

Appendix A Measurement, Monitoring and Verification Plan

Quest Carbon Capture and Storage Project

MEASUREMENT, MONITORING AND VERIFICATION PLAN

Shell Canada Limited
Calgary, Alberta

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Executive Summary

The Quest Carbon Capture and Storage Project (Quest CCS Project) promises to make a material early contribution to reducing CO₂ emissions generated by upgrading bitumen from the Alberta oil sands. The climate benefits and societal acceptability of this Project are both largely dependent on the quality of containment achieved within the Basal Cambrian Sands (BCS) storage complex.

Bachu et al. (2000) identified the most promising opportunities for CCS across Canada by matching the location of large localized CO₂ emissions with geological formations likely to support CO₂ storage. This systematic screening concluded the top ranking opportunities were located within the Alberta Basin due to the presence of deep permeable saline aquifers overlain by multiple extensive geological seals. The Quest project is located within the Alberta Basin and the geology of the selected storage site offers multiple layers of protection to prevent any CO₂ or brine from causing any impacts to the protected groundwater zone, the ecosystem, or the atmosphere. Each of these seals on its own is likely to be sufficient to ensure long-term containment of injected CO₂ and the displaced brine. However, no matter how detailed and extensive the appraisal program to characterize these geological barriers, some uncertainty and risk remain. Measurement, Monitoring and Verification (MMV) activities aim to verify the absence of any significant environmental impacts due to CO₂ storage. If necessary, MMV activities shall result in additional safeguards by triggering control measures that prevent or correct any loss of containment before significant impacts occur.

A risk-based workflow was applied. This approach relies on a systematic assessment of the whole suite of containment risks, followed by a review of the effectiveness of safeguards provided by geology, engineering and recognition of MMV performance targets. The proposed conceptual MMV plan is designed to provide early warning of any breach of containment triggering appropriate responses, thereby reducing risk and ensuring that the remaining risk is insignificant compared to everyday risks broadly accepted by society.

Transfer of long-term liability will depend on the actual storage performance verified through MMV activities. MMV will indicate that actual storage performance conforms to model-based forecasts and that these forecasts are consistent with permanent secure storage at an acceptable risk.

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Attachment D	Historic Rate of Well Integrity Failures
Attachment E	Changing Pressure inside the BCS
Attachment F	Monitoring Technology Capabilities

Glossary

Barrier	Something that decreases the likelihood of a threat leading to the occurrence of a risk event.
Consequence	A possible adverse outcome due to the occurrence of a risk event.
Mitigation	Something that decreases the severity or likelihood of significant consequences given the occurrence of a risk event.
Risk	The product of likelihood and consequence of an unwanted event.
Risk Event	This event might occur, and if uncontrolled, will cause unwanted consequences.
Safeguard	Something that reduces risk such as a barrier or mitigation.
Shell Well Redwater 11-32	The unique well identifier is 1AA/11-32-055-21W4/00.
Shell Well Redwater 3-4	The unique well identifier is 100/03-04-057-20W4/00.
Shell Well Radway 8-19	The unique well identifier is 100/08-19-059-20W4/00.
Threat	Something that could cause the occurrence of a risk event.

Abbreviations

AEC	atmospheric eddy correlation
ALARP	as low as reasonably practicable
AOI	Exploration Tenure Area of Interest for the Project
AOR	area of review of MMV activities for the Project
APM	annulus pressure monitoring
ARC	Alberta Research Council
BCS	basal Cambrian Sands
BGWP	Base of Groundwater Protection
BGS	British Geological Survey
CBL	cement bond logs
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CO ₂	carbon dioxide
CSA	Canadian Standards Association
DAS	fibre-optic distributed acoustic sensing
DHMS	down-hole microseismic monitoring
DHPT	down-hole pressure-temperature gauge
DNV	Det Norske Veritas
DTS	fibre-optic distributed temperature sensing
EPA	Environmental Protection Agency
ERCB	Energy Resources Conservation Board
ESS	ecosystem studies
GHG	greenhouse gas
GPS	global positioning system
GPZ	groundwater protection zone
HIA	satellite or airborne hyperspectral image analysis
HSE	United Kingdom Health and Safety Executive
HSSE	Health Safety Security and Environment
IEA	International Energy Agency
INJ	injection wells
InSAR	Interferometric Synthetic Aperture Radar
IPAC	International Performance Assessment Centre
IPAC-CO ₂	International Performance Assessment Centre for CO ₂
IPCC	Intergovernmental Panel on Climate Change
IRM	injection rate metering at wellhead
LOSCO ₂	line-of-sight gas flux monitoring
MCS	Middle Cambrian Shale
MMV	measurement, monitoring and verification
MNA	Monitored Natural Attenuation
MWIT	mechanical well integrity pressure testing
NETL	National Energy Technology Laboratory
OBW	observation wells in Winnipegosis (WPGS)
PTRC	Petroleum Technology Research Centre
Quest CCS project	Quest Carbon Capture and Storage Project
SEIS2D	time-lapse surface 2D seismic
SEIS3D	time-lapse surface 3D seismic
Shell	Shell Canada Limited

Abbreviations

SPH.....	soil pH surveys
SSAL	soil salinity surveys
TNO.....	Netherlands Organisation for Applied Scientific Research
UK	United Kingdom Department of Energy and Climate Change
UNSED.....	United Nations Conference on Environment and Development
USIT	time-lapse ultrasonic casing imaging
VSP.....	vertical seismic profiling
VSP3D.....	time-lapse 3D vertical seismic profiling
WEC	down-hole electrical conductivity monitoring
WHCO ₂	wellhead CO ₂ detectors
WHPT.....	wellhead pressure-temperature gauge
WPGS.....	Winnipegosis
WPH	down-hole pH monitoring
WRI	World Resources Institute
WRM.....	well and reservoir management

1 Introduction

This document describes the Measurement, Monitoring and Verification (MMV) Plan for the proposed Quest Carbon Capture and Storage Project (Quest CCS Project) in Alberta, Canada.

The scope of this document is to establish the framework and procedures that will ultimately define the MMV plan once the ongoing appraisal process concludes. This means that the MMV plan described here is a conceptual outline, based on clearly defined parameters covering the following four basic principles:

- the performance targets for MMV activities
- identifying and ranking explicit technology options
- how monitoring strategies are developed
- how to evaluate the expected effectiveness of these plans

The purpose of this document is to outline a conceptual MMV plan for the Quest CCS project based on a proactive verification plan that the storage complex is working as expected and the early detection of any leaks.

1.1 The Purposes of MMV

There are two interdependent primary purposes of MMV activities for the Quest CCS Project:

1. Verify storage performance (Conformance): implies normal operating conditions and assumes containment can be managed using well-established industry practices for well and reservoir management (WRM)
2. Ensure containment, which recognizes that:
 - a. the management of containment is a critical requirement to safeguard health, safety and the environment
 - b. the loss of containment could imply a consequence and impact outside of the BCS storage complex



To fulfil both purposes, there are several requirements. These are adapted from the IEA GHG proposed requirements for MMV (IEA 2006).

1. Verify storage performance of the BCS storage complex
 - Validate, calibrate and revise performance predictions according to observed actual performance.
 - Adapt injection and monitoring plans according to observed past performance to optimize future performance.
 - Provide the evidence base for setting the handover period by demonstrating the observed actual storage performance conforms to the predicted storage performance. Storage performance has two metrics:
 - i. CO₂ plume migration within the storage formation
 - ii. containment of CO₂ and brine within the BCS complex
 - Enable transfer of long-term liability by demonstrating storage performance conforms to predictions that show a trend towards long-term stability at the time of site closure.
 - Provide the evidence base for reporting CO₂ storage inventories.
2. Ensure containment within the BCS storage complex.
 - Verify no loss of containment occurred that would affect the CO₂ inventory.
 - Detect early warning signs of any potential loss of containment to prompt control measures that prevent or reduce any impacts to the environment or human health.

1.2 Project Overview

Shell Canada Limited, which will hold all necessary regulatory approvals in respect of the Project, is the managing partner of Shell Canada Energy. Shell Canada Energy will operate the Project, on behalf of the Athabasca Oil Sands Project (“AOSP”), which is a joint venture between Shell Canada Energy (60%), Chevron Canada Limited (20%) and Marathon Oil Canada Corporation (20%). The goal of the Quest CCS Project is to separate, capture and permanently store CO₂, thereby reducing greenhouse gas emissions from the existing Scotford Upgrader. The Scotford Upgrader is located about 5 km northeast of Fort Saskatchewan, Alberta, within Alberta’s Industrial Heartland, which is zoned for heavy industrial development.

The three components of the Quest CCS Project are:

- CO₂ capture infrastructure, which will be connected to the Scotford Upgrader. The method of capture is based on a licensed Shell amine system called ADIP-X.
- a CO₂ pipeline, which will transport the CO₂ from the Scotford Upgrader to the injection wells, about 50 km north of the upgrader. The CO₂ injection well locations are in the CO₂ storage area of interest.
- a storage scheme consisting of 3 to 10 injection wells, which will inject the CO₂ into the Basal Cambrian Sands (BCS), a deep underground formation, for permanent storage at a depth of about 2 km below ground level

2 MMV Design Framework

Standards for MMV are still developing for Carbon Capture and Storage (CCS) projects. This section describes the framework selected for developing an MMV program for the Quest CCS Project based on the following key elements:

1. the existing regulatory environment
2. a review of the existing global guidelines ([Attachment A](#))
3. precedents set by existing projects

2.1 Existing Regulations & Precedents

Alberta's existing regulations for the permitting and oversight of Acid Gas Disposal projects have proved effective for more than 40 schemes involving CO₂ over the last 20 years. The ERCB intends to use the same processes for regulating any CCS projects in Alberta (Zeidouni et al 2009; ERCB 2010). Therefore, the Quest CCS Project MMV plan must conform to these existing standards as a minimum requirement.

There are many different directives applicable to Acid Gas Disposal in Alberta. The following directives are particularly relevant for MMV as they specify requirements for measurements and monitoring.

- **Directives 7 & 17:** Specify requirements for measuring and reporting the amounts of acid gas injected.
- **Directive 20:** Specifies minimum requirements for well abandonment, testing to detect leakage and mitigation measures in the event of detecting leakage.
- **Directive 51:** Classifies injection and disposal wells according to the injected or disposed fluid and specifies design, operating, and monitoring requirements for each class of wells.
- **Directive 65:** Addresses enhanced hydrocarbon recovery, natural gas storage and acid gas disposal. For acid gas disposal projects, this directive specifies requirements to ensure confinement of the disposed fluid and its isolation. This directive also requires the applicant to prove that disposal will not affect hydrocarbon recovery.

In addition, two existing CCS projects in Canada create important precedents for MMV: the Weyburn-Midale CO₂ enhanced oil recovery project in Saskatchewan (PTRC 2004) and Pembina Cardium CO₂ enhanced oil recovery (EOR) project in Alberta (ARC 2009).

Outside Canada, there are four notable examples of commercial-scale CCS projects with ongoing MMV activities:

- Sleipner and Snøhvit in Norway
- In Salah in Algeria (Mathieson et al. 2010)
- Rangely in the United States

See [Attachment B](#) for further details. Other commercial-scale projects under development with more mature MMV plans include Gorgon in Australia.

Although injected volumes are substantially smaller, numerous Acid Gas Disposal projects in Alberta also provide important experience (Bachu and Gunter 2005).

2.2 Timeframe of Review

MMV activities will meet varying requirements during four distinct phases over the lifecycle of the CCS project:

1. **Pre-Injection Phase:** Monitoring tasks are identified, monitoring solutions evaluated and selected, risks are characterized, and baseline monitoring data are acquired.
2. **Injection Phase:** Monitoring activities are undertaken to manage containment risk and storage performance, and are adapted through time to ensure their continuing effectiveness.
3. **Closure Phase:** Some monitoring activities continue to manage containment risk and to demonstrate storage performance is consistent with expectations for long-term storage.
4. **Post-Closure Phase:** A few monitoring activities continue to validate the storage site is stable and the containment risk has diminished to a level where no further monitoring is required.

2.3 Area of Review

MMV will operate within an Area of Review (AOR) with sufficient extent to include any potential material impacts due to CO₂ storage including the displacement of brine. This area spans four distinct environmental domains (see [Figure 2-1](#)).

- **Geosphere:** The subsurface domain below the base of the groundwater protection zone including the BCS storage complex. The geological storage complex comprises a primary storage formation (Basal Cambrian Sands, BCS), a primary seal (Middle Cambrian Shale, MCS), a secondary seal (Lower Lotsberg Salt), and an ultimate seal (Upper Lotsberg Salt). Above the storage complex, the geosphere also contains two additional deep saline aquifers, the Winnipegosis and the Cooking Lake, that provide important opportunities for MMV.
- **Hydrosphere:** The subsurface domain within the groundwater protection zone where water salinity measured as the concentration of total dissolved solids is less than 4,000 milligrams per litre. The Alberta Environment (AENV) *Water Act* defines saline groundwater as that containing greater than 4000 milligrams per litre (mg/L) total dissolved solids (TDS).
- **Biosphere:** The domain containing ecosystems where living organisms exist.
- **Atmosphere:** The local air mass where any changes to air quality matter and the global air mass where any changes influencing climate matter.

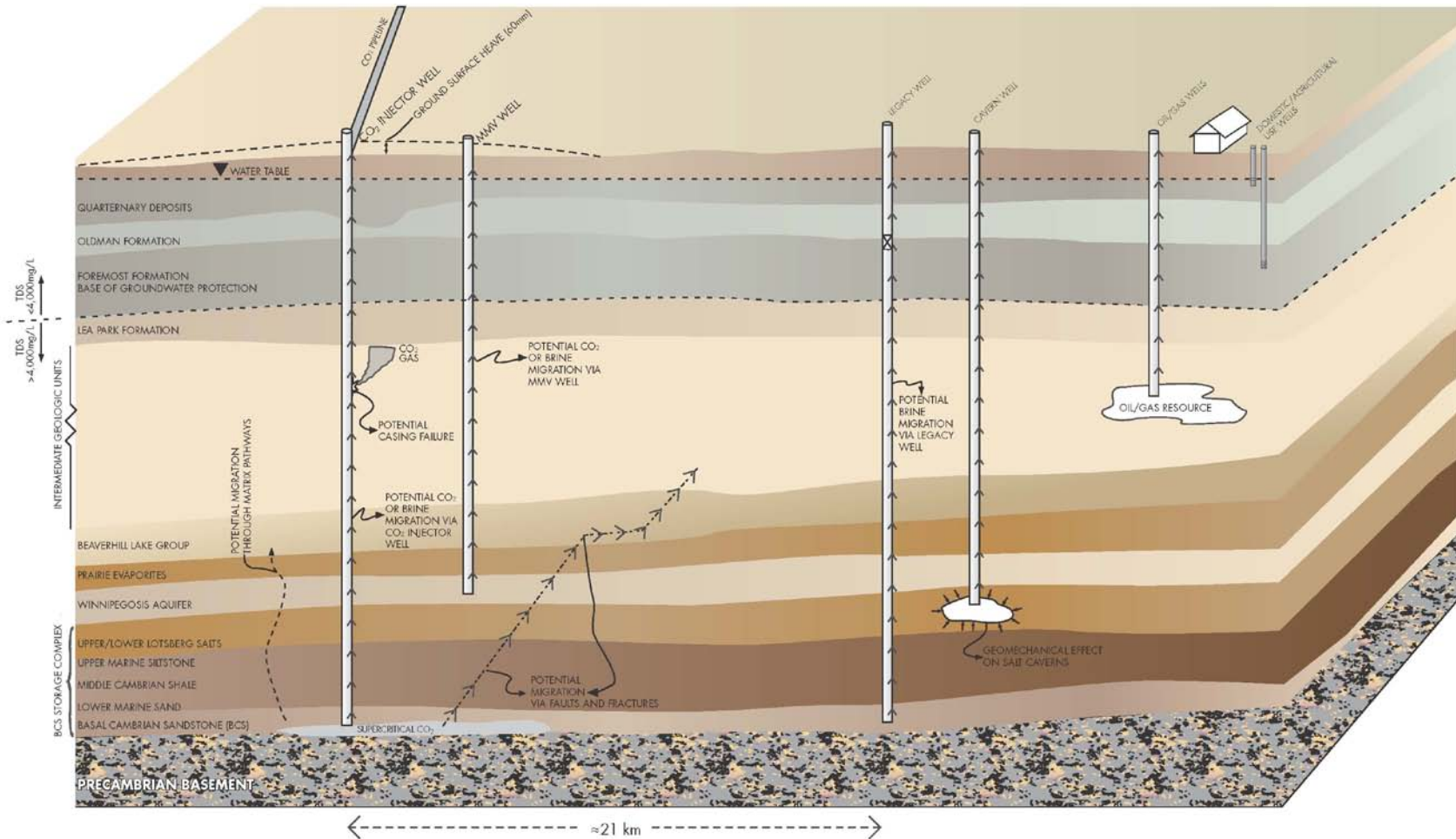


Figure 2-1 Schematic of the Selected Storage Site and the Identified Risks to Containment

2.4 Assumptions

The adopted framework for an adaptive MMV design results from choices based on several assumptions. The key assumptions influencing MMV design are as follows.

- The MMV plan will be designed based on risk mitigation. This builds on guidelines published by Det Norske Veritas (DNV2010).
- The Area of Review (AOR) for monitoring will have sufficient lateral extent to include the region of elevated fluid pressures within the BCS that could be sufficient to cause movement of fluids from the BCS to above the base of the groundwater protection zone. This is as per the emerging legislation within the European Union, United Kingdom and United States ([Attachment A](#))
- The monitoring program comprises:
 - base-case activities that follow a planned schedule
 - contingent activities that only occur in the event of detecting potential loss of containment of BCS brine or injected CO₂ from the storage complex
- The monitoring program will be adapted according to performance of the storage site and the monitoring technologies, revised performance predictions, and the qualification of new technologies.
- The post-closure period before transfer of liability will be determined according to the strength of evidence obtained from the monitoring program that actual storage performance conforms against the predicted performance over the first decade of injection. There are two performance metrics:
 - absence of BCS brine or CO₂ leakage from the storage complex
 - migration of the CO₂ plume within the storage complex

2.5 Design Principles

Royal Dutch Shell is committed to the following guiding principles for CCS projects (Shell 2009).

1. Protect human health and safety.
2. Protect ecosystems.
3. Protect underground sources of drinking water and other natural resources.
4. Ensure market confidence in emission reductions through proper greenhouse gas accounting.
5. Facilitate cost-effective, timely deployment.

In addition, the MMV plan will apply the following principles:

- It will comply with regulatory requirements as they mature.
- It is risk and uncertainty based, with clear trigger points identified and associated with corresponding actions.
- Select monitoring components intended to ensure containment in accordance with the principle of reducing risk to as low as reasonably practicable (ALARP).
- Select monitoring components intended to manage non-HSE critical aspects of storage performance based on technical feasibility and the economic value of information gained.
- The MMV plan must be adaptable and able to respond to any opportunities to improve the cost-effective management of lifecycle storage risks.

3 Measurement, Monitoring and Verification Design Workflow

Under normal operating conditions, the role of MMV is to collect the necessary evidence to verify that the actual storage performance is consistent with expected storage performance. To this end, information gained through monitoring must demonstrate that:

- all the injected fluids entered the intended disposal formation
- no fluids migrated out of the storage complex
- the development through time of CO₂ plumes and fluid pressures inside the storage complex was consistent with model-based predictions

Although exceptionally unlikely to occur, there is the possibility of CO₂ or BCS brine migrating out of the storage complex. To protect against this remote possibility, MMV must also provide:

- multiple independent monitoring systems with the sensitivity, speed, and scale to generate reliable early warning of any potential loss of containment
- intervention options to prevent, attenuate, or reverse any potential consequences due to the potential loss of containment

The approach is to design the MMV plan according to risk. The quality of the selected storage complex and engineering solutions means that less-than-expected storage performance is extremely unlikely. Nonetheless, there remains the possibility, that some aspects of storage performance might not fulfil expectations. MMV activities will focus on detecting and characterising these unlikely events, and there are clear and material benefits in focusing MMV activities according to the relative likelihood and potential consequence (risk) of these exceptional events, such as the MMV activities will focus on where the risk is highest. Tailoring MMV activities according to the particular qualities of the individual storage site (in this case the BCS) will maximize the additional protection provided by MMV.

This MMV planning strategy requires a systematic approach to risk assessment as the range and balance of the MMV activities are designed for the site-specific qualities of the BCS storage complex. The currently available appraisal and site characterisation forms the foundation of this initial conceptual MMV plan. As more information becomes available during further appraisal and early operations the MMV plan will need to adapt to accommodate the ever increasing understanding of the storage complex.

The Bowtie Method (DNV 2010a) provides an appropriate framework for a systematic risk assessment of events with the potential to affect storage performance. [Figure 3-1](#) illustrates a highly simplified bowtie risk analysis. The bowtie represents the relationship between the five key elements that describe how a risk might arise and how safeguards can provide effective protection against the risk and its associated consequences.

- **Top Event:** This is the unwanted event, placed in the centre of the bowtie.
- **Threats:** These possible mechanisms can lead to the top event.

- **Consequences:** These are the possible adverse outcomes due to the occurrence of the top event.
- **Preventative Measures:** These decrease the likelihood of a threat leading to the top event.
- **Corrective Measures:** These decrease the likelihood of significant consequences due to a top event.

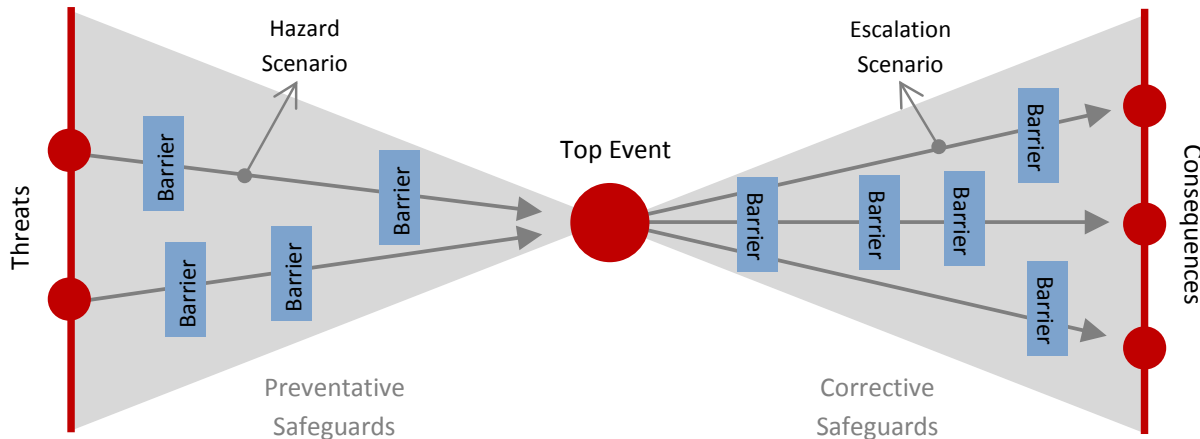


Figure 3-1 Schematic Diagram of the Bowtie Method

The Bowtie Method is a proven and effective method for analysing and communicating risks. The MMV plan must manage two distinct risks:

1. **Loss of conformance:** Conformance means that the behaviour inside the storage complex is consistent with model-based predictions. Therefore, lack of conformance is a project risk relating to the long-term liability and not a HSSE-critical risk. Therefore, a high-level risk analysis is sufficient for MMV planning.
2. **Loss of containment:** This is a HSSE-critical risk. Therefore a detailed and comprehensive approach to the bow-tie analysis is required

In both cases, two distinct types of preventative and corrective safeguards exist:

1. **Passive safeguards:** These safeguards are always present from the start of injection and do not need to be activated at the appropriate moment. These passive safeguards exist in two forms:
 - **Geological barriers** identified during site characterization
 - **Engineered barriers** identified during engineering concept selections
2. **Active safeguards:** These are engineered safeguards, brought into service in response to some indication of a potential upset condition in order to make the site safe.

Each active safeguard requires three key components in order to operate effectively:

1. a sensor capable of detecting changes with sufficient sensitivity and reliability to provide an early indication that some form of intervention is required.
2. some decision logic to interpret the sensor data and select the most appropriate form of intervention
3. a control response capable of effective intervention to ensure continuing storage performance or to control the effects of any potential loss of storage performance

This combination of a sensor, decision and control response becomes the MMV plan.

Therefore, structure of this document has been set-up to reflect this systematic risk-based approach to building an MMV program to:

1. Address Conformance Risks
 - a. identify and evaluate risks associated with any loss of conformance.
 - b. discuss initial safeguards for conformance
 - c. propose CO₂ storage performance targets for site closure and inventory reporting
2. Address Containment Risks
 - a. identify and evaluate risks associated with a loss of containment
 - b. provide a systematic evaluation of the wide range of geological and engineered safeguards already incorporated within the Project
 - c. recognize opportunities for incorporating additional safeguards through MMV activities
 - d. propose performance targets. MMV activities must verify actual performance statistics against these targets forming the basis of MMV technology screening.
3. Develop a Conceptual MMV Plan
 - a. identify options for intervening in routine storage operations with active control measures such as changing the injection policy. These controls mitigate risk by:
 - i. prevent any emerging threat, for instance by lowering the injection pressure to maintain the integrity of a geological seal within the storage complex
 - ii. control any unexpected occurrence of a threat before any significant consequences arise, such as by stopping injection to repair a compromised cement bond before any CO₂ rising outside the casing reaches fresh groundwater resources
 - b. evaluate a large variety and number of monitoring technologies capable of detecting changes within the storage complex, the groundwater, the biosphere and the atmosphere leading to a ranking of these technologies, according to their expected effectiveness and cost, for each particular monitoring task.
 - c. show how the monitoring technologies combine in a program of activities that start before CO₂ injection, adapt to changing circumstances during injection, continue in a reduced form after CO₂ injection and end once long-term storage risks are demonstrated to be insignificant

- d. confirm the future performance of these leading monitoring technologies within the Quest CCS site in an operational setting. The description of contingency monitoring plans shows the importance of an adaptive approach to MMV to mitigate any underperforming monitoring systems or to capture opportunities arising from technology developments likely to occur over the life of the Project.
4. Propose Annual Reporting Requirements
- a. propose a plan for routine reporting of MMV results to all stakeholders including regulatory authorities and the public
 - b. include plans for responding to any indication of loss of containment from the MMV monitoring systems or any complaints from the public about impacts due to suspected loss of containment

4 Conformance Risks

Under normal operating conditions, containment is assured, and the focus of the MMV program is to prove conformance. Conformance means that the storage complex is behaving in a predictable manner, consistent with the subsurface modeling.

4.1 The Risk Event

The unwanted event considered in this analysis is one where:

Significant discrepancy exists between the model based predictions and observed migration on the CO₂ plume and region of significantly elevated fluid pressure inside the BCS storage complex.

The definition of significance in the above remains to be discussed between the regulator and the project proponents. One possible measure of a significant discrepancy indicating a loss of conformance could be that the discrepancy must exceed a certain threshold representing the combined uncertainties associated within an agreed detectable range of modelling and monitoring results. Otherwise, unsuitably large modeling or monitoring uncertainty may lead to undetected fluid migration within the storage complex.

The following two sections characterize conformance risk in terms of the threats that might cause a loss of conformance and the potential consequences should this occur.

4.2 Potential Consequences

The potential consequences associated with loss of conformance are:

- the containment risk changes
- the post-injection closure period and terms for transfer of long-term liability changes
- the storage efficiency changes

4.2.1 Containment Risk Changes

Changes to the risk of containment may be positive or negative.

- Slower than expected pressure migration in a certain direction creates an opportunity to reduce MMV activities that were designed to mitigate the threat of fluid migration along pathways that will never experience elevated pressures.
- Faster than expected pressure migration in another direction creates a threat that additional MMV activities will be required as elevation pressures contact additional potential migration pathways that were not part of the base MMV plan.

4.2.2 Site Closure and Transfer of Long-Term Liability

Final agreement about the transfer of long-term liability is expected to be contingent on demonstrating conformance.

1. **Better than expected conformance:** Demonstration of better than expected conformance over the CO₂ injection period, for example a slower than expected plume expansion, and a forecast trend towards long-term stability of the CO₂ plume creates the opportunity to reduce the length of the expected closure period. Examples of this include a more localized than expected CO₂ plume or lower than expected increases in pore fluid pressure. The likely benefits of this are the avoidance of unnecessary monitoring activities and identification of scope for additional CO₂ storage within the site. Accordingly, the cost of post-closure stewardship will also be smaller.
2. **Worse than expected conformance:** Alternatively, if CO₂ migrates more rapidly or with a more complex morphology than predicted the expected closure period and related monitoring activities will likely increase to provide the additional information necessary to regain confidence in revised performance predictions. In this situation, the period and cost of post-closure stewardship will likely increase, and more stringent transfer conditions might be applied.

4.2.3 Storage Efficiency Changes

Storage efficiency has two key measures:

- the efficiency of pore-space utilisation for CO₂ storage
- the unit cost of CO₂ storage

The consequence of less injectivity than expected requires that additional injection wells be drilled to deliver the target storage rate. To avoid pressure interference that limits injectivity, the space between injectors must exceed some minimum distance (in the case of the Quest project the models indicate they must be greater than 5 km apart). Consequently, the footprint of the Quest CCS Project would increase.

Drilling more injectors in response to lower injectivity or capacity than expected also increases the cost of CO₂ storage per tonne. Costs escalate due to additional wells and pipeline laterals, and accompanying MMV activities. Similarly, remediation costs to prevent or correct any loss of containment might also substantially increase unit storage costs.

4.3 Potential Threats

There are two main threats towards demonstrating conformance:

- the original model is wrong
- the monitoring is wrong

4.3.1 Unexpected Modeling Errors

Model errors may arise from three sources.

1. Unexpected geological heterogeneities (model inputs) may strongly influence actual fluid transport in ways not represented by the models. Examples include a localized high permeability body, or a sealing fault.
2. The modeling process (model equations) may insufficiently represent the physical and chemical processes governing actual fluid transport. Examples include the relative permeability of CO₂ with respect to brine, and the reaction kinetics of CO₂ interacting with in-situ fluids and minerals.
3. Insufficient analysis of model uncertainties may lead to under-estimation of the predicted performance range. Examples include failing to identify the full range of model scenarios consistent with the observed storage performance history, and failing to fully account for uncertainties in the model equations.

Any of these represent a potential loss of conformance if the actual performance falls outside the predicted performance range.

4.3.2 Unexpected Monitoring Errors

Monitoring errors due to unexpected biases in the acquisition, processing or interpretation of monitoring data may result in a significant misrepresentation of the actual performance. This is a perceived loss of conformance, as the actual performance remains consistent with the predicted performance although the monitoring data indicate otherwise.

Distinguishing real from perceived loss of conformance is essential for implementing the right safeguards, as will be discussed in the next section.

4.4 Assessment of Safeguards

Safeguards provide opportunities to interrupt a developing threat before any significant consequences arise. Site selection, site characterization, and engineering concept selections provide the first round of safeguards incorporated into the Project. This section evaluates the effectiveness of these initial safeguards against identified conformance risks.

The conclusion is that with the initial safeguards in place the risks are already in the tolerable range. As several major development activities and project decisions have substantially reduced the risks and uncertainties about the expected performance of the BCS storage complex.

4.4.1 Basin-Scale Screening of CO₂ Storage Opportunities

Bachu et al. (2000) identified the most promising opportunities for CCS across Canada by matching the location of large localized CO₂ emissions with geological formations likely to support CO₂ storage. This systematic screening process concluded the top ranking opportunities are located within the central Alberta Basin due to the presence of deep permeable saline aquifers overlain by multiple extensive geological seals. On average, the geological formations within the Alberta Basin are conducive to storage of

CO₂. Nonetheless, many uncertainties remained about local geological properties on the scale of single storage sites.

4.4.2 Feasibility Study and Site Selection

Prior to site selection, a subsurface study evaluated the feasibility of storing CO₂ within the BCS saline aquifer. Existing exploration and appraisal wells, and 2D and limited 3D seismic as well as regional gravity and magnetic surveys provided an extensive and diverse data set. In addition, two new exploration wells drilled in the area supplied modern log and test data. Together these data supported an initial appraisal of the region surrounding the Scotford Upgrader near Edmonton. This study enabled a substantial reduction in subsurface uncertainties through better definition of aquifer thickness, porosity and permeability distributions as well as the number, thickness, composition and areal extent of the major geological seals. The conclusion was there is evidence of sufficient capacity, injectivity, and containment within the BCS storage complex to support the proposed storage project. The principle development decision supported by this study was selection of the site proposed for development as defined in the request for pore-space tenure submitted to Alberta Energy in December 2009.

Naturally, some uncertainties remain due to the potential for lateral property variations between the existing wells and seismic surveys. These uncertainties include the possibility of small-scale geological heterogeneities that might act as baffles limiting injectivity, or connected seals limiting capacity, or permeable pathways limiting containment. Oil and gas field developments routinely manage conformance risks such as these through the acquisition of appraisal data to guide the selection of development concepts such as the number, type and location of wells, plus the collection of early production and injection data to further constrain the subsurface understanding.

4.4.3 Site Characterization

Ongoing appraisal work to support Field Development Planning is delivering significant new subsurface information about the selected site. This includes the following:

- **High-resolution aeromagnetic survey:** Acquisition, processing and interpretation of these data indicate variations in the depth to the top of the Precambrian Basement and potentially the location of small faults (offsets less than 100 m) within the basement. Although the sensitivity and resolution of these data to basement structures is substantially less than seismic data, its areal coverage (8,500 km²) is substantially greater than the combined coverage of all available seismic data across the storage site and spans the entire AOR.
- **2D seismic surveys:** Reprocessing and interpretation of legacy 2D seismic data provides coverage over the entire storage site. The seismic lines are orientated north-south or east-west with a typical spacing of 2 to 3 km. These data demonstrate the presence and continuity of the geological seals over the entire storage site as well as the absence of any large faults crossing these seals. Within the basement, many small faults (offsets less than 20 m) and occasional larger faults (offsets of about 100 m) exist. The larger faults within the basement are located close to the north-west boundary of the storage site, and coincide with major terrain boundaries in the basement identified from aeromagnetic data. At these locations the BCS is interpreted as being locally absent but the primary seal, although thinner, remains intact, while the secondary and ultimate seals (Lower and Upper Lotsberg Salts) are

unaffected. Where seismic lines pass close to existing wells, the data from these two independent sources are consistent.

- **3D seismic survey:** Acquisition, processing and interpretation of new 3D seismic data over the central area (176 km²) of the storage site provide a detailed continuous image of the storage complex and overlying formations. Local variations in the structure of the BCS storage complex are resolved with a lateral resolution of 25 m and are consistent with 2D seismic data. The BCS is present throughout the 3D seismic image with an average dip direction consistent with the regional trend revealed by well data. Many small faults (offsets less than 20 m) exist within the basement, but no faults are detected crossing any of the seals within the BCS storage complex. These small faults control local variations in the depth to the basement, which in turn control the small variations (plus or minus 20 m) in the thickness of the BCS. Due to the small nature of these deep faults on the seismic image, there remains a small possibility that they extend just into the BCS, due perhaps to the process of differential compaction. If these faults do extent into the BCS, they are not likely to be sealing due to sand-on-sand contacts across the faults. If the faults are sealing, due perhaps to cataclysis, their mapped locations and orientations make it unlikely that they connect together sufficiently to limit injectivity. It is also unlikely that they compartmentalize the aquifer and limit storage capacity. Although these three conditions are each unlikely, there remains no guarantee that small faults cannot affect storage performance. Placement of the Radway 8-19 appraisal well, guided by this seismic image, close to a representative distribution of small faults affords an early opportunity to test the hydraulic properties of these faults.
- **Radway 8-19 appraisal well:** This is currently the only well penetrating the center of the BCS storage complex. Log and test data from this well confirm the expected depth, thickness and properties of all the geological formations within the storage complex.

4.5 Conformance Performance Targets

This section states the target level of risk or uncertainty reduction required through implementation of MMV safeguards. Performance targets should be specific, measurable, attainable, realistic, and time bound.

4.5.1 Performance Targets for Site Closure

Alberta Regulations governing site closure are still under development. To proceed now, we recognize two high-level qualification goals for site closure, adapted from internationally recognized guidelines (DNV 2010b).

1. An understanding of the total system relevant to CO₂ storage exists in sufficient detail to assess its future evolution adequately.
2. No significant negative impacts on human health or the environment occurred. Restrictions exist against any future activities that might compromise the integrity of the storage site.

To meet these high-level targets, MMV activities will be designed to deliver against the following targets during the site closure period.

- **Target:** Actual storage performance conforms to predicted storage performance within the range of uncertainty.
- **Target:** Knowledge of actual storage performance is sufficient to distinguish between two classes of possible future performance: those that result in permanent stable storage of the target mass of CO₂ inside the BCS and those that do not.
- **Target:** Measurements of any changes within the hydrosphere, biosphere, and atmosphere caused by CO₂ injected into the BCS storage complex are sufficient to demonstrate the absence of any significant impacts as defined by the Environmental Assessment

4.5.2 Performance Target for Storage Efficiency

The range of predicted pore-space utilization agreed with the regulator prior to CO₂ injection helps frame an appropriate performance target in the following form.

- **Target:** There is adequate evidence prior to site closure that actual pore-space utilization is consistent with the range of possible pore-space utilizations agreed prior to CO₂ injection, or any discrepancies between the two are tolerable.

4.5.3 Performance Target for CO₂ Inventory Reporting

Following the IPCC guidelines on CO₂ inventory reporting (IPCC 2006), the mass of CO₂ held within a geological storage complex is the difference between the mass of CO₂ injected into the complex and the mass of CO₂ emitted from the complex. Uncertainty about the CO₂ inventory therefore depends on uncertainties in the measured mass of injected and emitted CO₂.

The ERCB bulletin 2010-22 recommends the general provisions of Directive 007 and Directive 017 for CO₂ emissions monitoring.

Existing Acid Gas Disposal regulations require a maximum uncertainty in the monthly injected volume measurement of 5%. The sensitivity of emerging new technologies designed to measure CO₂ emission rates into the atmosphere depends on site-specific conditions. We propose the maximum uncertainty for these measurements be determined according to baseline monitoring data gathered at the storage site over at least 12 consecutive months prior to the start of CO₂ injection.

- **Target:** Measurement of monthly mass of CO₂ injected into the storage site has a maximum uncertainty of 5%.

5 Containment Risks

The project is designed for long-term secure containment of CO₂ and brine within the BCS storage complex. However, it is prudent to consider unlikely threats that may still occur with potential consequences. The following analysis of both the threats and potential consequences represents collective expert opinions and draws on existing risks descriptions provided by IPCC (2005), WRI (2008), EPA (2008a), and NETL (2009) as well as Acid Gas Disposal Projects in Alberta.

Containment focuses on the fact that the injected fluid should remain in the geological interval intended for long-term storage. Containment is a safety-critical risk, therefore a full containment Bowtie has been developed (see [Figure 5-1](#)).

5.1 The Top Event

As per the bowtie analysis in [Figure 5-1](#) the top event identified for this analysis is:

- Migration of CO₂ or BCS brine to above the Upper Lotsberg Salt, the ultimate seal of the BCS storage complex.

This is a natural choice as it represents the top of the storage complex. Prior to this event, the migrating fluids remain inside the intended geological formations. After this event, consequences due to loss of containment may arise as described in [Section 6.2](#). The number and impact of these consequences increases if fluid migration continues upwards uncontrolled. Therefore, the MMV plan proposed in [Section 7](#) focuses on early detection of a loss of containment.

5.2 Potential Consequences

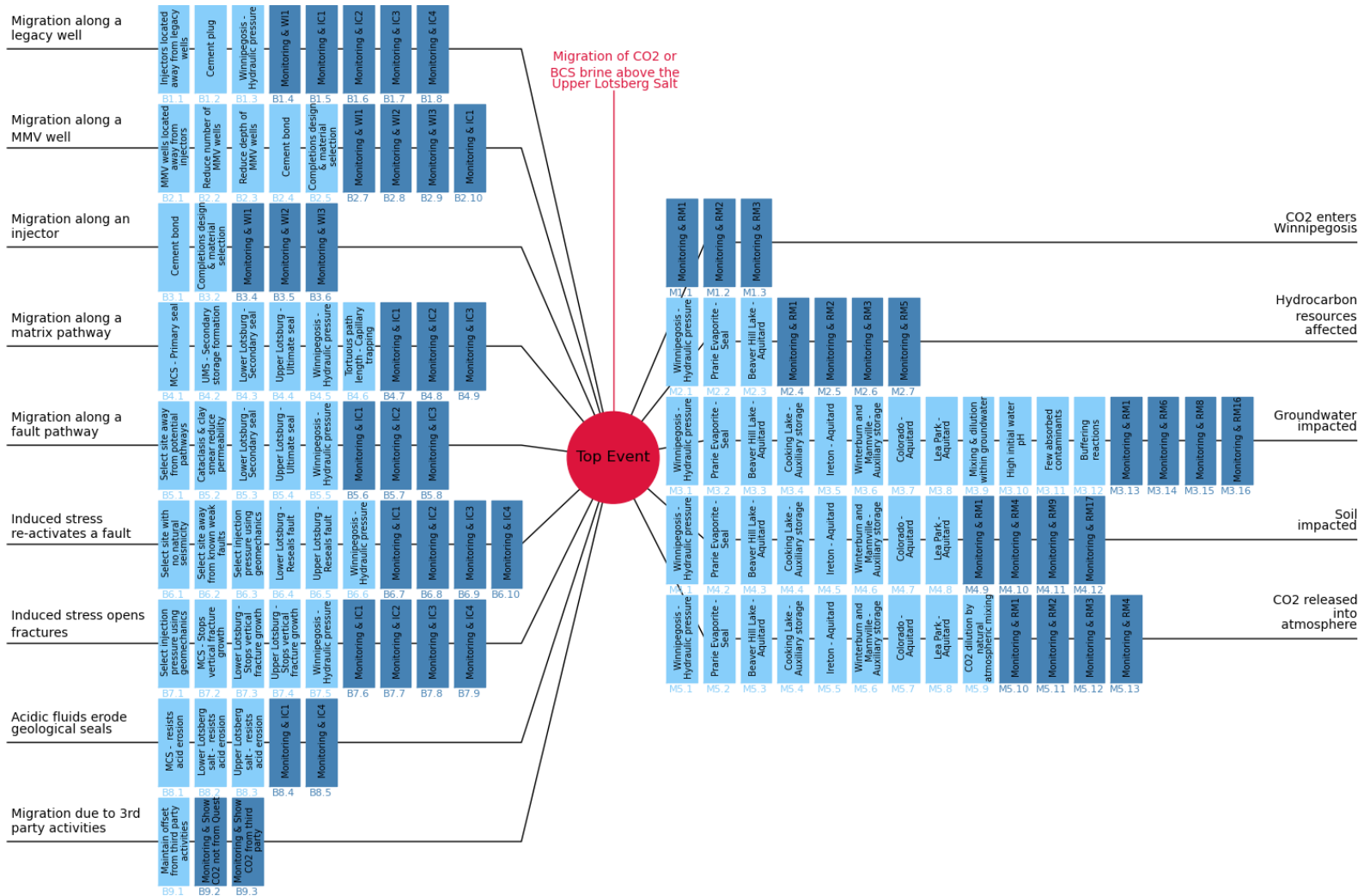
Five distinct environmental domains could be impacted as the result of a loss of containment. These domains are listed below in decreasing depth:

5.2.1 CO₂ Enters the Winnipegosis

The Winnipegosis is the first saline aquifer above the BCS storage complex at a depth of ~1600m MD. Therefore, a CO₂ or brine leakage into the Winnipegosis has no direct economic, health, safety or environmental impact and presents a potential early warning target MMV location. Any build-up of pressure and accumulation of CO₂ within the Winnipegosis would constitute a loss of the opportunity to potentially develop an independent CCS project within the Winnipegosis storage complex later.

The Winnipegosis is only recognized as an alternate CO₂ storage site because it is capped by another potential sealing formation in the form of the Prairie Evaporite.

Section 5: Containment Risks



NOTE: Identified with the potential to reduce the risk of loss of containment (top event) by reducing either its likelihood (left side) or its consequence (right side). Light blue denotes passive safeguards created by site and engineering concept selections. Dark blue denotes active safeguards where the unspecified monitoring activities pair with the control measures specified.

Figure 5-1 Initial Bowtie Representation of Safeguards

5.2.2 Hydrocarbon Resources Affected

Migration of CO₂ or brine out of the BCS storage complex might affect proven oil resources within the Leduc, Nisku and Wabamun formations and proven gas resources within the Nisku, Mannville Group and Colorado Group (see [Table 5-1](#) for depths and offset distances of the different hydrocarbon accumulations). For producing fields this might result in a slight increase in salinity or acidity of the produced fluids, although the lateral and vertical offset of the producing fields makes this unlikely. Any pressure changes would likely be negligible.

It should be recognized that for a zone to be hydrocarbon bearing it must add both another reservoir and impermeable seal to the geosphere, both of which add further barriers to migration of CO₂ out of the geosphere.

5.2.3 Groundwater Impacts

The protected groundwater zone (GPZ) is the zone above the base of groundwater protection up to the ground surface and comprises surface and underground water with a salinity, measured as the concentration of total dissolved solids, less than 4,000 parts per million. The depth of the GPZ varies across the AOR from 100 to 400 m MD. This zone supports extensive domestic, agricultural and commercial use throughout the AOR. The potential consequences to the groundwater are discussed in the environmental assessment (Section 17, Volume 2A).

5.2.4 Soil Contamination

Migration of CO₂ into the soil may increase soil acidity and introduce contaminants mobilized and transported by the passage of CO₂ through the subsurface. Changes in soil quality may be sufficient to stress the flora and fauna.

5.2.5 CO₂ Release to the Atmosphere

Any release of CO₂ from the BCS storage complex back into the atmosphere will reduce the effectiveness of the Project's contribution to climate change mitigation.

5.3 Potential Threats

Threats that might lead to a loss of containment take the form of nine independent potential pathways for fluids to migrate above the ultimate seal. The following sections describe the defining characteristics of each pathway.

5.3.1 Migration along a Legacy Well

Several abandoned third party wells penetrate all the seals of the BCS storage complex and may constitute a threat to containment of CO₂ and displaced brine ([Attachment C](#) and [Tables 5-2](#) and [5-3](#)). Given the density of wells drilled to this depth around Edmonton, more than 20 such penetrations might exist within the AOR if the selected site had not sought to avoid them. By careful site selection, the AOR for the Project has reduced this number down to three. This number increases in magnitude rapidly above the Upper Lotsberg Salts ([Figure 5-2](#)). For this reason, the BCS as the deepest saline aquifer in the basin is the preferred target injection formation.

Section 5: Containment Risks

Table 5-1 Distance to closest offset producers

Formation	Hydrocarbon Producers in Quest AOI	Closest offset well	Average depth to top reservoir in AOI (m)	Distance from 8-19-059-20W4 (km)	Comments
Viking	yes	100/09-31-059-20W4/00	590	3.4	
Joli Fou	yes	100/08-36-059-20W4/00	615	8.7	
Mannville	yes	100/15-20-059-20W4/00	623	1.2	Includes Ellerslie, Glaucontic Sands
Wabamun	yes	100/14-29-059-20W4/00	750	8.2	
Nisku	Yes	100/09-06-058-21W4/00	850	15	Leduc Reef
Ireton	Yes	103/06-07-058-21W4/00	900	15	Leduc Reef
Leduc	Yes	100/03-08-058-21W4/0	1000	15	Leduc Reef
Winnipegosis	no	-	1600	-	Saline Aquifer
BCS	no	-	2000	-	Saline Aquifer

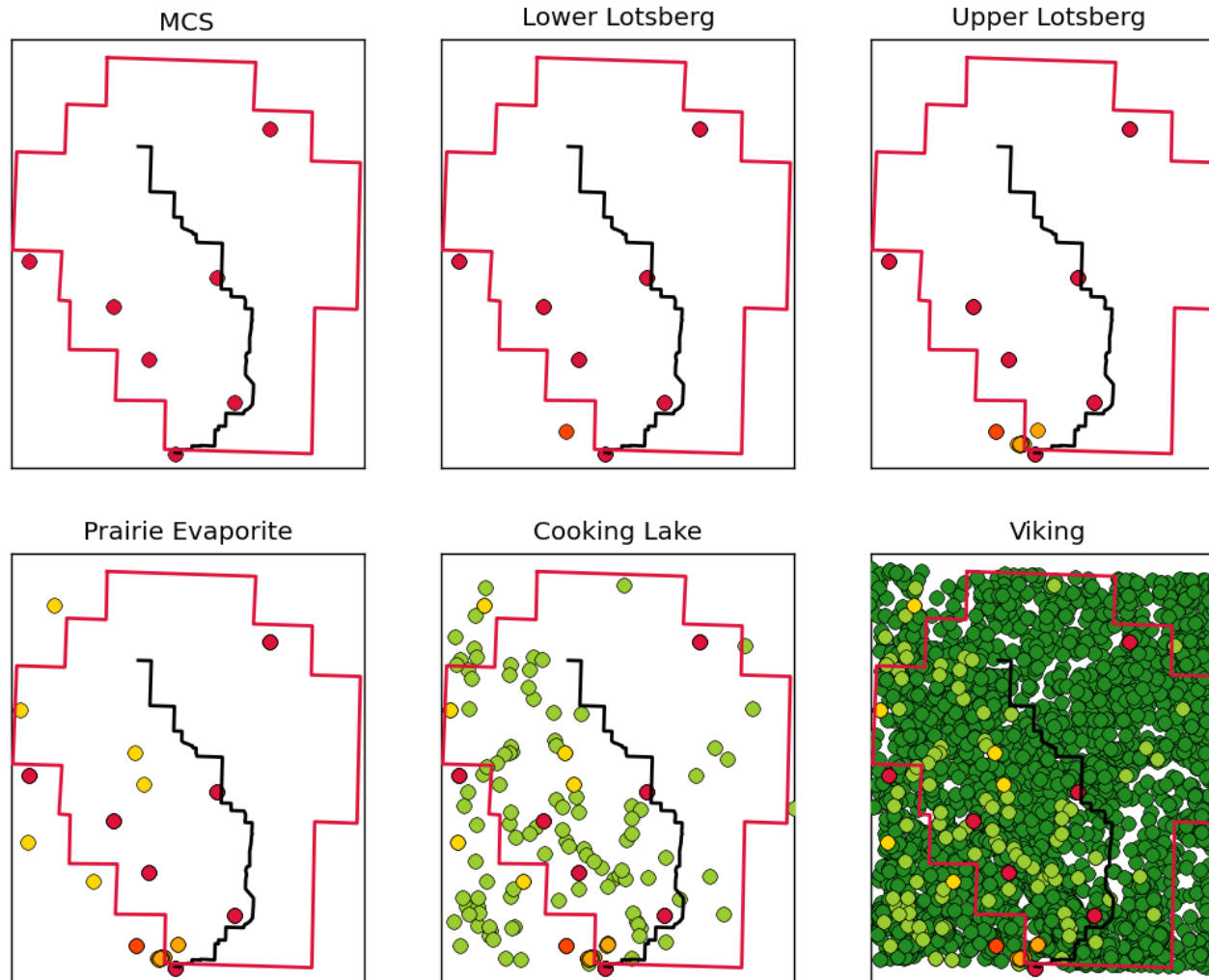
Table 5-2 Legacy Well Status

Well name and UWI	History	Seals Penetrated	Casings and holes	Cement plugs
Imperial Eastgate 100-01-34-057-22W400	Drilled and abandoned in 1955	- Upper Lotsberg - Lower Lostberg - MCS	- 9 5/8" casing to 277m - 9" openhole to 2205m (TD)	#1: 265 – 289 m #2: 644 – 710m #3: 887 – 981m #4: 1016 – 1048m #5: 1256 – 1292m #6: 2125 – 2205m
Imperial Egremont 100-06-36-058-23W400	Drilled and abandoned in 1952	- Upper Lotsberg - Lower Lostberg - MCS	- 13 3/8" casing to 186m - 9" openhole to 2235m (supposed TD)	#1: 172 – 195m #2: 624 – 670m #3: 844 – 875m #4: 969 – 1003m #5: 1178 – 1218m #6: 2140 – 2235m
Imperial Darling #1 100-16-19-062-19W400	Drilled and abandoned in 1949	- Upper Lotsberg - Lower Lostberg - MCS	- 13 3/8" casing to 183m - 9" (supposed) openhole to 2013m	#1: 168 – 198m #2: 525 – 587m #3: 708 – 740m #4: 762 – 792m
Imperial Baysel Riverdale 100-01-27-060-26W400	Drilled and abandoned in 1956	- Upper Lotsberg - Lower Lostberg - MCS	- 13 3/8" casing to 188m - 9" openhole to 2393m (TD)	#1: 175 – 200m #2: 710 – 765m #3: 971 – 1009m #4: 1136 – 1204m #5: 1531 – 1587m #6: 1750 – 1783m
Imperial Clyde #1 100-09-29-059-24W400	Drilled and abandoned in 1948	- Upper Lotsberg - Lower. Lostberg - MCS	- 13 3/8" casing to 135m - 9" openhole to 2295m (TD)	#1: 128 – 195m #2: 781 – 945m
Imperial Gibbons #1 100-02-16-056-22W400	Drilled and abandoned in 1949	- Upper Lotsberg - Lower Lostberg	- TD at 2024m Well report gathering in	Well report gathering in process
Imperial PLC Redwater LPGS 100-07-17-056-21W400	- Drilled in 1974 - Converted to LPG reproducer in 1975 - Abandoned in 2007	- Upper Lotsberg	- 13 3/8" casing to 188m - 9 5/8" casing to 1778m - 7" casing to 1770 - TD at 1861m	Well report gathering in process

NOTE: All legacy wells penetrating the BCS are abandoned.

Table 5-3 Appraisal Well Status

Well Name and UWI	TD	Status
SCL Redwater 102-11-32-55-21-W4M	2269m	Well cased and cemented to TD. BCS abandoned and well reconverted as a water disposal well
SCL-Redwater 03-04-57-20W4M	2190m	Well cased and cemented to TD. Well suspended with 19 joints of drill pipe and liner running tool cemented in hole. Top of cement at 1696.5m with top of fish at 1672m
SCL-Radway 8-19-59-20W4	2132m	Well cased and cemented to TD. Well suspended, will be part of the project injectors



NOTE: Shows the spatial distribution of existing wells recorded in the ERCB database and penetrating the base of each formation named above.

Figure 5-2 Spatial Distribution of Existing Wells in ERCB Database

Many of the legacy wells date from 1940 to 1960 so abandonment standards, execution, documentation and aging all contribute to uncertainty about the continuing integrity of legacy wells ([Attachment C](#)). Corrosion of casing, insufficient extent or quality of the initial cement bond outside the casing, an insufficient number, incorrect placement relative to the seals or quality of cement plugs inside the casing, or deterioration of any cement bonds through time will affect the integrity of these legacy wells. Therefore, the Quest CCS Project has been sited such that in all the current subsurface simulations the CO₂ plume does not reach these wells.

5.3.2 Migration along an Injector

Any well injecting CO₂ into the storage complex creates a threat to containment as it punctures the geological seals directly above the CO₂ plume. Any loss of external or internal well integrity will potentially allow migration of CO₂ and BCS brine out of the storage complex. This threat may arise for any of the following five reasons.

1. **Compromised cement:** Initial cement bond, or deterioration of the cement bond through time due to stress cycling, or chemical alteration may allow upward fluid migration outside the casing.
2. **Compromised casing:** Casing corrosion through time due to oxygen ingress, or contact with saline or acidic fluids may allow upward fluid migration inside or outside the casing.
3. **Compromised completion or wellhead:** Loss of integrity of the completion or wellhead due to undetected flaws in the initial design or execution or subsequent degradation due to corrosion, or deterioration of seals in the presence of CO₂ may allow fluids to escape through the wellbore.
4. **Well interventions:** During the course of normal operations, routine well interventions may result in loss of well control.
5. **Compromised abandonment:** Injection and observation wells will be properly abandoned prior to site-closure. Undetected flaws in the design or execution of well abandonment or subsequent degradation of materials may allow upwards migration of fluids.

5.3.3 Migration along an Observation Well

One method of monitoring storage performance inside the BCS storage complex is direct measurement of pressure and saturation changes within observation wells. Any such observation wells constitute a threat for the same reasons as the injectors.

Legacy, injector and observation wells each represent a different type of threat: legacy wells are avoidable, injectors are essential; however, observation wells are optional.

5.3.4 Migration along a Matrix Pathway

Sedimentary processes often generate extensive thick impermeable geological seals that retain fluids under pressure for millions of years. The Alberta Basin contains many such seals, and careful site selection process for the Quest AOR has been used to optimize the use of these natural barriers.

Nonetheless, permeable pathways may exist up through the geological seals due to the occasional juxtaposition of different sedimentary formations. The areal extent of geological seals may not cover the entire AOR or variations in seal thickness due to changes in the depositional environment or subsequent erosion may mean it is locally absent. For instance, a seal may truncate against a local basement high or a channel filled with sand may erode down through a seal. Sedimentary process may sometimes result in complex heterogeneities that interconnect to allow fluids under pressure to migrate up and out of the storage complex.

5.3.5 Migration along a Fault

Faults exist as discontinuities over a range of length-scales in many rock formations. However, large faults that transect regional scale geological seals within the Alberta Basin are rare (more than 100 km separates the Snowbird Tectonic Zone from the Hay River Shear Zone to the north). Even when present, many faults are sealing and retain fluids under pressure over geological time-scales. Mechanisms associated with fault slip, such as clay smear and cataclasis, reduce permeability within the fault zone. Other mechanisms, such as dilation and fracturing may enhance fault permeability. Although unlikely, it remains a credible possibility that permeable fault pathways exist somewhere within the AOR.

No faults are identified in the AOR that cut across the BCS storage container.

5.3.6 Induced Stress Reactivates a Fault

Any pre-existing sealing faults may re-activate due to stress changes induced by CO₂ injection. Effective normal stresses will decrease and may de-stabilize any pre-existing weak fault. In addition, shear stress loading these faults will increase or decrease depending on the fault orientation and the sense of residual shear stress held on the fault due to friction. Any decrease in shear stress will stabilize the fault making re-activation less likely and vice versa.

Renewed fault slip might increase local permeability by dilation or fracturing within the fault damage zone and perhaps allow the fault to propagate upwards. Equally likely is a reduction of permeability due to clay smear or cataclasis along the fault surface.

No faults are identified in the AOR that cut across any of the seals in the BCS container.

5.3.7 Induced Stress Opens Fractures

CO₂ injection may induce open fractures due to pore fluid pressure increase and temperature decrease inside the aquifer close to the well. Occurrence of any such fracturing does not constitute a threat to containment unless these fractures propagate upwards sufficiently to transect the geological seals and remains at least partially open to provide an enduring permeable pathway.

Fracturing induced by water injection for hydrocarbon recovery is common, but rarely do these fractures propagate upwards sufficiently to compromise the integrity of the top seal.

5.3.8 Acidic Fluids Erode Geological Seals

Injected CO₂ will acidify formation fluids in contact with geological seals. Depending on the mineralogy of the seals there is potential for many different chemical reactions to occur. Many of these reactions yield products that occupy a greater volume and therefore most likely reduce permeability; the converse is also possible. For acidic fluids to erode geological seals, minerals must be present that react and these reactions must increase not decrease permeability.

5.3.9 Migration Due to Third Party Activities

Any nearby third-party CCS projects may induce migration of CO₂ or brine into the AOR causing environmental impacts. Existing activities, such as mining, agriculture, or landfill inside the AOR may also cause environmental impacts. Inability to identify the true source of these impacts might trigger a perceived loss of containment from the Quest BCS storage complex. The closest CCS project under evaluation is the HARP project located in the Redwater Reef approximately 10 km lateral separation and approximately 1000 m vertical separation from the 8-19 well location.

5.3.10 Threats Deemed Not Credible

This analysis excludes many other possible threats as not credible or not having the potential to cause a significant impact. The four examples described below illustrate some of the many reasons for excluding these threats.

5.3.10.1 Surface Uplift

During injection, the distribution of increased pore fluid pressure inside the storage complex will induce an increase in bulk volume due to poro-elastic effects. This in turn induces deformations of the surrounding rock mass and the overburden will experience uplift and some associated strains. Geomechanical calculations based on mechanical rock properties gained from appraisal data and dynamic simulations of the pressure distributions induced by CO₂ injection yield results showing insignificant surface uplift (c. 60 mm maximum) and subsurface strain (c. 10⁻⁵ maximum). Surface uplift already observed above the In Salah CCS project in Algeria show similar deformation rates induced by similar rates of CO₂ injection into a formation at a similar depth (Rutqvista et al. 2008).

5.3.10.2 Lateral Migration within the Storage Complex

Lateral migration of the injected CO₂ or displaced brine is a conformance risk but is not a containment risk. Unexpected lateral migration poses no direct threat to containment. To escape the BCS storage complex, fluids must eventually migrate upwards. Lateral migration only creates an indirect risk to containment because it may bring fluids towards potential pathways for upwards fluid migration. Any safeguards in place against these direct containment risks will also be effective against the indirect risks.

5.3.10.3 Molecular Diffusion through Geological Seals

CO₂ will diffuse across geological seals at the molecular level even in the absence of any connected pore networks. However, this physical process takes millions of years due to the thickness and extremely low rates of diffusion of geological seals within the BCS storage complex.

5.3.10.4 Capillary Migration through Geological Seals

Injection pressure must exceed the capillary entry pressure and sufficient time must pass for fluid front to permeate through an almost impermeable and thick seal. Salinity differences between the BCS and Winnipegosis brines indicate long-term isolation between these two aquifers. Injection should never exceed the MCS capillary entry pressure. The MCS permeability and thickness mean that even if injection exceeds the capillary entry pressure, flow through the restricted pore network will take hundreds of years and then only result in an insignificant flux. Stratigraphic heterogeneities that may provide localized permeable pathways through geological seals pose a substantially greater threat.

5.4 Assessment of Safeguards

Safeguards provide opportunities to interrupt a developing threat before any significant consequences arise. Site selection, site characterization, and engineering concept selections provide the first round of safeguards incorporated into the Project. This section evaluates the effectiveness of these initial safeguards against containment risks. The conclusion is that with the initial safeguards in place the risks are already in the tolerable range.

5.4.1 Containment Safeguards

5.4.1.1 Preventative Measures

The system of preventative safeguards named in [Table 5-4](#) represents a wide range of measures to reduce the likelihood of each threat triggering the top event. An effective safeguard will prevent the occurrence of the top event on most occasions (e.g., 90% success rate). Individual safeguards do not need to be perfect as multiple imperfect but independent safeguards will still be effective. For example, two barriers that fail independently at the rate of 1 in 3 deliver the same protection as a single barrier that only fails at the rate of 1 in 9.

5.4.1.2 Safeguards for Legacy Wells

Wells represent a deliberate breach of the geologic seals and as such pose the greatest risk to containment and legacy wells are likely the most vulnerable given uncertainty about their current and future integrity. The most effective form of safeguard is to eliminate this risk. The selected site allows for injection of CO₂ no closer than 21 km to any legacy well penetrating the BCS. Only seven such legacy wells exist within 31 km of anticipated injectors. After 25 years of injection, the expected rise in pore fluid pressure around these seven legacy wells will likely be insufficient to raise BCS brine into the groundwater protection zone ([Attachment E](#)). Thereafter, pressures will tend to decline and the risk of fluids migrating upwards along legacy wells diminishes.

Section 5: Containment Risks

Table 5-4 Active Control Options

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

NOTE: Identified with scope to prevent any loss of containment or to provide corrective controls that avoid or reduce consequences should loss of containment unexpectedly occur. Each of these options corresponds to a discrete operational activity initiated by a management decision based on monitoring information.

Given the average density of wells drilled to this depth around Edmonton, many other suitable storage sites of this size would likely contain more than 20 legacy wells within a radius of 30 km. Two-thirds of the legacy wells risk is eliminated by selecting a site with an unusually low number of legacy wells. The risk reduces further by allowing sufficient separation distances so that no significant interaction can occur between the storage complex and the remaining legacy wells.

No system of safeguards is perfect. In this case, uncertainty currently remains about the amount of pressure build-up and rate of pressure migration throughout the BCS. There is a small possibility that some known legacy wells will experience greater pressures sooner than expected.

The previous abandonment of all seven legacy wells provides additional safeguards. Abandonment reports ([Attachment C](#)) document the number of cement plugs within each well. However, the results of any positive pressure tests are not available to verify the initial integrity of these abandoned wells and the current integrity may be still less due to degradation over the last 50 to 60 years.

5.4.1.3 Safeguards for Injectors

Injectors designed, drilled, completed and operated for the dedicated purpose of CO₂ injection allow for a wide range of engineered safeguards. Multiple casing strings, CO₂-tolerant casing, CO₂-tolerant cement, and cement placement along the entire well bore all provide independent layers of protection. Logging and pressure testing will verify initial well integrity. Although the continuing long-term integrity of such dedicated CO₂ injectors is highly likely, as demonstrated by many mature CO₂ EOR projects worldwide, some risk remains.

In-well monitoring must be a central part of MMV activities to verify well integrity over the entire project lifecycle and afford opportunities for early intervention to control any unexpected loss of well integrity promptly.

5.4.1.4 Safeguards for Observation Wells

Observation wells within the BCS pose a somewhat similar threat to containment as injectors as they will experience substantially elevated pore fluid pressures and CO₂. This risk is unique in that it is entirely voluntary given it can be perfectly eliminated by not drilling these wells at all or at least not drilling them into the storage complex. The potential benefits of accepting additional containment risk to allow direct measurements of conformance are uncertain. In-direct non-invasive conformance measurements should be feasible and may be sufficient. Currently there is no compelling reason to accept additional containment risk.

Therefore, this risk will be avoided to the extent possible by incorporating the safeguard that no observation wells will penetrate the Upper Lotsberg Salt.

5.4.1.5 Safeguards against any Matrix Pathways

The BCS storage complex contains three regional geological seals optimized by the site selection. Well control from just outside the AOR and 2D seismic lines every 2 to 3 km oriented north-south and east-west inside the AOR provide reliable information about the areal extent and thickness of these seals (see [Figure 1-1](#)).

- The primary seal, the Middle Cambrian Shale, is approximately 20 to 55 m thick over the entire AOI; the thinnest zones within the AOR occurs over occasional basement highs identified within 5 km of the north-west boundary of the AOR.
- The secondary seal, the Lower Lotsberg Salt, is typically approximately 10 to 35 km thick within the AOI and thins towards the west terminating just beyond the western boundary of the AOR.
- The ultimate seal, the Upper Lotsberg Salt, is approximately 55 to 90 m thick over the entire AOI and extends beyond the AOR boundary in all directions.

The depth of the BCS and the compensational stacking of the multiple seals inside and above the storage complex means any migration pathway must be long and highly tortuous. The length and tortuosity of any matrix pathway also provides a safeguard as such long migration routes increase the attenuation of any escaping fluids through capillary trapping and natural dispersion.

Each seal on its own is likely sufficient to ensure long-term containment of the injected CO₂ and displaced BCS brine. Nonetheless, a small risk remains that an unidentified localized permeable pathway allows significant fluid migration across any one of these seals. The presence of three independent seals within the storage complex substantially lowers the likelihood of fluids escaping – but does not eliminate this risk.

5.4.1.6 Safeguards against any Fault Pathways

No evidence exists of faults extending from the BCS through any of the three geological seals inside the storage complex. 2D seismic lines image all intersected faults with offsets exceeding 20 m. All of these faults appear within the basement with no evidence of faulting within the overlying sedimentary formations, although typical line spacing is approximately 2 to -3 km. Additionally, two 3D surveys covering a total area of 210 km² image the same fault system and detects fault offsets larger than 10 to 15 m. Once again, there is no evidence of any of these faults extending above the basement.

There is a very remote chance that small faults that transect but do not offset the primary seal may still generate a permeable pathway due to dilation or fracturing within the fault damage zone. Mechanisms such as ductile creep, clay smear, and cataclysis will however likely dominate and reduce permeability within the fault zone. Even if the shale seal happens to be brittle in parts, the two Lotsberg Salt seals will likely seal any fault zones due to salt creep. Core material recovered from the Basal Red Beds formation (Redwater 11-32) directly below the Lower Lotsberg Salt contains open fractures completely filled with salt.

In the extremely unlikely event of unexpected faults possessing unexpected permeability for fluids to escape the storage complex, the maximum flux will likely still be less than any unexpected migration of fluids along wells that provide a potential direct flow path from the storage complex to the surface (BGS 2010).

5.4.1.7 Safeguards against Fault Re-activation

Renewed slip on any pre-existing fault within the storage complex due to natural processes such as tectonics or induced by CO₂ injection may create permeable pathways for fluids to escape the BCS storage complex. The selected site has no recorded history of earthquakes and the monitoring network is sufficient to detect earthquakes of at least magnitude 2.

In-situ stress measurements indicate little initial deviatoric stress, which means that each principal stress is approximately equal to the mean stress. Faults remain stable due to their internal frictional resistance to further slip. Any decrease in the effective normal stress acting on the fault will diminish its frictional resistance to slip. This will happen within the BCS due to the expected increase in pore fluid pressure associated with CO₂ injection.

The absence of any significant shear stress acting on any small faults within the BCS means fault re-activation is unlikely despite any reduction to its frictional resistance.

Due to the large volume of injected CO₂, shear stresses will increase slightly during injection favouring re-activation of low-angle faults (dip of 30 degrees) inside the BCS or high angle faults (dip of 60 degrees) outside the BCS. These changes in shear stress will be small compared to the confining stress so fault re-activation remains unlikely. The frictional resistance of any pre-existing faults is largely uncertain so fault re-activation, although extremely unlikely, remains a possibility. If fault re-activation occurs, the region of renewed slip would likely remain confined to the pre-existing fault surfaces shown by existing seismic data do not extend across any of the seals. Even in the event of fault re-activation, it remains unlikely to threaten the integrity of the primary seal, let alone the secondary or ultimate seals. Moreover, clay smear and salt creep would most likely plug any permeable pathways should any fault re-activation occur within these seals.

5.4.1.8 Safeguards against Fractures Opening

Any injection-induced fracturing within the BCS cannot threaten containment unless these fractures propagate more than 330 m upward to pass through the ultimate seal.

Within a homogeneous medium, fractures tend to propagate most easily upwards due to the decrease in confining stress that opposes fracture opening. Geological formations are rarely homogeneous and typically contain horizontal layering that effectively arrest vertical fracture propagation due to any one of a number of different mechanisms.

1. **Minimum horizontal stress** may be higher within a particular layer, which arrests vertical fracture growth.
2. **Weak frictional interfaces** may slide in response to an approaching fracture, causing the fracture to arrest at the interface.
3. **Stiffness contrasts** between layers of more than a factor three suppress the stresses required to propagate the fracture from one layer to the other.
4. **Strength contrasts** between layers may arrest fractures at the interface with strong layers.

5. **Permeability contrasts** between layers may arrest fractures within permeable layers as the rate of fluid leak-off into the formation leaves insufficient pressure to propagate the fracture any further.
6. **Ductility contrasts** between layers may arrest fractures at the interface with layers that deform plastically instead of allowing brittle failure.

All six mechanisms are likely to operate throughout each of the geological seals inside the storage complex meaning even if fractures do open inside the BCS there is little chance they will ever threaten containment. The limestone shale (LMS) seal is a highly inter-bedded sand-shale system providing many weak interfaces as likely barriers to fracture growth. The measured compressive horizontal stress within the primary seal (middle Cambrian shale, or MCS) is 1.5 times greater than that in the BCS, which provides another effective barrier to vertical fracture propagation.

Existing regulations for acid gas disposal require the bottom-hole injection pressure never to exceed 90% of the measured fracture pressure within the disposal formation. This safeguard should ensure injection proceeds without opening fractures within the BCS. Some small uncertainty remains that fractures maybe initiated.

However, once injection ceases, reservoir pressures immediately start to decline gradually and so does the risk of open fractures.

5.4.1.9 Safeguards against Acidic Fluids

Mineralogy of the primary seal, the MCS, favours the reduction of permeability due to reactions with acidified brine. CO₂ dissolved in BCS brine lowers the pH from 5.5 to 4.0. The bulk of the minerals within the shale remain un-reactive in contact with this acidified brine.

Both Lotsberg Salt formations are made of pure halite that does not react with acidified brine. Salt creep would most likely fill any voids created by dissolution of currently unidentified reactive minerals before any permeable pathways transect the seals.

5.4.1.10 Safeguards against Third-Party Activities

Provision of exclusive porespace tenure is the prime safeguard against threats from any third-party CCS projects. The possibility of competing or indistinguishable environmental impacts from adjacent CCS projects is avoidable if the tenure region is sufficiently large to encompass the zone of elevated pore fluid pressures capable of lifting BCS brine above the base of the groundwater protection zone.

5.4.2 Corrective Measures

In the unlikely event of fluids escaping above the Upper Lotsberg Salt there remain a large number of additional geological formations to trap, delay, disperse, or attenuate these fluids and so reduce the likelihood of any environmental impacts (see [Figure 1-1](#)).

The first formation encountered is the Winnipegosis, a carbonate formation, with sufficient porosity to provide secondary storage. On top is the Prairie evaporite, a regional seal that extends outside the AOR in all directions and is 100 to 50 m thick inside the AOR with no indication of faulting seen on seismic.

Numerous seals that retain hydrocarbon accumulations exist within the next 1,200 m thick interval up to the base of the groundwater protection zone. These include the Beaverhill Lake, Ireton, Colorado, and Lea Park aquitards. Between these seals are numerous porous formations that provide secondary storage opportunities for any fluids escaping the BCS storage complex. These include the Cooking Lake, Winterburn, and Mannville aquifers.

Any migration pathways upwards through this stacked system of aquifers and aquitards will be highly tortuous given the lack of any large faults observed on seismic. Such long migration routes increase the attenuation of any escaping fluids through capillary trapping and natural dispersion.

A number of factors will mitigate the impact of CO₂ leakage on shallow groundwater quality. These include:

1. simple mixing and dilution of CO₂-impacted groundwater with ambient groundwater
2. pH buffering reactions such as calcite dissolution and/or silicate mineral weathering
3. limited trace metal availability in aquifer minerals
4. trace metal scavenging by secondary mineral precipitation

5.5 Containment Performance Targets

This section states the target level of risk or uncertainty reduction required through implementation of MMV safeguards. Performance targets should be specific, measurable, attainable, realistic, and time bound.

The proposed performance targets for MMV activities designed to ensure long-term containment are as follows.

- **Target:** Measurements of any changes within the hydrosphere, biosphere, and atmosphere caused by CO₂ injected into the BCS storage complex are sufficient to demonstrate the absence of any significant environmental impacts on an annual basis.

An annual performance review should evaluate actual storage and monitoring performance and if necessary revise the assessment of the four factors governing containment performance.

1. threat initiation rates
2. consequence impact ratings
3. safeguard failure rates
4. uncertainties about safeguard failure rates.

In response to any such changes, the MMV plan will be adapted so it meets the performance target, and it might be adapted to avoid exceeding the performance target in any manner that reduces the cost-effectiveness of MMV. Possible adaptations to the MMV program include the following options.

- replace an under-performing monitoring technology with an alternative
- replace an under-performing control measure with an alternative
- change the frequency of monitoring
- add or remove a safeguard

The preferred method for selecting from these many options is the same as the method described below for selecting the initial MMV design.

6 Measurement, Monitoring and Verification Concept Selection

6.1 Identification of Additional Risk Reduction Measures

Operations at the Quest CO₂ storage site will be designed to deliver long-term containment and maintain the confidence of stakeholders that the risk of a future loss of containment is acceptable given the beneficial contributions made towards mitigating climate change. The risks of actual storage performance failing to meet these requirements diminished substantially due careful site selection ensuring the presence of many different geological safeguards that either prevent any threats to containment from developing or mitigate the effects of any escaping fluids to avoid any significant impacts to human health and safety or the environment. Likewise, engineered safeguards incorporated into the project design provide similar layers of protection. Nonetheless, given the potential impact, it is prudent to have MMV plans in place to:

- verify storage performance
- give an early warning of the potential loss of containment
- deliver significant additional risk reductions

6.2 Additional Conformance Safeguards

Definition of the Field Development Plan marks the conclusion of appraisal activities. At this stage, subsurface models are as complete as possible prior to CO₂ injection and the range of predicted outcomes based on the Field Development Plan should indicate secure permanent storage of CO₂ inside the BCS complex regardless of any remaining uncertainties.

6.2.1 Additional Preventative Measures

Once CO₂ injection starts there is a range of measures available to reduce the likelihood of any loss of conformance occurring due to the threats identified previously.

6.2.1.1 Additional Safeguards against Unexpected Geological Heterogeneity

No matter how wide the range of geological models built, there will be other possible geological heterogeneities not properly represented. One additional safeguard is to gain early access to monitoring information with sufficient temporal and spatial resolution in order to characterize these geological heterogeneities before any loss of conformance arises, an example of such a technology would be time lapse seismic. Frequent updating of models to match observed performance should correct any discrepancies before they become significant. The frequency of such discrete monitoring activities will be time dependent:

- The rate of movement of the CO₂ front will generally decrease with time, the frequency of discrete monitoring activities such as time-lapse seismic should also decrease with time.

- More frequent initial monitoring will likely give early benefits in terms of uncertainty reduction and model updates.
- Reducing the frequency with the rate of movement of the CO₂ front will help avoid escalation of monitoring costs.

6.2.1.2 Additional Safeguards against Model Errors

Even if existing numerical codes used to predict storage performance are correct, future code developments, despite efforts to the contrary, might introduce new or reveal existing subtle model errors. This is not a reason to reject such code developments, as they will likely bring significant benefits through reduced computation time or increased spatial or temporal resolution. Instead, a continuing process of regular benchmarking will guard against this risk. Benchmarking checks for consistency between solutions obtained by independent numerical codes to the same storage simulation problems. Sometimes, model errors may arise due to the manner of application of a numerical code to a storage simulation task. The use of existing modelling standards, guidelines and assurance processes help to prevent these errors.

6.2.1.3 Additional Safeguards against Uncertainty in Predictions

Uncertainty estimates prior to injection should be large enough to include the actual storage performance observed during injection but small enough to allow regulatory approval before CO₂ injection commences. Uncertainty about the ultimate storage performance will be greatest prior to injection, but these should undergo progressive reduction during injection as updated models include more and more information from the observed storage performance. A final additional safeguard is to access new monitoring technology developments that increase the reliability or frequency of monitoring information without increasing costs.

6.2.1.4 Additional Safeguards against Monitoring Errors

Deploying only qualified monitoring technologies should reduce the likelihood of monitoring errors. Qualification is gained either because the technology is a widely accepted industry practise or through a validated field trial performance. Application of technical standards, guidelines and assurance processes for the acquisition, processing and interpretation of monitoring data provide a further safeguard.

6.2.2 Additional Corrective Measures

Revised storage performance models may forecast a state outside the predicted range of storage states. If this is not tolerable, then several control measures exist to correct this trend before any loss of conformance arises. For example, if injection rates are tending to decline and routine well interventions have no impact, then drilling an additional injector should correct this trend before the initial spare injection capacity is insufficient to maintain the target injection rate. These control measures include, but are not limited to:

- re-distributing injection across existing wells
- drilling new vertical or horizontal injectors
- drilling additional wells to extract reservoir fluids and re-inject elsewhere
- stopping injection

6.3 Additional Containment Safeguards

There are additional containment safeguards through MMV activities. Each of these active safeguards requires three key components to be effective:

1. **a sensor** capable of detecting changes with sufficient sensitivity and reliability to provide an early indication that some form of intervention is required.
2. **decision logic** to interpret the sensor data and select the most appropriate form of intervention.
3. **a control response** capable of effective intervention to ensure continuing containment or to control the effects of any potential loss of containment.

As before, a single barrier may be effective against multiple threats. However, for multiple active barriers to be effective against a single threat none can share the same detector, or decision logic, or control response. Otherwise, a single point failure would disable the entire group of barriers.

There is an important distinction between prevention and correction measures. From a precautionary standpoint, deep monitoring that prompts early intervention to avoid any loss of containment is preferred. However, these monitoring techniques might be less effective and more expensive than shallow monitoring alternatives. In this case, a proper balance between prevention and correction will achieve better outcomes from the same finite resource.

6.3.1 Additional Preventative Measures

[Table 6-1](#) summarizes the control response options for preventing any loss of containment. There are two categories.

1. **Injection controls** to change the manner of CO₂ injection into the storage complex. These include re-distributing injections rates across existing wells, drilling additional injectors, drilling producers and re-injectors to manage reservoir pressures, and stopping injection.
2. **Well interventions** to restore well integrity. These include repairing the cement bond, replacing the completion, or abandoning a well that cannot be repaired.

Table 6-1 Remediation Measures

Remediation Method	Type	Evidence For	Evidence Against
RM8 Pump and Treat	Active, Physical, Ex-Situ	<ol style="list-style-type: none"> 1. Can remove contaminants from shallow to deep depths 2. Relatively insensitive to the nature of contaminants 3. Can be quick where hydraulic characteristics are good 4. Uses conventional wastewater treatment processes 5. Effluent quality can be easily monitored 	<ol style="list-style-type: none"> 1. Can be problematic if hydraulic characteristics are unfavourable 2. Requires ongoing source of power 3. Relatively high capital cost 4. Requires operational maintenance of equipment 5. Necessitates handling of produced water 6. Can be challenging in winter environments
RM9 Air Sparging or Vapour Extraction	Active, Physical, Ex-Situ	<ol style="list-style-type: none"> 1. Remediation of gaseous and dissolved contaminants 2. Can be used as a means of exposure control 	<ol style="list-style-type: none"> 1. Can be problematic if hydraulic characteristics are unfavourable 2. Generally limited to volatile contaminants 3. Limited to contaminants near the vadose zone 4. Requires ongoing source of power 5. Relatively high capital cost 6. Requires operational maintenance of equipment 7. Necessitates scrubbing of effluent 8. Diminishing returns as contaminants become less concentrated 9. Can be challenging in winter environments
RM10 Multi-phase Extraction	Active, Physical, Ex-Situ	<ol style="list-style-type: none"> 1. Removes gaseous, free liquid and dissolved contaminants 2. Relatively quick removal of concentrated contamination 3. Relatively insensitive to nature of contaminants 	<ol style="list-style-type: none"> 1. Can be problematic if hydraulic characteristics are unfavourable 2. Requires ongoing source of power 3. Relatively high capital cost. 4. Requires operational maintenance of equipment 5. Limited to contamination near the water table 6. Necessitates handling of produced fluids.
RM11 Chemical Oxidation	Active, Chemical, In-Situ	<ol style="list-style-type: none"> 1. Removes contaminants from shallow & intermediate depths 2. Relatively low surface disturbance 3. Relatively quick degradation of organic contaminants 4. Able to treat high concentrations of contaminants 5. Does not require handling of produced groundwater 	<ol style="list-style-type: none"> 1. Can be problematic if hydraulic characteristics are unfavourable 2. Requires operational maintenance of equipment 3. Can be corrosive for other underground infrastructure 4. Potential for Health and Safety Issues
RM12 Bioremediation	Active or Passive, Biological, In-Situ	<ol style="list-style-type: none"> 1. Relatively low surface disturbance 2. Does not require handling of produced groundwater 3. Relatively low capital cost 	<ol style="list-style-type: none"> 1. Generally limited to organic contaminants 2. May not be suitable for highly concentrated or toxic contaminants 3. Requires operational maintenance of equipment 4. Can be challenging in winter environments

Table 6-1 Remediation Measures (cont'd)

Remediation Method	Type	Evidence For	Evidence Against
RM13 Electrokinetic Remediation	Active, Physical and Chemical, In-Situ	<ol style="list-style-type: none"> 1. Treats inorganic contaminants not easily treated otherwise 2. Can be used in areas of low permeability 	<ol style="list-style-type: none"> 1. Requires source of power 2. Requires eventual groundwater extraction to remove contaminants that have not been immobilized 3. Relatively immature technology
RM14 Phytoremediation	Passive, Biological, In-Situ	<ol style="list-style-type: none"> 1. Relatively passive method of remediation requiring little operational maintenance 2. Relatively low capital cost 3. Treats inorganic contaminants not easily treated otherwise 	<ol style="list-style-type: none"> 1. Limited to very shallow contamination 2. Requires periodic removal and disposal of plants 3. May not be suitable for contaminants with high toxicity or concentration 4. Requires a high level of ongoing monitoring 5. Generally long term remedial method 6. Can be challenging in winter environments
RM15 Monitored Natural Attenuation	Passive, Physical and Chemical and Biological, In-Situ	<ol style="list-style-type: none"> 1. Requires little operational maintenance 2. Relatively low cost in the short to medium term. 3. Relatively low surface disturbance 	<ol style="list-style-type: none"> 1. Requires a high level of subsurface assessment 2. Requires a high level of ongoing monitoring 3. Generally a long term remedial method 4. May not be acceptable to all stakeholders
RM16 Permeable Reactive Barriers	Passive, Chemical, In-Situ	<ol style="list-style-type: none"> 1. Requires little operational maintenance 2. Treats inorganic contaminants not easily treated otherwise 	<ol style="list-style-type: none"> 1. Limited to shallow to intermediate depths of contamination 2. Requires a high level of ongoing monitoring 3. Capital costs increase markedly with depth 4. Barriers may need replacing

6.3.1.1 Additional Safeguards for Legacy Wells

Intervention in any legacy well is not a straightforward option due to their nature of abandonment and ownership. However, controlling CO₂ injection does provide several options to respond to any indications of unexpected pressure build-up around a legacy well of suspect integrity. Examples are:

- Reducing injection rates of wells closest to the suspect legacy wells and increasing rates elsewhere to compensate should sufficiently delay further pressure build-up around the legacy well (IC1).
- If not, stopping injection at the closest wells may alleviate the situation (IC4) and then drilling any replacement injectors necessary (IC2).
- Finally, intervention in the legacy well to re-plug with cement (WI1) or drilling producers to prevent further pressure build-up (IC3) may be required.
- Drill a dedicated water production well to alleviate pressure (IC3)

6.3.1.2 Additional Safeguards for Observation Wells

Ready access to observation wells makes well intervention options attractive. Any observation well of suspected integrity might be remedied through:

- re-cementing (WI1), or replacing the completion (WI2)
- well abandonment (WI3)
- reducing or stopping CO₂ injection in the nearby injector.(IC1, IC4)

6.3.1.3 Additional Safeguards for Injectors

The additional safeguards described for observation wells (WI1, WI2, WI3, IC1, and IC4) are also effective for injectors for the same reasons. Different or more monitoring solutions may be required due to the greater containment threat posed by injectors, especially if observed wells never penetrate the ultimate seal.

6.3.1.4 Additional Safeguards against Matrix Pathways

Indications of upward fluid migration along a matrix pathway can trigger a re-distribution of injection rates across existing injectors (IC1) and may necessitate drilling additional injectors (IC2) or extracting fluids to create a hydraulic barrier (IC3).

6.3.1.5 Additional Safeguards against Fault Pathways

The additional safeguards against migration along matrix pathways (IC1, IC2, and IC3) are also effective against migration along fault pathways for the same reasons. Different monitoring solutions may be required to detect fluids migrating along fault rather than matrix pathways.

6.3.1.6 Additional Safeguards against Re-activating Faults

Indications of any fault re-activation will trigger interventions to reduce the likelihood of continued fault slip threatening containment. These interventions may include:

- reduction of injection rates close to the re-activated fault to delay and maybe prevent any further pressure build-up (IC1)

- stopping injection (IC4) whilst drilling one or more injectors to maintain injectivity (IC2)
- drilling one or more producers and extracting fluids (IC3) to avoid the threat

6.3.1.7 Additional Safeguards against Opening Fractures

Interventions that delay, avoid, or reverse pressure build-up around injectors can arrest any upwards propagating opening fractures before they transect the ultimate seal.

- reducing injection rates of the closest injector may be sufficient (IC1)
- drilling additional injectors (IC2) to allow further reductions of injection rate into the suspect well or even stopping injection into this well (IC4) should suffice
- drilling producers to extract fluids and reduce pressures inside the BCS (IC3), and potentially stopping all injection (IC4), provides an ultimate safeguard

6.3.1.8 Additional Safeguards against Acidic Fluids

The number and quality of natural geological safeguards against acidic fluids eroding seals leaves almost no requirement for additional active safeguards. Nonetheless, should monitoring indicate migration of fluids upwards towards the ultimate seal then interventions such as reducing (IC1) or stopping (IC4) injection near this location will prevent any loss of containment even if this particular cause is not identified.

6.3.1.9 Additional Safeguards against Third-Party Activities

Third-party activities may accidentally cause environmental impacts within the AOR that create a perceived loss of containment from the BCS storage complex. Without safeguards in place to correct this perception, it will likely trigger disruptive and ineffective interventions to CO₂ injection and may require costly remediation efforts that inappropriately raise the cost of CO₂ storage. Monitoring activities that demonstrate the source of such environmental impact is not this CO₂ storage project or is attributable to a third party help safeguard the Project.

6.3.2 Additional Corrective Measures

Tables 5-4 and 6-1 summarize the corrective control response options for avoiding, limiting, or recovering from any significant impacts in the unlikely event of CO₂ or displaced BCS brine migrating above the Upper Lotsberg Salt. There are three categories.

1. **Well interventions** to restore well integrity. These include repairing the cement bond, replacing the completion, or abandoning a well that cannot be repaired. These are different to the preventative well interventions. Preventative and corrective well interventions aim to restore well integrity below and above the ultimate seal respectively.
2. **Exposure controls** to prevent contaminants reaching sensitive environmental domains where significant impacts might occur such as the protected groundwater zone.
3. **Remediation measures** to recover from any significant impacts in the unlikely event of an uncorrected loss of containment.

6.3.2.1 Additional Safeguards to Protect the Winnipegosis

No additional safeguards appear necessary to protect the Winnipegosis, the second deepest saline aquifer. The only impact is the lost opportunity for a potential additional independent CCS development. In this situation, no CO₂ storage capacity is lost as it effectively joins the BCS storage complex.

Nonetheless, any loss of well integrity resulting in CO₂ or BCS brine entering the Winnipegosis requires correction by repairing any impaired cement bond (RM1), or replacing any impaired part of the well completion (RM2). Should these measures fail, it always remains possible to plug and abandon the well (RM3).

6.3.2.2 Additional Safeguards to Protect Hydrocarbon Resources

Well interventions (RM1, RM2 and RM3) would correct any loss of well integrity resulting in migration of CO₂ or BCS brine into hydrocarbon bearing formations. When necessary, drilling a dedicated well to inject water as a hydraulic barrier (RM), offers scope to block any migration pathways detected elsewhere.

6.3.2.3 Additional Safeguards to Protect Groundwater

The GPZ is potentially the most sensitive environmental domain and therefore likely requires the greatest number of additional safeguards. Any indication of changes to water quality, which if uncorrected might eventually lead to exceeding water quality guidelines, should trigger one or several additional control measures.

Well interventions (RM1, RM2 or RM3) allow options to immediately correct any suspected loss of well integrity within this zone. Exposure controls (RM4, RM6 and RM7) can avoid or delay any impacts in the unlikely event of an uncontrolled migration of CO₂ or BCS brine towards the Base of Groundwater Protection (BGGWP). Should all earlier safeguards prove insufficient to avoid contaminating some part of the protected groundwater, then prompt remediation measures will likely reverse these impacts before they can become significant. Contamination of the deepest parts of the BGWP requires a certain type of remediation (as per [Table 6-1](#)) The Bow-tie includes as representation of these safeguards RM1, RM6, RM8 etc as depending on individual circumstances not all options are likely to be effective. Each of these control options require either wellbore or groundwater monitoring of sufficient sensitivity and frequency to provide an early warning that allows intervention before any significant impacts occur, such as impacting the current potable water quality. [Section 6.5](#) describes provisions for just such a hydrosphere monitoring system.

6.3.2.4 Additional Safeguards to Protect Soils

Any indication of early soil acidification or brine incursion would trigger control measures to remove the source of potential contamination (as per [Table 6-1](#)). The Bow-tie includes as representation of these safeguards RM1, RM2 or RM3, or limit exposure of the soil (RM4, RM6) and if necessary recovery from any significant impacts to soil quality (RM9 and RM17).

[Section 6.5](#) describes provisions for a biosphere monitoring system of sufficient sensitivity and frequency to allow early interventions before any significant loss of soil quality occurs.

6.3.2.5 Additional Safeguards to Prevent CO₂ Entering the Atmosphere

CO₂ inventory reporting requires monitoring for any CO₂ emissions from the storage complex into the atmosphere. Any indication of CO₂ fluxes in excess of natural variations will trigger further investigation. Isotopic analysis of this CO₂ will likely distinguish between natural sources and emissions from the storage complex. If emissions do arise from the storage complex and occur close to an injector or observation well then well interventions (RM1, RM2 or RM3) may prevent any further emissions. Should these emissions arise elsewhere or well interventions fail, then exposure control measures (RM4, RM5) will be implemented.

6.3.3 Routine versus Contingency Monitoring Requirements

Decision logic informed by information gained through monitoring activities will trigger these interventions. Therefore:

- These monitoring activities will be part of the routine monitoring program.
- The detection systems designed to trigger corrective interventions cannot be part of contingency monitoring plans held in reserve and only deployed in the event of detecting the occurrence of the top event. If this were so, then any failure to detect the top event would render all active correction measures useless.
- To be effective, independent monitoring systems will trigger each active corrective safeguard.
- The role of contingency monitoring plans is to characterise any environmental impacts subsequent to their detection and to verify the effectiveness of any recovery measures.

6.4 Assessment of Monitoring Technologies

This section evaluates the many reasons and methods for monitoring storage performance to achieve two goals.

1. Judge the expected effectiveness of safeguards dependent of monitoring capabilities.
2. Generate a ranked list of monitoring technologies capable of performing each monitoring task.

This assessment provides the framework to select monitoring technologies for inclusion in the MMV plan but does *not* make a selection. Selection of initial monitoring activities still depends on the outcome of:

1. ongoing appraisal activities
2. the results of field trials
3. pre-injection baseline data acquisition
4. the first years of operational monitoring

Through time, the selected monitoring solutions must be adapted to respond to new threats or opportunities as they emerge.

Lack of certainty about the future performance of individual monitoring systems within the AOR dictates the need for an adaptive rather than a prescriptive monitoring plan, for the following reasons:

- Single monitoring solutions may fail or exceed expectations for unforeseen reasons.
- Adaptive monitoring means allowing sufficient flexibility and redundancy to respond to these changing circumstances.
- Prescriptive monitoring with no flexibility to adapt through time to local site conditions appears less complex and less expensive only if we ignore uncertainties about future monitoring performance.

6.4.1 Method of Assessment

The method adopted for assessing monitoring technologies is as follows.

1. Define the monitoring tasks required to support the identified active safeguards.
2. Identify candidate monitoring technologies with potential to fulfill at least one monitoring task.
3. Screen the candidate technologies against the tasks assuming the information gained is both free and perfect, and then regret any still judged incapable of the task.
4. Evaluate the effectiveness of technologies against the tasks using expert opinions. Document this process by recording and scoring evidence for and against including any uncertainty.
5. Estimate the lifecycle monitoring costs of each technology.
6. Estimate the lifecycle benefits generated by each technology in terms of risk reduction.
7. Rank technologies according to their overall benefits and costs to the Project.
8. Evaluate the effectiveness of the identified active safeguards triggered by high-ranking monitoring technologies.

6.4.2 Identification of Monitoring Tasks

[Table 6-2](#) lists the monitoring tasks required to support each active safeguard identified to protect conformance (Section 7.2) and containment (Section 7.3) risks.

These tasks divide into four distinct groups:

1. **Containment monitoring tasks below the Upper Lotsberg Salt:** To trigger preventative controls to avoid or reduce the likelihood of fluids migrating above the BCS storage complex.
2. **Containment monitoring tasks above the Upper Lotsberg Salt:** In the unlikely event of any loss of containment, this monitoring will be designed to:
 - a. Trigger corrective controls to avoid or reduce the likelihood of significant environmental impacts.
 - b. Contingencies must also exist to allow for additional monitoring in the event of any detected loss of containment to characterize the impact and verify the efficacy of any correction measures applied.

3. **Conformance monitoring tasks within the BCS storage complex:** To verify that the build-up and migration of pore fluid pressures and CO₂ through time remains consistent with the range of published forecasts and provide the necessary information to revise and narrow the range of these forecasts whenever appropriate.
4. **CO₂ inventory measurement tasks:** To report the rate and volume of CO₂ injected into the storage complex and potentially emitted from the storage complex into the atmosphere.

Table 6-2 Monitoring Tasks Included Within the MMV Plan

Monitoring Tasks

Containment Monitoring Tasks Below the Upper Lotsburg Salt

- T1 Detect migration of CO₂ or brine along a legacy well
- T2 Detect migration of CO₂ or brine along a MMV well
- T3 Detect migration of CO₂ or brine along an injector
- T4 Detect migration of CO₂ or brine along matrix pathways
- T5 Detect migration of CO₂ or brine along a fault pathway
- T6 Detect fault reactivation
- T7 Detect induced fractures opening
- T8 Detect fluid migration through pathways created by acidic fluids
- T9 Third -party activities induce CO₂ or brine migration

Containment Monitoring Tasks Above the Upper Lotsburg Salt

- C1 Detect CO₂ or brine entering the Winnipegosis
- C2 Detect and characterise any contamination of protected groundwater
- C3 Detect and characterise any contamination of surface soils
- C4 Detect and quantify any CO₂ releases into the atmosphere

Conformance Monitoring Tasks within the BCS

- S1 Detect migration of CO₂ within the BCS
- S2 Detect migration of pressure within the BCS

CO₂ Inventory Measurement Tasks

- I1 Monitor injection pressure per well
 - I2 Monitor injection rate per well
 - I3 Monitor injection volume per well
 - I4 Monitor total injection volume
-

6.4.3 Identification of Monitoring Technologies

The 56 identified monitoring technologies were drawn from a range of authoritative sources proposing technologies suitable for MMV (IPCC 2006; IEA 2006; EPA 2008; NETL 2009; Chadwick et al. 2008; BGS 2010) and supplemented by expert knowledge available within the Shell Group. There are various approaches to classifying these technologies to ease discussion, each with their own difficulties. The categories adopted here are as follows.

1. **In-Well Monitoring:** These are direct measurements of down-hole changes made either by permanent sensors incorporated into the well design, or by occasional petrophysical logging or well integrity testing activities that require well intervention. This group of technologies provides detailed information about changes within the well and the near-well environment (e.g. within 5 m), but provides no information about changes further afield.
2. **Geochemical Monitoring:** These are the methods of monitoring chemical changes throughout the subsurface using geochemical measurements within observation wells. These measurements are made either by permanent sensors incorporated into the well design, or through the occasional collection of fluid samples from the well for laboratory analysis. This group of technologies may provide detailed information about the transport and reaction of chemical species above the storage complex indicative of any loss of containment and its potential impacts.
3. **Geophysical Monitoring:** These are the methods of monitoring physical changes throughout the subsurface using remote-sensing techniques. This group of technologies may provide detailed images of the spatial distribution of CO₂ and increased pore fluid pressures within or above the storage complex.
4. **Near-Surface Monitoring:** These are the methods of monitoring near-surface changes within the biosphere or atmosphere.

Many technologies within the first three categories depend on sensors within wells – four different types of wells may support these kinds of monitoring:

- a. **CO₂ injection wells in the BCS:** The measurements may be taken either during the injection period and/or in the post-injection but pre-abandonment phase.
- b. **Observation wells in the BCS:** To provide additional direct monitoring opportunities inside the storage complex.
- c. **Observation wells in the Winnipegosis:** To provide direct monitoring opportunities within the first permeable formation above the ultimate seal.
- d. **Observation wells in the Protected Groundwater Zone:** To provide direct monitoring opportunities to verify the absence of any adverse impacts to groundwater quality or provide early warning of the need for corrective measures to protect groundwater quality.

Only the first type of wells is a necessity. The other three types are options available for inclusion within the MMV program just like any of the monitoring technologies themselves. Appraisal activities for site characterisation are not yet complete, until then the target depths for observation wells remain subject to change. For example, permeability within the Winnipegosis may be insufficient or too uncertain to support the required monitoring tasks. In this case, other permeable formations above the storage

complex and below the protected groundwater such as the Cooking Lake saline aquifer might offer better opportunities for monitoring.

Together, all the identified monitoring technologies possess a wide range of complimentary and overlapping capabilities (Table 6-3) with varying degrees of sensitivity, resolution, reliability and cost.

6.4.4 Technology Screening and Evaluation

The next step is to simplify the evaluation of these technologies by screening their known capabilities against the monitoring requirements. This was completed in two steps:

1. **Technology screening:** Table 6-4 summarizes the effectiveness of the numerous identified technologies against their ability to perform the identified monitoring tasks.
2. **Technology Evaluation:** Each technology that survived the screening process its effectiveness to perform the identified monitoring tasks was assessed according to the following criterion: **Evaluation Criterion:** The monitoring technique is fast enough, precise enough, and big enough to trigger the control response correctly.

Figure 6-1 and Figure 6-2 summarizes these results for all containment and conformance monitoring tasks respectively. For each containment-monitoring task, there is a wide range of partially effective monitoring technologies. No monitoring technology is perfect – but the combination of multiple technologies with different imperfections provides a highly effective integrated monitoring system. Although the final evaluation of these technologies depends on the conclusion of the ongoing appraisal activities – there are clearly many highly effective technology combinations available to fulfill the monitoring requirements.

Table 6-3 Monitoring Technologies – Technical Capabilities

Monitoring System		Information Gained	Availability	Coverage
Well Monitoring				
Cement bond logs	CBL	Initial quality of cement bond	Once, during well completion	Entire well length
Time-lapse ultrasonic casing imaging	USIT	Casing corrosion detection	During well intervention	Injection and monitoring wells
Time-lapse EM casing imaging	EMIT	Casing corrosion detection	During well intervention	Injection and monitoring wells
Time-lapse multi-finger calliper	CAL	Tubing corrosion detection	On demand	Injection wells
Annulus pressure monitoring	APM	Pressure leak detection	Continuously	Injection and monitoring wells
Injection rate metering at wellhead	IRM	Rate and volume of CO2 injected	Continuously	Injection wells
Wellhead pressure-temperature gauge	WHPT	Injection pressure, temperature	Continuously	Injection wells
Operational Integrity Assurance System	OIA	Exception based well monitoring	Continuously	Injection wells
Down-hole pressure-temperature gauge	DHPT	Downhole pressure, temperature	Continuously	Injection and monitoring wells
Mechanical well integrity pressure testing	MWIT	Leak detection	On demand	Injection and monitoring wells
Well-head CO2 detectors	WHCO2	CO2 leak detection	Continuously	Injection and monitoring wells
Tracer injection & gamma logging	TRL	Leak detection & CO2 conformance	Continuously / On demand	Injection and monitoring wells
Time-lapse saturation logging	SATL	Leak detection & injection profile	During well intervention	Injection and monitoring wells
Time-lapse temperature logging	TMPL	Leak detection outside casing	During well intervention	Injection and monitoring wells
Time-lapse annular flow noise logging	AFNL	Leak detection outside casing	During well intervention	Entire borehole
Time-lapse density logging	DENL	Leak detection outside casing	During well intervention	Entire borehole
Time-lapse sonic logging	SONIC	Leak detection outside casing	During well intervention	Entire borehole
Fibre-optic distributed temperature sensing	DTS	Leak detection outside casing	Continuously	Entire length of FO down-hole
Fibre-optic distributed pressure sensing	DPS	Leak detection outside casing	Continuously	Many discrete locations down-hole
Real time casing imager	RTCI	Leak detection outside casing	Continuously	Region of wrapped FO down-hole
Fibre-optic distributed acoustic sensing	DAS	Leak detection outside casing	Continuously	Entire length of FO down-hole
Pressure interference testing	PII	Fraction of path containing CO2	On demand	Injection and monitoring wells
Pressure fall-off test	PFOT	Storage capacity	On demand	Injection wells

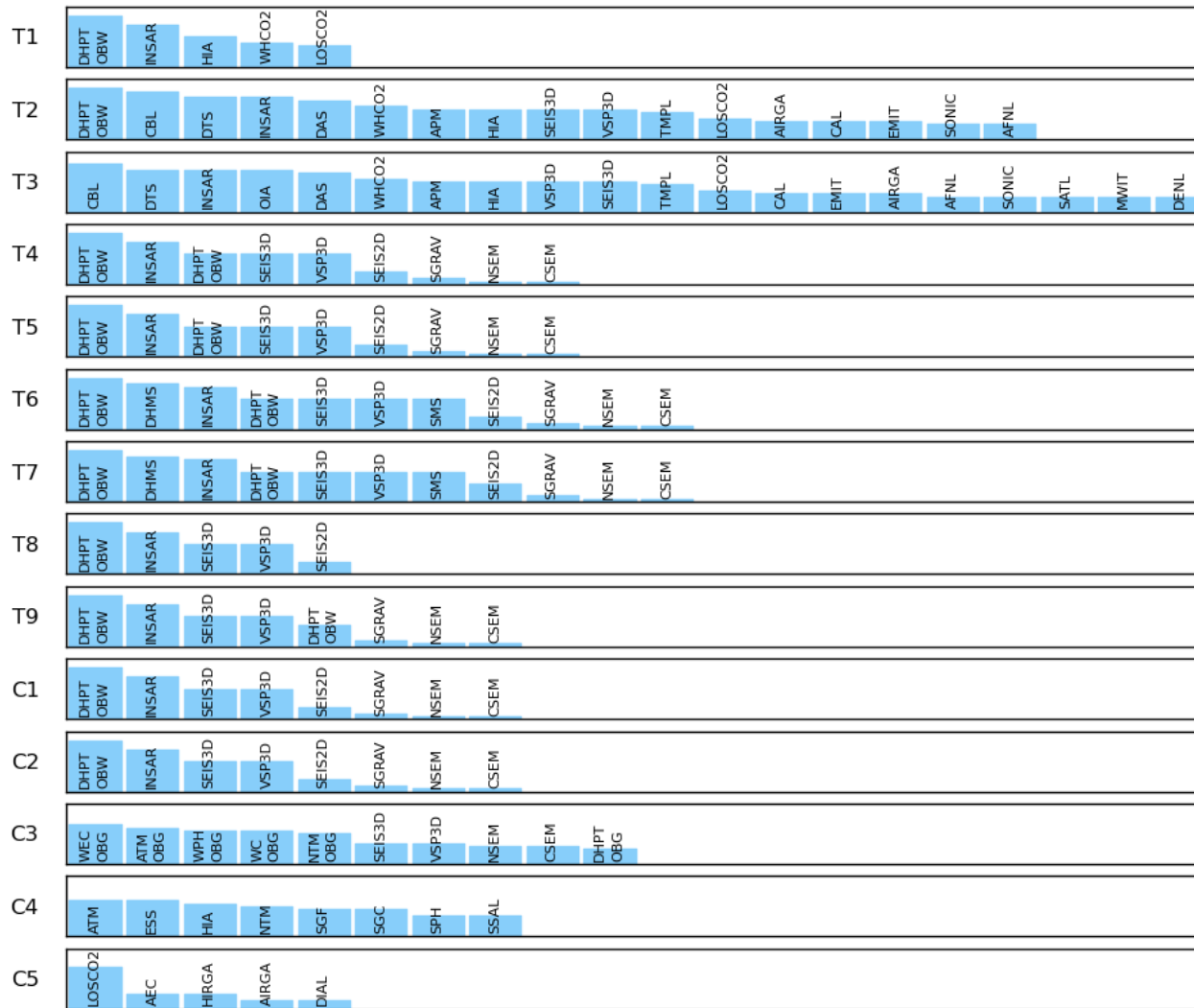
Table 6-3 Monitoring Technologies – Technical Capabilities (cont’d)

Monitoring System		Information Gained	Availability	Coverage
Geochemical Monitoring				
Water chemistry monitoring	WC	Leak detection, storage mechanisms	On demand	Monitoring wells
Down-hole electrical conductivity monitoring	WEC	Brine leak detection & impact assessment	Continuously	Monitoring wells
Downhole pH monitoring	WPH	CO2 leak detection & impact assessment	Continuously	Monitoring wells
Artificial tracer monitoring	ATM	Leak detection & impact assessment	On demand	Monitoring wells
Natural isotope tracer monitoring	NTM	Leak detection & impact assessment	on demand	Monitoring wells
U-tube fluid sampling	UTUBE	Leak detection, storage mechanisms	Continuous, or on-demand	Monitoring wells
Isotube fluid sampling	ITUBE	Leak detection, storage mechanisms	Continuous, or on-demand	Monitoring wells
Ground water gas analysis	GWG	Leak detection & impact assessment	On demand	Discrete locations across AOR
Soil CO2 gas flux surveys	SGF	CO2 leak detection & impact assessment	On demand	Discrete locations across AOR
Soil CO2 gas concentration surveys	SGC	CO2 leak detection & impact assessment	On demand	Discrete locations across AOR
Soil pH surveys	SPH	CO2 leak detection & impact assessment	On demand	Discrete locations across AOR
Soil salinity surveys	SSAL	Brine leak detection & impact assessment	On demand	Discrete locations across AOR

Table 6-3 Monitoring Technologies – Technical Capabilities (cont’d)

Monitoring System		Information Gained	Availability	Coverage
Geophysical Monitoring				
Time-lapse 3D vertical seismic profiling	VSP3D	3D distribution of CO2 plume	On demand, winter only	Within 1km of the wellbore
Time-lapse surface 3D seismic	SEIS3D	3D distribution of CO2 plume	On demand, winter only	Entire CO2 plume
Time-lapse surface 2D seismic	SEIS2D	2D distribution of CO2 plume	On demand, winter only	Entire CO2 plume
Surface microseismic monitoring	SMS	Microseismic catalogue	Continuously, or on demand	Underneath geophone array
Down-hole microseismic monitoring	DHMS	Microseismic catalogue	Continuously, or on demand	<600m of monitoring well geophones
Time-lapse surface microgravity	SRAV	Areal distribution of CO2 plume	On demand	Entire CO2 plume
Time-lapse down-hole microgravity	DHGRAV	Detection of CO2 plume near borehole	On demand	Monitoring wells
Time-lapse surface controlled source EM	CSEM	Spatial distribution of CO2 plume	On demand, winter only	Entire CO2 plume
Time-lapse cross-well controlled source EM	CSEM-X	Cross-well distribution of CO2 plume	On demand	Section between wells within c. 500m
Time-lapse cross-well seismic	SEIS-X	2D distribution of CO2 plume	On demand	Section between wells within c. 500m
Magnetotelluric - natural source EM	NSEM	Spatial distribution of CO2 plume	On demand, winter only	Entire CO2 plume
InSAR - Interferometric Synthetic Aperture Radar	INSAR	Pressure front & fault re-activation	Monthly	Entire region of elevated pressure
GPS - Global Positioning System	GPS	Pressure front & fault re-activation	Continuously or on demand	Entire region of elevated pressure
Surface tiltmeters	STLT	Pressure front & fault re-activation	Continuously	Entire region of elevated pressure
Down-hole tiltmeters	DHTLT	Vertical distribution of pressure changes	Continuously	Monitoring wells
Surface Monitoring				
DIAL - Differential absorption LIDAR	DIAL	CO2 leakage rate to atmosphere	On demand	Areal coverage over parts of AOR
Line-of-sight gas flux monitoring	LOSCO2	CO2 leakage rate to atmosphere	Continuously or on demand	Areal coverage over parts of AOR
Atmospheric eddy correlation	AEC	CO2 leakage rate to atmosphere	On demand	Discrete locations across AOR
Airborne infra-red laser gas analysis	AIRGA	CO2 leakage rate to atmosphere	On demand	Areal coverage of entire AOR
Hand-held infra-red gas analysers	HIRGA	Leak detection & impact assessment	On demand	Discrete locations across AOR
Satellite or airborne hyperspectral image analysis	HIA	Leak detection & impact assessment	Monthly	Entire AOR and beyond
Ecosystem studies	ESS	Leak detection & impact assessment	On demand	Discrete locations across AOR

NOTE: The monitoring technologies considered for MMV have a diverse and overlapping range of technical capabilities.



NOTE: Monitoring technologies ranked according to their expected effectiveness for each containment monitoring task described in Table 6-3 demonstrate a wide range of viable options exists. The height of each blue bar denotes the expected success rate from 0 to 100%.

Figure 6-1 Ranked Monitoring Technologies for Containment



NOTE: As in Figure 6-1, except for the two key conformance monitoring tasks: measure the distribution of CO₂ inside the BCS (S01), and measure the distribution of pressure inside the BCS (S02).

Figure 6-2 **Ranked Monitoring Technologies for Conformance**

6.4.5 Technology Ranking

Monitoring for containment is a safety-critical task and takes precedence over conformance monitoring. Therefore, technology ranking considers only the benefits and costs of each technology in relation to the conformance monitoring tasks. [Figure 6-3](#) shows the ranking of each monitoring option according to a combined evaluation of benefits and costs. This cost-benefit assessment is the basis for selecting technologies to perform the containment monitoring tasks. Many of these monitoring technologies will also support the conformance monitoring tasks at the same time for no additional cost. Should, however, some additional monitoring be required to satisfy all the conformance monitoring tasks then these must be justified by a value of information assessment on a case-by-case basis.

6.4.5.1 Ranking Benefits

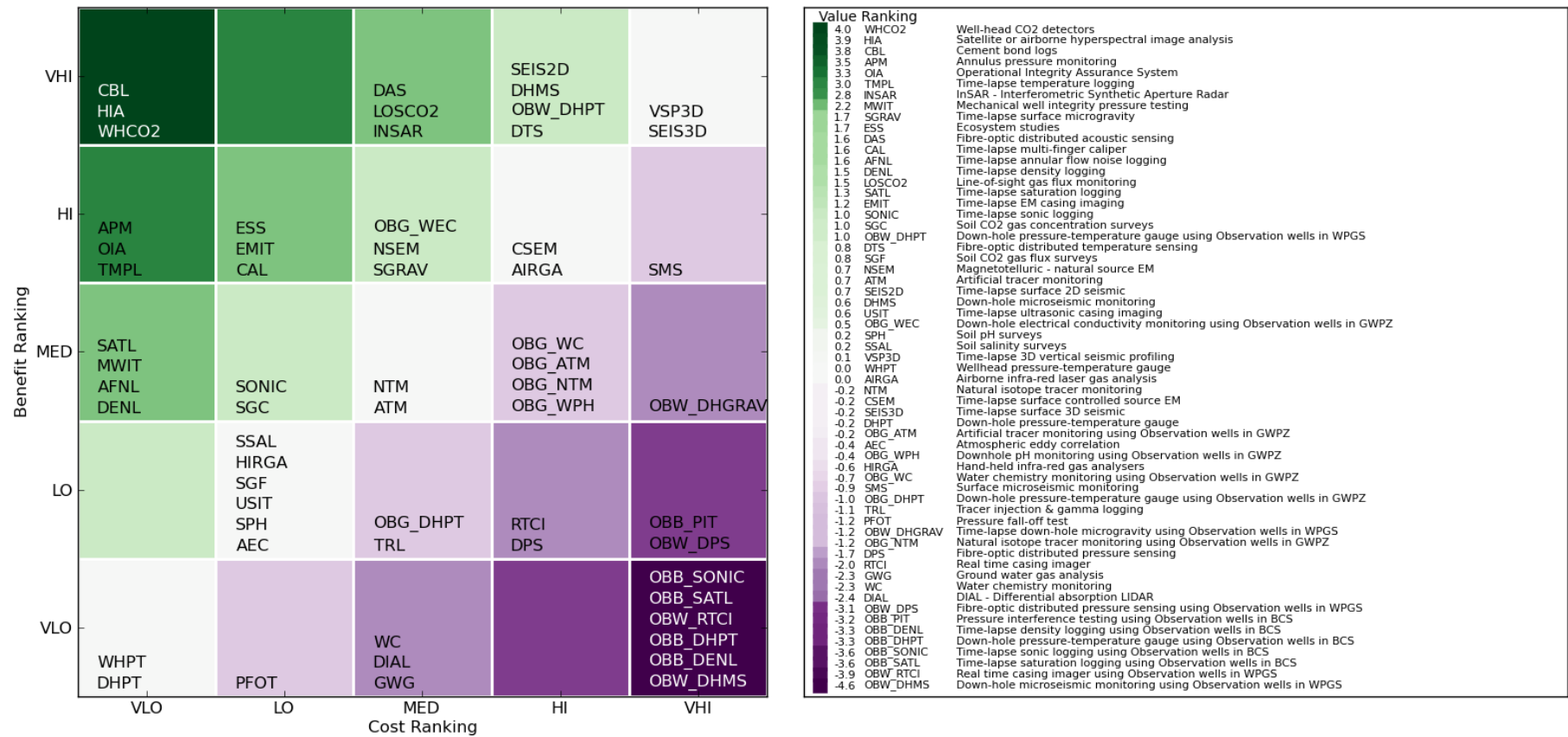
Individual monitoring systems may be applicable to multiple tasks. For instance, time-lapse seismic methods might be highly effective at monitoring the conformance of CO₂ inside the BCS and partially effective at a range of different containment monitoring tasks. The metric used for estimating the total benefit of each technology is simply the number of monitoring tasks weighted by their expected likelihood of success. This is a simple measure useful only for comparing the relative benefits of each technology assuming all monitoring tasks are equally important. This ranking is sufficient to support the matching of monitoring technologies with the active safeguards described in [Section 7.3.2](#).

6.4.5.2 Ranking Costs

The estimated lifecycle costs for each monitoring technology depends on the notional acquisition schedule shown in [Table 6-5](#). Estimates of any initial capital costs and the subsequent operating costs relied on current local market conditions. [Figure 6-3](#) shows the resulting cost ranking. These estimates are not final and remain subject to change.

[Figure 6-3](#) shows a good distribution of costs and benefits. Not all high-benefit technologies are also high cost and several high-cost technologies deliver little benefit. Some care is required when interpreting this 5-by-5 matrix as differences of less than 20% may disappear.

The criteria for selecting monitoring technologies cannot translate to a dividing line on this matrix with everything above the line *in* and everything else *out*. The prime reason for this is that not all technologies are independent, for instance if time-lapse VSP fails then so will 2D and 3D surface seismic. Moreover, if time-lapse 3D surface seismic succeeds then 2D surface seismic provides no new information. Allowance for these inter-dependencies is essential and once again relies on expert judgement.



NOTE: Ranking of monitoring technology options according to a combined evaluation of benefits and costs. Colours denote the difference between the benefit and cost rankings as an indicator of value.

Figure 6-3 Cost Benefit Ranking of MMV Technologies

Table 6-5 Preliminary Monitoring Schedule

Monitoring Systems		Quantity	Frequency	Frequency	Frequency	Frequency
			1	2	3	4
Wells						
Injection wells	INJ	5	-	-	-	-
Observation wells in BCS	OBB	5	-	-	-	-
Observation wells in WPGS	OBW	5	-	-	-	-
Observation wells in GWPZ	OBG	15	-	-	-	-
In-Well Monitoring						
Cement bond logs	CBL	10	Once	-	-	-
Time-lapse ultrasonic casing imaging	USIT	10	Once	Every 5 years	Every 10 years	-
Time-lapse EM casing imaging	EMIT	10	Once	Every 5 years	Every 10 years	-
Time-lapse multi-finger caliper	CAL	10	Once	Every 5 years	Every 10 years	-
Annulus pressure monitoring	APM	10	Continuous	Continuous	Continuous	-
Injection rate metering	IRM	5	-	Continuous	-	-
Wellhead pressure-temperature gauge	WHPT	5	-	Continuous	Continuous	-
Operational Integrity Assurance system	OIA		-	Continuous	-	-
Down-hole pressure-temperature gauge	DHPT	10	-	Continuous	Continuous	-
Mechanical well integrity pressure testing	MWIT	5	Once	Every year	Every year	-
Well-head CO2 detectors	WHCO2	10	-	Continuous	Continuous	-
Tracer injection / wireline logging	TRL	1	-	Every 5 years	Every 10 years	-
Time-lapse saturation logging	SATL	10	-	Every 5 years	Every 10 years	-
Time-lapse temperature logging	TMPL	10	-	Every 5 years	Every 10 years	-
Time-lapse annular flow noise logging	AFNL	10	-	Every 5 years	Every 10 years	-
Time-lapse density logging	DENL	10	-	Every 5 years	Every 10 years	-
Time-lapse sonic logging	SONIC	10	-	Every 5 years	Every 10 years	-
Fibre-optic distributed temperature sensing	DTS	10	Continuous	Continuous	Continuous	-
Fibre-optic distributed pressure sensing	DPS	10	Continuous	Continuous	Continuous	-
Real time casing imager	RTCI	10	Continuous	Continuous	Continuous	-
Fibre-optic distributed acoustic sensing	DAS	10	Continuous	Continuous	Continuous	-
Pressure interference testing	PIT	5	-	Every year	Every year	-
Pressure fall-off test	PFOT	5	-	Every year	Every year	-

Table 6-5 Preliminary Monitoring Schedule (cont'd)

Monitoring Systems		Quantity	Frequency 1	Frequency 2	Frequency 3	Frequency 4
Geochemical Monitoring						
Water chemistry monitoring	WC	15	Every year	Every year	Every 2 years	-
Down-hole electrical conductivity monitoring	WEC	15	Continuous	Continuous	Continuous	-
Downhole pH monitoring	WPH	15	Continuous	Continuous	Continuous	-
Artificial tracer monitoring	ATM	1	Every year	Every year	Every 2 years	-
Natural isotope tracer monitoring	NTM	15	Every year	Every year	Every 2 years	-
U-tube fluid sampling	UTUBE	5	Every year	Every year	Every 2 years	-
Isotube fluid sampling	ITUBE	5	Every year	Every year	Every 2 years	-
Ground water gas monitoring	GWG	15	Every year	Every year	Every 2 years	-
Soil gas flux monitoring	SGF	1	Every year	Every year	Every 2 years	-
Soil gas concentration monitoring	SGC	1	Every year	Every year	Every 2 years	-
Soil pH surveys	SPH	1	Every year	Every year	Every 2 years	-
Soil salinity surveys	SSAL	1	Every year	Every year	Every 2 years	-

Table 6-5 Preliminary Monitoring Schedule (cont'd)

Monitoring Systems		Quantity	Frequency	Frequency	Frequency	Frequency
			1	2	3	4
Geophysical Monitoring						
Time-lapse 3D vertical seismic profiling	VSP3D	5	Once	7 times	-	-
Time-lapse surface 3D seismic	SEIS3D	5	Once	Every 5 years	Once	-
Time-lapse surface 2D seismic	SEIS2D	5	Once	Every 5 years	Once	-
Time-lapse cross-well seismic	SEISX	5	Once	Every 5 years	Once	-
Surface microseismic monitoring	SMS	5	-	Continuously	-	-
Down-hole microseismic monitoring	DHMS	5	-	Continuously	-	-
Time-lapse surface microgravity	SGRAV	5	Once	Every 5 years	Once	-
Time-lapse down-hole microgravity	DHGRAV	5	Once	Every 5 years	Once	-
Time-lapse surface controlled source EM	CSEM	5	Once	Every 5 years	Once	-
Time-lapse cross-well controlled source EM	CSEMEX	5	Once	Every 5 years	Once	-
Magnetotelluric - natural source EM	NSEM	5	Once	Every 5 years	Once	-
InSAR - Interferometric Synthetic Aperture Radar	INSAR	1	Monthly	Monthly	Monthly	-
GPS - Global Positioning System	GPS	1	Continuous	Continuous	Continuous	-
Surface tiltmeters	STLT	1	Continuous	Continuous	Continuous	-
Down-hole tiltmeters	DHILT	5	Continuous	Continuous	Continuous	-
Surface Monitoring						
DIAL - Differential absorption LIDAR	DIAL	5	Continuous	Continuous	Continuous	-
Line-of-sight gas flux monitoring	LOSCO2	5	Continuous	Continuous	Continuous	-
Atmospheric eddy correlation	AEC	1	Continuous	Continuous	Continuous	-
Airborne infra-red laser gas analysis	AIRGA	1	Once	Every year	Every 2 years	-
Hand-held infra-red gas analysers	HIRGA	1	Every year	Every year	Every 2 years	-
Satellite or airborne hyperspectral image analysis	HIA	1	Every year	Every year	Every 2 years	-
Ecosystem studies	ESS	1	Every year	Every year	Every 2 years	-

NOTE: This preliminary schedule of monitoring for each candidate technology is the basis for estimating life-cycle monitoring costs. Monitoring frequencies were adapted to suit the different requirements of each MMV time period: 1. pre-injection phase, 2. injection phase, 3. closure phase, and 4. post-closure phase. This example is for the development scenario of 5 injection wells and assumes without commitment an equal number of Winnipegosis or BCS monitoring wells and three times this number of groundwater monitoring wells. The MMV program will be selected from these options and the monitoring schedule will be revised again at that time.

6.4.6 Description of Notable Technologies

The remainder of this section describes some of the more notable technologies in more detail.

- **Down-hole pressure gauges** (DHPT) within observation wells completed in the Winnipegosis (OBW) would provide continuous monitoring. Any sustained pressure rise above both the established level of natural variations and the known drift rate of the gauge may provide an early indication of loss of containment. The sensitivity of a pressure gauge is 0.2 parts per million (corresponding to 3 Pa in the Winnipegosis), with an expected drift rate of 0.7 Pa per annum. If the hydraulic properties of the Winnipegosis measured by appraisal wells are representative then fluids entering this formation through a point source can be detected if the rate exceeds 3-30 kg/day, corresponding to 1-10 parts per million of the daily injected volume. The duration of fluid escape prior to detection could be 25 to 150 days for a gauge located 2 to 3 km from the source. No other method is likely to exceed the speed and sensitivity of this detection capability. The Winnipegosis is a carbonate, so there is a possibility of low permeability zones between the source and the gauge allowing fluids to escape undetected. If ongoing appraisal of the Winnipegosis indicates this risk is unacceptable then the Cooking Lake aquifer offers an alternative. The observation well design will support the option to plug the Winnipegosis interval and re-complete within the Cooking Lake aquifer.
- **InSAR** delivers monthly monitoring of surface displacements with millimetre precision over the entire AOR. Surface displacements induced by subsurface volume increases accompanying increased pore fluid pressure are readily detectable by InSAR. Lateral resolution of a detected subsurface anomaly depends on signal-to-noise but is likely 0.5 to 1.0 of the depth of the anomaly. Any fluids escaping above the ultimate seal will generate a localized surface uplift anomaly inconsistent with any possible anomaly due to stored fluid volumes below the primary seal. Detecting the former and distinguishing it from the latter provides an early indication of any loss of containment throughout the AOR. The smallest detectable mass of escaped fluids is likely 100,000 to 200,000 tonnes corresponding to 0.4 to 0.8% of the CO₂ mass planned for injection over 25 years. Considerable uncertainty about the bulk compressibility means this result may change following ongoing appraisal activities.
- Surface displacement distributions consistent with volume changes inside the BCS provide a good indication of pressure migration within the storage complex and its conformance with model-based predictions. Indications of unexpected pressure migration towards any potential migration pathways such as legacy wells indicate an increased threat to containment. Any step-like anomalies within the distribution of surface displacements provide a good indication of fault re-activation, revealing the location, strike, dip, burial depth, and rate of slip. Other distinctive anomalies may indicate and characterize any widespread opening of fractures.
- **Time-lapse seismic** should image the CO₂ plume but be insensitive to the displaced brine. Inside the plume, CO₂ likely replaces about 40% of the initial pore fluids and due to its higher compressibility causes a reduction in the bulk p-wave velocity of about 8% relative to the initial brine saturated. The difference between two seismic surveys, one acquired before injection and the other sometime later, will show increased reflection amplitudes from the top of the basement in places where CO₂ resides in the overlying BCS. The expected repeatability of these measurements is about 20% (normalized root-mean-square). Calculations to simulate this time-lapse

seismic response based on appraisal data indicate 10,000 to 60,000 tonnes of CO₂ is detectable above the noise with a lateral and vertical resolution of about 25 m and 10 m respectively. If the available appraisal data are not representative and seismic repeatability is much worse than anticipated, then time-lapse seismic may fail to detect any change no matter how large the CO₂ plume.

- During the first period of injection, 3D vertical seismic profiles (VSP3D) provide a cost-effective means of acquiring time-lapse seismic around each injector. Depending on reservoir properties and the rate of injection, the CO₂ plume may exit the region imaged by VSP after 2 to 15 years. Thereafter, 3D surface seismic surveys will be required to track the CO₂ plumes at considerably greater expense and therefore a much-reduced frequency. According to the rate of expected CO₂ movements, 3D VSP surveys might be appropriate every 1 to 3 years followed by 3D surface seismic surveys every 5 to 10 years. The final 3D surface seismic survey would be planned a couple of years prior to closure so that conformance can be proven.
- **Distributed temperature and acoustic noise monitoring** using fibre-optics permanently installed in injectors would provide a continuous capability to detect any fluids migrating upwards outside the casing. The risk to well integrity is minimized by placing the control line housing the fibres in-between two casing strings to eliminate any obstacles to obtaining a good quality cement bond between the outside casing and the formation. Monitoring different optical properties along these fibres yields measurements of temperature and acoustic noise with a resolution of 1 to 10 m. The injected CO₂ will be 25 to 47°C cooler than in-situ temperatures providing a clear temperature signal in the event of any fluids migrating upwards outside the casing. Low mass flux rates are harder to detect. Dynamic models of heat transport for this process indicate flux rates of just 3 kg per day should be detectable. Acoustic noise generated by fluid flow outside the casing provides an independent detection opportunity – sensitivity in this case depends on the rate and turbulence of the flow.
- **Down-hole electrical conductivity and pH monitoring** within groundwater observation wells can provide continuous monitoring for any impacts to existing water quality due to CO₂ or brine ingress. Annual fluid sampling, or more frequently if the continuous data indicate a need, should provide highly sensitive measurements of any water chemistry changes.
- **Line-of-sight CO₂ gas flux monitoring** is able to continuously map the areal distribution of any CO₂ emissions from the storage complex into the atmosphere. This system measures CO₂ concentrations according to the differential absorption of a laser beam at frequencies tuned to those absorbed by CO₂ molecules. This system uses many different fixed paths between a central laser and a network of surrounding corner reflectors. Measurement of wind vectors and inversion of all these data using a model for CO₂ advection and dispersion yields the distribution of CO₂ flux rates. A recent pilot successfully demonstrated this new technology.
- Numerical simulations indicate this system should detect CO₂ emission rates of 3 kg/hour over a 2-by-2 km area. A larger version capable of monitoring a 6-by-6 km area should be able to detect 250 kg/hour. This is sufficient to cover much more than the surface projection of the CO₂ plume expected around a single injector after 25 years of injection. For a five well system that injected 25 million tonnes of CO₂ after 25 years, each of the five separate CO₂ plumes contains 5 million tonnes so the smaller and larger monitoring systems will detect any CO₂ emissions exceeding 5 or 440 ppm per annum, respectively.

6.5 Conceptual Base-Case Monitoring Plan

As new information about storage and monitoring performance becomes available through time, the MMV base-case plan shall be adapted using the process described in [Section 6.5](#) and Section 7.6. The initial base-case monitoring will be finalized at the same time as the Field Development Plan once the ongoing appraisal process concludes. Consequently, the base-case plan described below is conceptual. This conceptual plan does not constitute a commitment and will be subject to change in response to the final appraisal information. These changes will affect the shape and the content of the MMV plan but not the outcomes, which must still meet the performance targets.

[Figure 6-4](#) summarizes the conceptual MMV plan. The schedule of monitoring activities shown covers the four monitoring domains (atmosphere, biosphere, hydrosphere, and geosphere) and wells associated with the Project that cross cut all these domains. This figure also shows how the expected schedule changes for each activity between the four time phases for MMV (pre-injection, injection, closure, and post-closure). This schedule combines continuous monitoring using permanent sensors and discrete monitoring activities to gain additional information periodically. In this example, many in-well monitoring activities continue to the end of the closure period. This is contingent on abandonment of these wells only happening at the end of the closure period. There may be greater benefits to earlier abandonment to allow for post-abandonment monitoring but this likely requires the removal of bottom-hole sensors and the loss of direct monitoring inside the BCS. This decision will likely depend on actual storage performance during injection and early part of the closure period.

6.5.1 Injection Well Monitoring Plan

An initial cement bond log (CBL), annual mechanical well integrity tests (MWIT), repeat casing integrity logs (USIT) every 5 years, and continuous annulus pressure monitoring (APM) and well-head CO₂ monitoring (WHCO₂) provide ongoing direct verification of well integrity during the injection period. During the closure period, APM, WHCO₂ and MWIT continue as before, but USIT only occurs once just prior to well abandonment.

Injection rate metering (IRM) at the wellhead, and pressure and temperature monitoring at the wellhead (WHPT) and at the BCS injection interval (DHPT) provide continuous measurements throughout the injection period. Once injection stops, only WHPT and DHPT continue until well abandonment. Permanent fibre-optic sensors support continuous distributed temperature and acoustic sensing (DTS and DAS) to verify the absence of any fluids migrating upwards outside the casing. These measurements start just before CO₂ injection and end just before site closure. An operational integrity assurance system will combine all these continuous streams of data to provide an exception-based monitoring capability that automatically generates an early warning of potential loss of well integrity.

During the closure phase, the injection well infrastructure would also support the opportunity for low cost data acquisition through potential logging and sampling to verify the CO₂ storage mechanism in the BCS.

Finally, each injector may support the repeated injection of an artificial tracer.

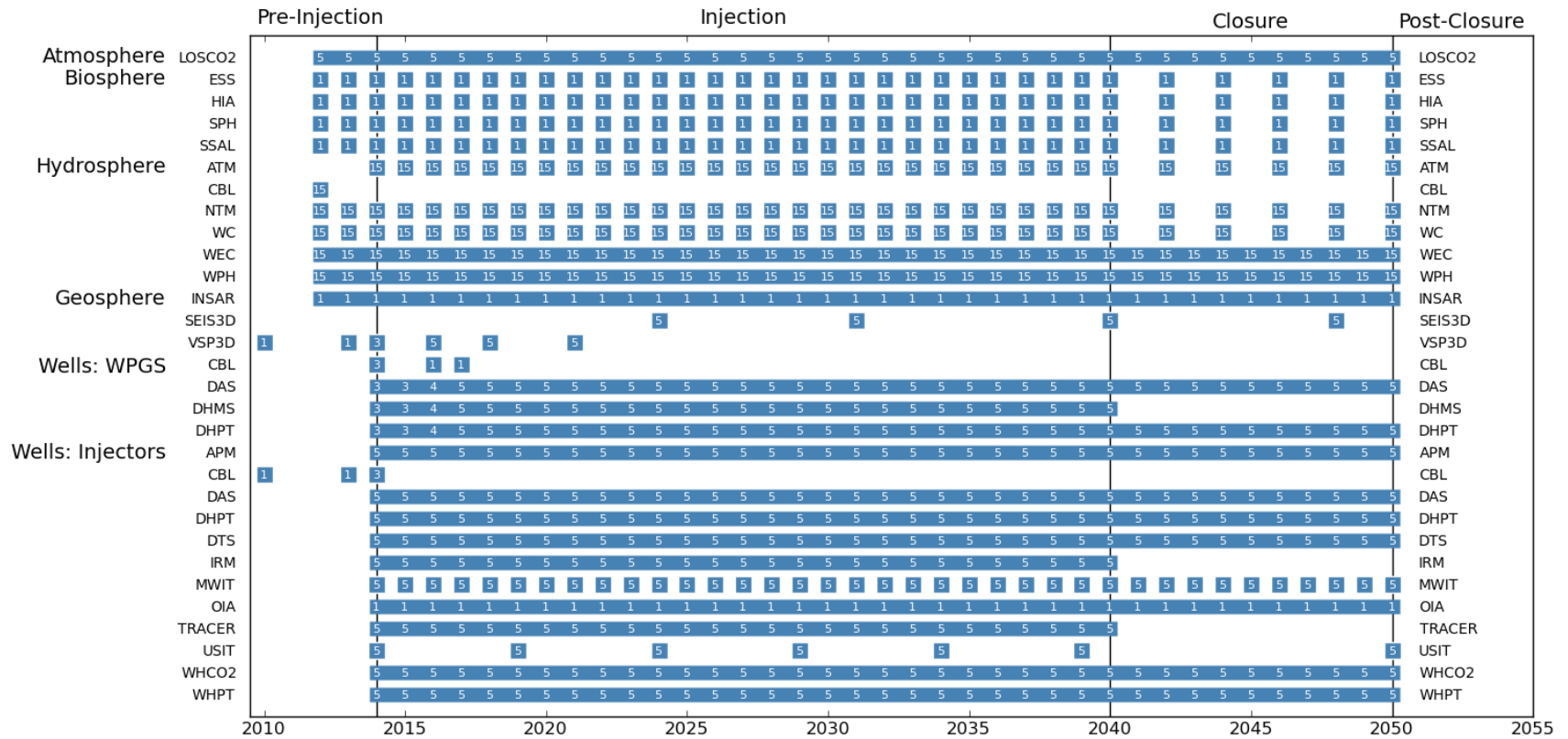


Figure 6-4 Schedule of Measurement, Monitoring and Verification Activities

6.5.2 Geosphere Monitoring Plan

The geosphere monitoring system comprises a balance between non-invasive remote sensing methods and in-well measurements directly above the ultimate seal within the Winnipegosis formation.

- InSAR provides essentially continuous monitoring of the footprint of pressure changes inside the BCS and time-lapse seismic (VSP3D, SEIS3D) tracks the CO₂ plume moving behind this pressure front. InSAR requires two years of monitoring prior to CO₂ injection to establish a baseline.
- Time-lapse seismic requires a single survey prior to CO₂ injection as a baseline. These baseline data for surface seismic do not appear in the MMV schedule as the design of the appraisal seismic surveys also supports time-lapse seismic. For the time-lapse VSP's the baseline will be acquired at the time of drilling. The interval between VSP surveys starts small and lengthens in line with the rate of expected advance of the CO₂ front. Once the CO₂ front extends beyond the VSP image area, time-lapse seismic monitoring continues at the surface with the last survey scheduled two years prior to site closure to ensure the interpreted results are available to support the site closure process.
- Sensors inside Winnipegosis observation wells provide continuous pressure monitoring to detect any early signs of fluids escaping above the ultimate seal.
- Down-hole microseismic monitoring (DHMS) should detect any early signs of fractures propagating towards the ultimate seal or fault re-activation.
- A CBL and DTS or DAS within these wells provide a means of verifying well integrity.

6.5.3 Hydrosphere Monitoring Plan

Groundwater monitoring wells completed at least two years prior to CO₂ injection support continuous electrical conductivity (WEC) and pH (WPH) monitoring of the ground water to establish a baseline and to verify the absence of significant impacts to groundwater quality throughout the injection and closure periods. Fluid sampling and laboratory analysis of water chemistry start with annual measurements two years prior to CO₂ injection and continue with measurements every two years throughout the closure period. Analysing these same fluids samples for natural and potentially artificial tracers follows the same schedule with the exception that artificial tracers do not require any baseline data.

6.5.4 Biosphere Monitoring Plan

Ecosystem studies (ESS), hyper-spectral image analysis (HIA), and soil pH (SPH) and salinity (SSAL) annual monitoring for two years prior to CO₂ injection will establish a sufficient baseline. Monitoring during injection generates the information necessary to verify the absence of any significant impacts to the biosphere or to trigger corrective controls measures if necessary. During the closure period, bi-annual monitoring is sufficient as average pressures inside the storage complex will decrease and the forces driving migration of the CO₂ plume and BCS brine become much smaller.

6.5.5 Atmosphere Monitoring Plan

Line-of-sight CO₂ flux monitoring (LOSCO₂) provides continuous monitoring of any material CO₂ flux from the storage complex into the atmosphere. Installation of these sensors systems two years prior to the start of CO₂ injection will generate baseline data sufficient to understand existing CO₂ fluxes including any seasonal variations. The background variations may be larger than expected due to the site location within Alberta's Industrial Heartland. In this case, baseline data shall provide the evidence to motivate revising the CO₂ inventory reporting performance target. The ability to relocate these monitoring systems from time-to-time allows opportunities for occasional temporary monitoring outside the expected surface footprint of the subsurface CO₂ plume.

6.6 Contingency Monitoring Plan

The initial MMV plan includes monitoring to support corrective safeguards as shown on the right-hand side of the bowtie. However, not all monitoring efforts will be part of the initial MMV plan – some efforts are only activated (contingent) on detecting signs of unexpected storage or monitoring performance.

Contingency monitoring arises through adaption of the MMV plan to changing circumstances as previously described. One aspect of this contingency monitoring is the need to characterize any impacts or to verify the effectiveness of any remediation measures in the unlikely event of any loss of containment. Time-lapse seismic methods are a natural choice.

- time-lapse seismic likely delivers the required coverage and sensitivity
- base-case activities will generate the necessary seismic baseline data
- seismic acquisition can often proceed with only a limited lead-time
- replicate seismic processing methods already proven by base-case activities

Another aspect of contingency monitoring is preparation of alternative monitoring systems as potential replacements for any under-performing monitoring technologies. Key example of this are:

- The preference to deliver conformance monitoring through non-invasive geophysical techniques, i.e. time-lapse seismic methods and InSAR. Should one or both of these methods prove insufficient within the first 5 years of injection then there remains the opportunity to drill observation wells into the BCS to acquire direct measurements of pressure and ultimately CO₂ build-up at a very limited number of discrete locations. In this situation, the additional risk to containment created by drilling further wells through all geological seals at the center of the storage complex is unavoidable without forfeiting some requirements for conformance monitoring. In selecting this option, the same active safeguards identified to ensure long-term integrity of injectors should also protect these BCS observation wells.
- If InSAR monitoring of natural scatterers proves insufficient there remains the opportunity to deploy corner reflectors to ensure sufficient reliable monitoring targets.

One final aspect of contingency monitoring is to optimize the deployment of high-cost monitoring technologies such as time-lapse seismic. Time-lapse VSP surveys should track the CO₂ plume for the first 4-16 years depending on injectivity performance. According to results obtained from these VSP data and updated model-based predictions for the short-term advance of the CO₂ plume, the switch to more expensive surface seismic methods will be delayed as long as possible without any loss of information.

6.7 Technology Qualification

Technology qualification is a process to reduce the risk of relying on unreliable monitoring technologies without creating additional monitoring costs. Technologies may become qualified through examination of a documented set of activities to prove the technology meets the specified requirements for its intended use. DNV (2010) describes a technology qualification process for the selection and qualification of geological storage sites for CO₂. This process is flexible enough to allow the use of emerging new technologies and structured enough to allow regulatory control if required. This same process is also appropriate to qualify monitoring technologies for MMV.

Qualification of an individual technology requires the following steps.

1. Define the performance criteria for qualification
2. Document the performance evidence
3. Evaluate the evidence against the criteria

This process shall be followed at the time of selecting the initial MMV plan and again before including alternative technologies in any revised MMV plan.

7 Revised Storage Performance Evaluation

This section describes the expected improvement in storage performance gained through MMV activities. The goal here is to demonstrate that residual containment risks after MMV are broadly acceptable or at least tolerable and as low as reasonably practicable.

7.1 Assessment of Additional Safeguards

7.1.1 Conformance Safeguards

The result of evaluating a wide range of different technologies against the identified tasks for conformance monitoring is that several effective options exist to meet the proposed performance targets.

- **Site Closure:** Time-lapse seismic methods and InSAR that respectively provide indicators of CO₂ and pressure development inside the BCS storage complex should satisfy the first performance target for site closure. These are both non-invasive techniques with zero threat to containment. If within the first five years of CO₂ injection the performance of these two monitoring methods proves insufficient there is still the opportunity to drill observation wells into the BCS to provide direct measurement of pressure and ultimately CO₂ development at a very limited number of locations to still satisfy the performance target. Deploying safeguards in these observation wells similar to those already identified for injectors will help ensure containment.

The second performance target shall be satisfied through extensive monitoring under the program of MMV activities to ensure containment.

- **Storage Efficiency:** The strategy described above for monitoring pressure and CO₂ development satisfies the performance target for storage efficiency as well. In combination with frequent bottom-hole pressure measurements in the wells themselves, which can be used to constrain and history match reservoir models.
- **CO₂ Inventory:** A fiscal meter located where the CO₂ pipeline leaves the Scotford site, wellhead injection meters and the combination of wellhead and bottom-hole pressure gauges will satisfy existing regulatory requirements for measuring the injected volume of CO₂ with a maximum monthly uncertainty of 5%. There are also opportunities to adopt emerging new technology for measuring any CO₂ emissions from the storage site into the atmosphere with at least the same maximum uncertainty. Together these monitoring systems will satisfy the proposed performance target for CO₂ inventory reporting.

7.1.2 Containment Safeguards

Assessment of containment safeguards follows the bowtie approach again to provide a more detailed analysis of these safety-critical risks. For increasing numbers of safeguards, we will estimate the reduced likelihood or impact of each consequence, and the sensitivity to uncertainty about the effectiveness of each safeguard:

- The top ranking uncertainties remain as before related to the geological formations overlying the BCS storage complex.
 - Ongoing appraisal activities will reduce these uncertainties.
 - Therefore, this MMV plan should be revisited once the appraisal program has concluded.
 - The next group of influential uncertainties concern many of the top ranking monitoring technologies.
 - Some of these uncertainties may reduce through ongoing technical feasibility studies.
 - Others may reduce through early field trials, potentially as part of the program of baseline monitoring prior to CO₂ injection.
 - Others still may only reduce during the first 5 years of CO₂ injections, e.g. time-lapse seismic methods.

8 Reporting

Quest will integrate within existing operations. As such, much of the environmental monitoring data and operational performance will be reported and communicated through existing mechanisms. Shell expects that Quest will also require additional reporting not currently completed at the Scotford Upgrader.

8.1 Scotford Upgrader Current Reporting Requirements

The following is a list of current reporting requirements for the Scotford Upgrader that will likely be expanded to include the performance and emissions of Quest:

- Monthly and Annual Air report, AENV
- Annual Operations Report and meeting, ERCB
- Annual GHG reporting, SGER, AENV
- Annual GHG reporting, CEPA, Environment Canada
- NPRI, Environment Canada
- Annual Groundwater Report, AENV
- Annual and monthly production reporting, ERCB

8.2 Anticipated Additional Reporting Requirements

It is expected that Quest will also require additional reporting including but not limited to the following:

1. An annual progress report similar to that in accordance with ERCB Directives 7 and 17 and a monthly report of volumes injected to the Petroleum Registry of Alberta. Uncertainty in the monthly volume of injected CO₂ reported will not exceed 5%.
 - This shall be published within 6 months of the expiration of each calendar year. This report shall include but is not limited to, the following:
 - A table of the injected volume of gas on a monthly, annual and cumulative basis, since start-up
 - A table and plot of the net volume of gas stored on a monthly basis
 - A table and plot showing the monthly injection rates
 - A plot of both bottom hole reservoir pressures and wellhead injection pressures, along with a summary of any pressure test data obtained and the results and evaluations of all bottom-hole pressure surveys conducted, during the reporting period
 - A gas analysis representative of the composition of the gas injected during the reporting period
 - A discussion of the volume of gas injected into the storage site

- A summary of any change or modification in the operation of the Project, including well work-overs, recompletions and suspensions, or any surface facility operations during the reporting period
 - Results and evaluation of all monitoring done during the reporting period
2. Annual performance reporting to NRCAN and Alberta Department of Energy. The format and content of this report will be determined as discussions with both of these agencies continue.
 3. An annual report summarizing the results of the MMV program including detection of leaks (chronic and acute). There are many possible formats for communicating this information including using a third party auditor and, or external review panel, as an example. The final program, format to be presented publically, audience and frequency of publication will be developed as the project and associated consultation progresses.

8.3 Communication Venues

The Scotford Complex has a number of mechanism and forums in which Shell communicates with the public giving and receiving information pertaining to the performance. This includes:

- Community Newsletter- once per quarter
- Community Meeting- once per year
- Report to the community- once every 2 years

Information on the performance of Quest will be integrated into these reporting venues.

Scotford also has an Emergency Response Plan that is activated in the event of an emergency. The Project is developing a stand-alone ERP for wells and pipeline, and will append emergency response plans for the capture infrastructure to the existing Scotford site ERP, prior to operations. In the event there is a release of CO₂, the appropriate plans will be activated.

8.4 Multi-stakeholder Groups

Shell Canada Energy as operators of the Scotford Upgrader, participates in a number of regional groups including, but not limited to:

- The Fort Air Partnership which monitors ambient air quality,
- The NCIA which is conducting a regional groundwater study and has constructed a regional noise model and the
- Northeast Region Community Awareness and Emergency Response (NRCAER) Hotline for posting operational information of interest to community members

Shell will investigate the feasibility and appropriateness of expanding its involvement in these groups to include the Quest project.

9 Summary

The Quest Carbon Capture and Storage Project promises to make a material early contribution to reducing CO₂ emissions generated by upgrading bitumen from the Alberta oil sands. The climate benefits and societal acceptability of this Project are both largely dependent on the quality of containment achieved within the Basal Cambrian Sands storage complex.

The geology of the selected storage site offers multiple layers of protection to prevent any CO₂ or brine from causing any significant impacts to the protected groundwater zone, the ecosystem, or the atmosphere. No matter how detailed and extensive the appraisal program to characterize these geological barriers some small uncertainty and risk will remain. MMV activities will be designed to verify the absence of any significant environmental impacts due to CO₂ storage. If necessary, MMV activities will create additional safeguards by triggering control measures that will be designed to prevent or correct any loss of containment before significant impacts occur.

A systematic assessment of containment risks and the effectiveness of safeguards provided by geology, engineering and MMV demonstrated significant risk reductions so that the remaining risk is insignificant compared to everyday risks broadly accepted by society. Transfer of long-term liability will depend on the actual storage performance verified through MMV activities. MMV must demonstrate actual storage performance conforms to model-based forecasts and that these forecasts are consistent with permanent secure storage at an acceptable risk to gain climate change benefits.

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Attachment A Emerging MMV Guidelines

According to the Kyoto Protocol (1998) and the Copenhagen Accord (2010), project activities under the Clean Development Mechanism (CDM) must result in emission reductions that are “real, measurable and long-term”. CCS offers one route towards achieving such emissions reductions (IEA 2007). The Intergovernmental Panel on Climate Change (IPCC 2005) found that existing technologies are sufficient to meet these requirements for monitoring and verification of underground geological storage of CO₂.

The Greenhouse Gas Inventory Guidelines (IPCC 2006) consider underground storage sites to be a source of CO₂ emissions. This means the difference between the amount of injected and emitted CO₂ is a measure of the inventory of stored CO₂. For potential CCS CDM projects to be an effective mitigation for climate change, annual CO₂ emissions rates should be less than 0.01% of the mass of CO₂ stored underground (Hepple and Benson 2004), or perhaps less than 0.001% (Shaffer 2010). The IPCC (2006) evaluated a wide range of feasible monitoring methods for detecting emissions from an underground storage site and concluded the performance of each individual method will be site specific.

The IEA Greenhouse Gas Research and Development Program supported the development of guidelines in three key areas related to monitoring for verification of geological storage of CO₂:

1. Risk assessment (Quintessa 2004),
2. Monitoring tool selection (IEA 2006)
3. Site selection, characterization and qualification (DNV 2010a), DNV 2010b)

The latter, developed by a joint industry project (JIP) including Shell and led by Det Norske Veritas (DNV), represent the most comprehensive guidelines and examples yet for safe and sustainable geological storage of CO₂. This JIP advocates a site-specific risk-based approach.

Independently, the World Resource Institute issued general guidelines (WRI 2008) for CCS operators and regulators, including recommendations for monitoring and verifications plans to follow a site-specific risk assessment that allows flexibility to select appropriate monitoring methods adapted through time to suit the different risk profiles at each stage of the project.

A.1 Future Regulatory Expectations

The volume and time-scale of CO₂ storage required for CCS to be an effective mitigation for climate change greatly exceeds the existing experience acquired through Acid Gas Disposal projects. This necessitates the development of new standards for CCS projects. The Canadian Standards Association (CSA) and the International Performance Assessment Centre for Geologic Storage of Carbon Dioxide (IPAC-CO₂) recently announced a joint agreement to develop Canada’s first carbon capture and storage standard for the geologic storage of industrial emissions (CSA 2010). International and other national authorities, industry and environmental non-governmental organizations will most likely influence the development of these standards.

A.1.1 International Authorities

Several international authorities published guiding principles for CCS developments to aid the harmonization of standards between jurisdictions (IPCC 2005; IPCC 2006; OSPAR 2007; WRI 2008; DNV 2010a). These are likely to influence future regulations.

A.1.2 Government Authorities

Many governments are developing country-specific frameworks for CCS regulations: Australia, Brazil, Canada, China, European Union, Germany, Indonesia, Norway, Poland, Qatar, South Africa, The Netherlands, UK, and USA. Some of this initial work adds to the existing guidance from international authorities.

European Union: The European Council Directive on permanent underground CO₂ storage (European Council 2009) develops the OSPAR (2007) principles for monitoring to state the following six objectives for monitoring.

1. Demonstrate CO₂ behaves as expected.
2. Detect any migration or leakage.
3. Measure any environmental or health damage.
4. Determine effectiveness of CO₂ storage as GHG mitigation.
5. In case of leakage, assess effectiveness of corrective measures.
6. Update risk assessment and monitoring plan based on performance of the storage site.

Further monitoring requirements arise because the transfer of liability to the authorities after site closure is contingent on demonstrating the permanence of CO₂ storage according to three criteria.

1. Actual CO₂ behavior conforms to modeled behavior within range of uncertainty.
2. Absence of any detectable leaks.
3. Storage site is evolving towards long-term stability.

The European Council Monitoring and Reporting Guidelines (MRG), a draft amendment to the Emissions Trading Scheme (ETS), also stipulate additional monitoring requirements beyond the 2009 EC Directive in the instance of detecting actual emissions from the storage site to quantify the emissions and the efficacy any remediation activities.

United Kingdom: Government response to consultation on CCS (UK 2009a; UK 2009b) accepts four key clarifications of the monitoring requirements for CCS.

1. Monitoring should cover the volume affected by CO₂ storage rather than just the volume occupied by the CO₂ plume itself.
2. The post-closure period before transfer of liability will be determined individually for each project depending on the behavior of the storage site during operation based on evidence from the monitoring program.
3. The duration and type of post-transfer monitoring will be decided based on evidence from the monitoring program and will determine the 'transfer fee'.
4. Site closure includes removal of infrastructure and sealing of wells before handover to the authorities with the possible exception of some wells that may be maintained for monitoring purposes.

A subsequent study commissioned by the UK (BGS 2010) identified technologies and methodologies judged suitable for MMV in the UK.

USA: Environmental Protection Agency (EPA) consultation on Federal requirements for geological storage of CO₂ (EPA 2008) proposes a broadly similar monitoring requirements to elsewhere.

1. The Area of Review (AOR) for monitoring is considered to include the pressure front defined as the region of elevated pressures sufficient to cause movement of formation fluids into the protected groundwater zone.
2. Determination of the AOR is initially based on predictive models and should be re-determined in the event of any significant discrepancy between predicted and actual performance or within 10 years of the last determination, whichever is the sooner.
3. Monitoring the CO₂ plume and pressure front may be achieved with a combination of direct and in-direct techniques selected according to site-specific requirements.
4. Continuous monitoring of injection with automatic alarms and shut-off equipment is recommended as an important safety consideration. The EPA proposes to require down-hole safety shut-off value.
5. Duration of the site closure period is not specified but anticipated to be determined according to demonstrated performance of the storage site.

EPA (2008) proposes a quantitative risk assessment methodology as a high-level approach towards determining the suitability of sites for geological storage of CO₂. The US Department of Energy's National Energy Technology Laboratory (NETL) provide guidance for MMV (NETL 2009), including a classification of monitoring technologies according to their readiness for monitoring CO₂ storage sites.

A.1.3 Industry Authorities

Advocacy by industries and companies with relevant expertise may influence future regulations.

- **CO₂QUALSTORE:** A joint industry project (JIP) led by Det Norske Veritas (DNV) includes partners from a number of sectors; oil and gas companies (BP, BG Group, Petrobras, Shell and Statoil); energy companies (DONG Energy, RWE Dea and Vattenfall); technical consultancy and service providers (Schlumberger and Arup); the IEA Greenhouse Gas Research and Development Programme; and two Norwegian public enterprises (Gassnova/Climit and Gassco). This JIP draws together experience and good practises to generate guidelines and recommendations for geological storage of CO₂ including MMV (DNV 2010a, DNV 2010b).
- **Royal Dutch Shell** advocates that the IPCC GHG inventory guidelines (2006), the World Resource Institute guidelines (WRI 2008) and the DNV guidelines (DNV 2010a) form the basis for any MMV program.

Attachment B Analog Measurement, Monitoring and Verification Plans

Five fully-integrated, large scale CCS projects are in commercial operation today storing more than 0.5 million tonnes CO₂ per year. Four projects - Sleipner, In Salah, Snøhvit and Rangely – inject CO₂ from a natural gas production facility where it is separated from the natural gas sent to market. In the first three cases, the CO₂ is injected into saline aquifers, while in the fourth it is used for EOR. A fifth project captures CO₂ at the Great Plains Synfuels Plant and transports it for EOR to the Weyburn-Midale project. All five are contributing to the knowledge base needed for widespread CCS use. The following summary of these projects was adapted from IEA (2010).

Sleipner

The Sleipner project began in 1996 when Norway's Statoil began injecting more than 1 million tonnes a year of CO₂ under the North Sea. This CO₂ was extracted with natural gas from the offshore Sleipner gas field. In order to avoid a government-imposed carbon tax equivalent to about USD 55/tonne, Statoil built a special offshore platform to separate CO₂ from other gases. The CO₂ is re-injected about 1 000 metres below the sea floor into the Utsira saline formation located near the natural gas field. The formation is estimated to have a capacity of about 600 billion tonnes of CO₂, and is expected to continue receiving CO₂ long after natural gas extraction at Sleipner has ended.

In Salah

In August 2004, Sonatrach, the Algerian national oil and gas company, with partners BP and Statoil, began injecting about 1 million tonnes per year of CO₂ into the Krechba geologic formation near their natural gas extraction site in the Sahara Desert. The Krechba formation lies 1 800 metres below ground and is expected to receive 17 million tonnes of CO₂ over the life of the project.

Snøhvit

Europe's first liquefied natural gas (LNG) plant also captures CO₂ for injection and storage. Statoil extracts natural gas and CO₂ from the offshore Snøhvit gas field in the Barents Sea. It pipes the mixture 160 kilometres to shore for processing at its LNG plant near Hammerfest, Europe's northernmost town. Separating the CO₂ is necessary to produce LNG and the Snøhvit project captures about 700 000 tonnes a year of CO₂. Starting in 2008, the captured CO₂ is piped back to the offshore platform and injected in the Tubåsen sandstone formation 2,600 metres under the seabed and below the geologic formation from which natural gas is produced.

Rangely

The Rangely CO₂ Project has been using CO₂ for enhanced oil recovery since 1986. The Rangely Weber Sand Unit is the largest oilfield in the Rocky Mountain region and was discovered in 1933. Gas is separated and reinjected with CO₂ from the LaBarge field in Wyoming. Since 1986, approximately 23-25 million tonnes of CO₂ have been stored in the reservoir. Computer modeling suggests nearly all of it is dissolved in the formation water as aqueous CO₂ and bicarbonate. Though Rangely uses CO₂ for EOR, it is considered a CCS project insofar as it follows an MMV plan that satisfactorily assesses the viability of the long-term storage of the CO₂.

Weyburn-Midale

About 2.8 million tonnes per year of CO₂ are captured at the Great Plains Synfuels Plant in the US State of North Dakota, a coal gasification plant that produces synthetic natural gas and various chemicals. The CO₂ is transported by pipeline 320 kilometres (200 miles) across the international border into Saskatchewan, Canada and injected into depleting oil fields where it is used for EOR. Although it is a commercial project, researchers from around the world have been monitoring the injected CO₂. The IEA Greenhouse Gas R&D Programme's Weyburn-Midale CO₂ Monitoring and Storage Project was the first project to scientifically study and monitor the underground behavior of CO₂. Canada's Petroleum Technologies Research Centre manages the monitoring effort. This effort is now in the second and final phase (2007-2011), of building the necessary framework to encourage global implementation of CO₂ geological storage. The project will produce a best-practices manual for carbon injection and storage.

MMV Capability Transfer between CCS Projects

The CO₂QUALSTORE joint industry project (JIP) led by Det Norske Veritas (DNV) recently compiled a workbook of examples for underground storage of CO₂ including MMV plans (DNV 2010b). The JIP includes the following partners from a number of sectors; oil and gas companies (BP, BG Group, Petrobras, Shell and Statoil); energy companies (DONG Energy, RWE Dea and Vattenfall); technical consultancy and service providers (Schlumberger and Arup); the IEA Greenhouse Gas R&D Programme; and two Norwegian public enterprises (Gassnova/Climit and Gassco). This workbook provides guidance on how site-specific performance targets can be defined and includes practical examples of how to follow the guidance and its various steps. This workbook represents the most recent collection of shared experience and good practises applicable to MMV. This guidance and the good practises illustrated through the examples are central to the approach taken by Shell to all current CCS development projects including Quest.

Attachment C Legacy Wells

Location of Legacy Wells

Seven wells penetrate all geological seals down to the basement. None of these wells are closer than 21 km to any of the injection locations considered. The one well in the centre of the storage area is the Radway 8-19 appraisal well. The number of well penetrations through the base of the other named formations only increases significantly above the Prairie evaporite.

Abandonment Status of Legacy Wells

There are seven third-party abandoned wells penetrating the storage complex of the Quest project within the AOI. Most of the wells were completed open-hole for appraisal, notably across the BCS, and were then abandoned by installing multiple cement plugs in the open-hole section. The last well however was reconverted to become a gas storage well and then abandoned in 2007.

The available well reports do not confirm the integrity of the plugs and therefore their initial and current conditions are not known and cannot be ascertained without intervening in the wells, which is a risky and complex operation. A recent field visit confirmed there is no equipment left on site on any of these locations.

At least two wells have their deepest cement plug located above the storage complex. This creates the potential for open communication between the BCS and the Winnipegosis. However, all these wells are located more than 21 km from the planned injectors, significantly far from the expected extent of the CO₂ plume. Therefore potential CO₂ migration through these wells outside of the storage complex is very unlikely. Still, these wells are located within the AOI and although not expected, may experience a notable pressure increase ([Attachment E](#)).

There are also four third-party active gas injection wells penetrating part of the ultimate seal of the storage complex.

- Provident 16 (100-14-01-056-22W400)
- Provident 15 (100-12-01-056-22W400)
- Provident 14 (102-11-01-056-22W400)
- Provident 12 (100-11-01-056-22W401)

They have all been drilled and completed recently (2006-2009) and are still active, hence accessible for further investigation. Besides, they are all located on the edge of the AOI, therefore potential CO₂ migration through these wells outside of the storage complex is very unlikely.

Recently, three Shell wells were drilled in 2008, 2009 and 2010 penetrating the BCS as part of the appraisal phase of the Quest project. All wells are still accessible. Redwater 3-4 well will be re-entered either for abandonment or for converting it into an observation well.

Attachment D Historic Rate of Well Integrity Failures

The occurrence of sustained casing pressure is an indicator for a loss of well integrity. Of the approximately 20,000 oil and gas wells tested in Alberta, 10% experienced sustained casing pressure (Watson and S Bachu 2008). Of the 7,000 underground gas injection wells in the USA, 6% experienced sustained casing pressure, of which 90% had a leakage rate of less than 200 tonnes per year and 60% had a leakage rate of less than 35 tonnes per year (Marlow 1989).

A review of malfunctions of underground gas storage sites worldwide in depleted oil and gas fields, aquifers and salt caverns (HSE 2008) demonstrates the historical rate of well failures is less than 1 in 120,000 per well year. The modes of well failure recognized include releases through failed or leaky boreholes, casing failure and well valve failure resulting in release rates of 200 tonnes per year. This excludes sudden blowouts resulting in substantially greater release rates. Most of the operating experience comes from underground gas storage in depleted oil or gas fields with between 600,000 and 860,000 well years recorded and just five failure events identified.

Taking past performance as a guide, the likelihood of well integrity being insufficient to prevent a chronic leak is less than 1 in 120,000 for an average well in any one year.

Attachment E Changing Pressure inside the BCS

The extent of the storage AOI is guided by the expected extent of the pressure front after 25 years of injection at an average rate of 1.08 Mt/a. At that point, the pressure response in the BCS will likely extend some 20 to 30 km away from the injectors. The permeability distribution in the BCS governs the speed and directionality of the pressure front development. The injected volume and the capacity of the BCS storage complex govern the magnitude of the pressure change.

The legacy wells likely pose the greatest threat of allowing formation brine to flow out of the BCS storage complex. Therefore, site selection for the storage AOI focused on ensuring maximum offset to existing legacy wells. However, because appraisal data indicate the BCS reservoir is extensive and well connected on a regional scale, the pressure front will likely exert influence far from the injection wells. The closest BCS penetration by a legacy well (Egremont 6-36) is a distance of 21 km WSW from the Radway 8-19 location, whilst the closest up-dip legacy well (Darling No.1) is 31 km NNE of the Radway 8-19 well.

Site selection maximizes offset to existing legacy wells, but some residual risk around brine migration into intermediate aquifers overlying the BCS remains, particularly after a sustained period of injection. Given the BCS reservoir pressure (D65, Section 6.5) and in situ fluid gradient (D65, Section 6.1) a minimum incremental pressure of 3.5 MPa in the BCS is required to lift BCS brine with a density equivalent to 11.7 kPa/m into the Base of Ground Water Protection (BGWP) zone. Dynamic models for a range of subsurface scenarios indicate that the pressure increase at distances of 20 to 30 km away from the injection well locations after 25 years of injection will be less than half the pressure required to lift BCS brine up to the BGWP zone or to surface. The pressure increase from a hypothetical alternative injection scheme in the BCS would have an incremental effect on the BCS pressure so that an equivalent CCS project, equidistant from a legacy well as the Quest injectors, would double the pressure increase seen at this legacy well. In this case, legacy wells pose a greater threat to containment. A pore-space tenure AOI that essentially extends to include the closest legacy wells to the southwest and the northeast mitigates this risk. Monitoring these legacy wells may be required later in field life, particularly if additional CCS projects start operating nearby.

Attachment F Monitoring Technology Capabilities

Table 6-3 summarizes the capability of each monitoring technology considered for inclusion in the MMV plan. These technologies fall into four categories:

1. In-Well Monitoring
2. Geochemical Monitoring
3. Geophysical Monitoring
4. Surface Monitoring

Many technologies exist with independent capabilities for measuring different physical, chemical, or biological changes. Many other technologies exist with similar or overlapping capabilities. The frequency (availability) of monitoring information gained and the region of coverage are both critical factors affecting the value each technology offers for MMV. Rarely will a technology offer continuous monitoring over a broad region. More often, a choice exists between less frequent monitoring with broad coverage and more frequent monitoring with restricted coverage. These differing capabilities informed the screening and evaluation of all these technologies against the identified monitoring tasks for MMV.

