Project - fully integrated CCS (capture, transport, storage & MMV)
- JV among Shell (60%); Chevron (20%); and Marathon (20%)
- Improves GHG performance of Oil Sands operations
- Capture at the Scotford Upgrader from 3 Hydrogen Units
- Capacity to capture over one million tonnes of CO₂ per year or up to 35% of Scotford Upgrader direct emissions
- CO₂ transported by pipeline
- Deep saline aquifer storage
Goldeneye is a depleted field CO$_2$ store

- The Goldeneye candidate store is a depleted gas field, over 100km offshore, with facilities only some 10 years old.

- It was studied extensively as part of UK Demo 1 where the source was the Longannet Power Station near Edinburgh.
  - 2Mtpa CO$_2$ to be stored over 10 years
  - Full Front End Engineering Design study conducted for offshore Demo 1
  - Technical maturity at a “Final investment decision” level

- Information presented today will be based on the results of the Demo 1 study

The Peterhead project is a 340MW post combustion capture plant retrofitted to an existing Combined Cycle Gas Turbine at the SSE Peterhead Power Station. Storage is also planned in the Goldeneye depleted gas field. At this point further details of this project are still confidential.
For QUEST the BCS Storage Complex Provides Multiple Independent Seals

**BCS Storage Complex**
- Deep saline aquifer (~2km), porous sandstone (Por~16%, K~300mD)
- Multiple continuous seals to minimize containment risk
- No significant faulting visible from wells or seismic
- Well below hydrocarbon bearing formations (<1200m) and potable water zones (<200m)
- Few legacy wells, nearest at ~20 km

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**Ultimate Seal**
- 85m
- Prairie Evaporite

**Deep MMV Target**
- Winnipegosis

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**Ultimate Seal**
- 84m
- Upper Lotsberg

**Secondary Seal**
- 34m
- Lower Lotsberg

**Primary Seal**
- 44m
- MCS – Middle Cambrian Shale
- LMS – Lower Marine Sand

**Injection Target**
- 41m
- BCS – Basal Cambrian Sand
- PreCambrian Basement
Similarly the Goldeneye store has been selected because of the multiple seals & additionally a proven ability to hold gas

- Approximately 100km from land
- Depleted field with capacity for over 30 mln tonnes CO$_2$
- High quality reservoir – highly permeable, high injectivity
- Excellent containment barriers
  - Proven as a gas store for over 50 million years
  - Store seal, complex seals, and many buffers
  - Small number of wells, all cemented at store seal
  - Depleted: therefore lacks energy to drive fluid out of reservoir into water bearing formations above
Why do we monitor?
MMV to Verify Safe CO₂ Storage

Neither storage site would have passed selection if the passive geological and engineered safeguards had not been judged to make the store inherently safe.

Monitoring further increases confidence in the storage security by working to satisfy the following aims:

- Ensure Conformance to indicate long-term security of storage
  - Validate, calibrate, update performance predictions
  - Adapt injection & monitoring to optimise performance
  - CO₂ inventory reporting

- Ensure Containment to demonstrate current security of storage
  - Confirm no environmental impacts
  - Detect early warning signs of any unexpected loss of containment
  - If necessary, activate additional safeguards
Multiple Independent Containment Safeguards In-Place

Legend

- **Passive** safeguards; these are always present
- **Active** safeguards, these are only present if triggered by monitoring
The site specific containment risk assessment identifies where active monitoring safeguards are required.
How to Build an Active Safeguard

**Detector**

- **A sensor** capable of detecting changes with sufficient sensitivity and reliability to provide an early warning

**Decision Logic**

- **Decision logic** to interpret the sensor data and select the most appropriate form of intervention

**Control Response**

- **A control response** to ensure continuing containment or to control any potential loss of containment

Is it fast enough, precise enough and big enough?
Systematic Evaluation of Passive Safeguards

- Evidence based using collective expert judgement
- Informed by appraisal data and site characterization studies
- Subject to independent expert review

<table>
<thead>
<tr>
<th>Threat</th>
<th>Safeguard</th>
<th>Evidence For</th>
<th>Evidence Against</th>
<th>EF</th>
<th>EA</th>
</tr>
</thead>
</table>
| T6 Induced stress re-activates a fault | B6.1 Select site with no natural seismicity | 1. No recorded seismicity within AOR  
2. Central Alberta is tectonically stable  
3. No faults seen in overburden  
4. Faults not critically stressed before injection | 1. Past may not indicate future seismicity | 0.6 | 0.2 |
| | B6.2 Select site away from known faults | 1. No faults through seals on 2D/3D seismic | 1. Not all faults (offsets<20m) identified  
2. Widespread basement faults; offsets<20m  
3. Reactivated fault may grow upwards | 0.3 | 0.3 |
| | B6.3 Select max injection pressure using geomechanics | 1. Inject at >14MPa below BCS fracture pressure  
2. Fault-normal stresses remain compressive  
3. Compressor & pipeline rated to 14.5MPa | 1. Injection induces shear stress on faults | 0.6 | 0.2 |
| | B6.4 Lower Lotsberg - Reseals fault | 1. Salt creep re-seals fault after slippage  
2. Expected salt thickness is 2-36 m | 1. Pinches out beyond the SW edge of AOI  
2. Salt creep may take years to re-seal fault | 0.2 | 0.4 |
| | B6.5 Upper Lotsberg - Reseals fault | 1. Salt creep re-seals fault after slippage  
2. Expected salt thickness is 53-91 m | 1. Salt creep may take years to re-seal fault | 0.3 | 0.3 |
Many Independent Control Response Options Exist

<table>
<thead>
<tr>
<th>Preventative Controls</th>
<th>Corrective Controls</th>
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<tbody>
<tr>
<td><strong>Injection Controls</strong></td>
<td><strong>Well Interventions</strong></td>
</tr>
<tr>
<td>IC1 Re-distribute injection across existing wells</td>
<td>RM1 Repair leaking well by re-plugging with cement</td>
</tr>
<tr>
<td>IC2 Drill new vertical or horizontal injectors</td>
<td>RM2 Repair leaking injector by replacing completion</td>
</tr>
<tr>
<td>IC3 Extract reservoir fluids to reduce pressure</td>
<td>RM3 Plug and abandon leaking wells that cannot be repaired</td>
</tr>
<tr>
<td>IC4 Stop injection</td>
<td><strong>Exposure Controls</strong></td>
</tr>
<tr>
<td><strong>Well Interventions</strong></td>
<td>RM4 Inject fluids to increase pressure above leak</td>
</tr>
<tr>
<td>WI1 Repair leaking well by re-plugging with cement</td>
<td>RM5 Inject chemical sealant to block leak</td>
</tr>
<tr>
<td>WI2 Repair leaking injector by replacing completion</td>
<td>RM6 Contain contaminated groundwater with hydraulic barriers</td>
</tr>
<tr>
<td>WI3 Plug and abandon leaking wells that cannot be repaired</td>
<td>RM7 Replacement of potable water supplies</td>
</tr>
<tr>
<td><strong>Remediation Measures</strong></td>
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<tr>
<td>RM8 Pump and Treat</td>
<td>RM9 Air Sparging or Vapour Extraction</td>
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<tr>
<td>RM10 Multi-phase Extraction</td>
<td>RM11 Chemical Oxidation</td>
</tr>
<tr>
<td>RM12 Bioremediation</td>
<td>RM13 Electrokinetic Remediation</td>
</tr>
<tr>
<td>RM14 Phytoremediation</td>
<td>RM15 Monitored Natural Attenuation</td>
</tr>
<tr>
<td>RM16 Permeable Reactive Barriers</td>
<td>RM17 Treat acidified soils with alkaline supplements</td>
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## Systematic Evaluation of Monitoring Technologies

- Evidence-based using collective expert judgement
- Informed by appraisal data and site characterization studies
- Subject to independent expert review

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<tr>
<th>Task</th>
<th>Technology</th>
<th>Indicator</th>
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| 6  | Detect fault reactivation | DHPT | Down-hole pressure-temperature gauge in a WPGS observation well | Sustained Winnipegosis pressure increase detected by down hole pressure gauge | 1. Industry standard technology  
2. Continuous monitoring  
3. Early warning before brine or CO2 arrives  
4. Sensitive to low flux rates (1 ppm)  
5. Detection within 1-6 months | 1. Gauge drift may mask indicator  
2. Natural changes may mask indicator  
3. WPGS pressure barriers may mask indicator  
4. WPGS permeability may be insufficient | 0.8 | 0.1 |
|  | | DHMS | Down-hole microseismic monitoring | A sustained cluster of microseismic events located above the primary seal that migrates upwards with time | 1. Industry standard technology  
2. Continuous monitoring  
3. Detect magnitude -3 events up to 600m away  
4. Event location error c. 10-20 m | 1. Not all fault slip creates microseismic events  
2. Not all microseismic events are detectable | 0.7 | 0.2 |
|  | | INSAR | InSAR - Interferometric Synthetic Aperture Radar | Short spatial wavelength surface uplift anomaly around a potential fault | 1. Detects dilation of any shallow formation  
2. Sensitive to uplifts >1mm/year  
3. Monthly monitoring over entire AOR | 1. Natural monitoring targets maybe limited  
2. Cannot monitor through snow cover | 0.6 | 0.2 |
|  | | SEIS3D | Time-lapse surface 3D seismic | Appearance of an amplitude anomaly above the primary seal around a potential fault | 1. Areal coverage over entire CO2 plume  
2. Expect to image the CO2 plume  
3. Lateral resolution c. 25 m  
4. Vertical resolution c. 10 m | 1. No sensitivity expected to brine migration  
2. Acquisition noise may mask indicator  
3. Only monitor every few years  
4. Leak may go undetected for years  
5. Unable to detect CO2 leaks <10-60 ktonnes | 0.3 | 0.3 |
Example: Lateral migration, time lapse seismic

- CO₂ saturation, 10Mt injected
  - OGOC
  - OOWC

- CO₂ saturation, 20Mt injected
  - OGOC
  - Aquifer storage
  - OOWC

- Minimum amplitude with noise
  - CO₂ signal on the ‘difference amplitude map’

- Minimum amplitude with 4D noise
  - CO₂ signal on the ‘difference amplitude map’
Technology Selection Based on Cost-Benefit Ranking

- Cost ranking based on estimated unit costs and schedule of monitoring
- Benefits ranking based on number of tasks supported weighted by the expected success rates
- Subject to regular re-evaluation based on performance
Diversified Monitoring Program Eliminates Dependence on any Single Technology

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<td><strong>Atmosphere</strong></td>
<td>Line-of-Sight CO2 Flux Monitoring</td>
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<tr>
<td><strong>Biosphere</strong></td>
<td>Remote sensing, Brine &amp; CO2 Tracer Monitoring</td>
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<tr>
<td><strong>Hydrosphere</strong></td>
<td><strong>Groundwater Monitoring Wells</strong>: Water Electrical Conductivity, pH, Brine &amp; CO2 Tracer Monitoring</td>
<td><strong>Landowner Water Wells</strong>: Brine &amp; CO2 Tracer Monitoring</td>
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<tr>
<td><strong>Geosphere</strong></td>
<td></td>
<td><strong>Time-Lapse 3D VSP</strong></td>
<td><strong>INSAR</strong></td>
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<td><strong>Time-Lapse 3D Surface Seismic</strong></td>
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<td><strong>Wells: Monitors</strong></td>
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<td><strong>WPGS Observation Wells</strong>: Down-Hole Pressure &amp; Temperature</td>
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<td><strong>WPGS Observation Wells</strong>: Down-Hole Microseismic Monitoring</td>
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<td><strong>BCS Observation Well</strong>: Down-Hole Pressure &amp; Temperature</td>
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<td><strong>Injection Rate Metering, Tracer Injection</strong></td>
<td><strong>CBL, USIT</strong></td>
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<td><strong>Down-Hole Pressure &amp; Temperature, Distributed Temperature Sensing, Distributed Acoustic Sensing, Annulus Pressure Monitoring, Wellhead Pressure &amp; Temperature, Wellhead CO2 sensor, Mechanical Well Integrity Testing, Operational Integrity Assurance</strong></td>
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Being offshore the Goldeneye monitoring programme spans different domains. Both programmes pay specific attention to the injection well penetrations in the natural containment system until they have been sealed at closure.

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<td><strong>Geochemical sniffers under platform</strong></td>
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<td><strong>Sonar</strong></td>
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<td><strong>Sea bed</strong></td>
<td><strong>Mapping, Sampling, + E&amp;A wells</strong></td>
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<td><strong>Time-Lapse 3D streamer and OBN seismic</strong></td>
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<td><strong>Saturation front and pressure monitoring, geochemical samples</strong></td>
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In closing

- Neither storage site would have passed selection if the passive geological and engineered safeguards had not been judged to make the store inherently safe.
- Both storage projects use the risk assessment to determine where potential migration paths could occur and implement additional active safeguards.
- An active safeguard must have detection, decision logic, and a control response in order to be valid.
- The combination of active and passive safeguards further decreases the potential for leakage.