Disclaimer
This Report, including the data and information contained in this Report, is provided to you on an "as is" and "as available" basis at the sole discretion of the Government of Alberta and subject to the terms and conditions of use below (the "Terms and Conditions"). The Government of Alberta has not verified this Report for accuracy and does not warrant the accuracy of, or make any other warranties or representations regarding, this Report. Furthermore, updates to this Report may not be made available. Your use of any of this Report is at your sole and absolute risk.

This Report is provided to the Government of Alberta, and the Government of Alberta has obtained a license or other authorization for use of the Reports, from:

> Canadian Natural Upgrading Limited, Chevron Canada Limited and 1745844 Alberta Ltd., as owners, and Shell Canada Energy as operator, for the Quest Project
>
> (collectively the "Project")

Each member of the Project expressly disclaims any representation or warranty, express or implied, as to the accuracy or completeness of the material and information contained herein, and none of them shall have any liability, regardless of any negligence or fault, for any statements contained in, or for any omissions from, this Report. Under no circumstances shall the Government of Alberta or the Project be liable for any damages, claims, causes of action, losses, legal fees or expenses, or any other cost whatsoever arising out of the use of this Report or any part thereof or the use of any other data or information on this website.

Terms and Conditions of Use
Except as indicated in these Terms and Conditions, this Report and any part thereof shall not be copied, reproduced, distributed, republished, downloaded, displayed, posted or transmitted in any form or by any means, without the prior written consent of the Government of Alberta and the Project.

The Government of Alberta's intent in posting this Report is to make them available to the public for personal and non-commercial (educational) use. You may not use this Report for any other purpose. You may reproduce data and information in this Report subject to the following conditions:

- any disclaimers that appear in this Report shall be retained in their original form and applied to the data and information reproduced from this Report
- the data and information shall not be modified from its original form
- the Project shall be identified as the original source of the data and information, while this website shall be identified as the reference source, and
- the reproduction shall not be represented as an official version of the materials reproduced, nor as having been made in affiliation with or with the endorsement of the Government of Alberta or the Project

By accessing and using this Report, you agree to indemnify and hold the Government of Alberta and the Project, and their respective employees and agents, harmless from and against any and all claims, demands, actions and costs (including legal costs on a solicitor-client basis) arising out of any breach by you of these Terms and Conditions or otherwise arising out of your use or reproduction of the data and information in this Report.

Your access to and use of this Report is subject exclusively to these Terms and Conditions and any terms and conditions contained within the Report itself, all of which you shall comply with. You will not use this Report for any purpose that is unlawful or prohibited by these Terms and Conditions. You agree that any other use of this Report means you agree to be bound by these Terms and Conditions. These Terms and Conditions are subject to modification, and you agree to review them periodically for changes. If you do not accept these Terms and Conditions you agree to immediately stop accessing this Report and destroy all copies in your possession or control.

These Terms and Conditions may change at any time, and your continued use and reproduction of this Report following any changes shall be deemed to be your acceptance of such change.

If any of these Terms and Conditions should be determined to be invalid, illegal or unenforceable for any reason by any court of competent jurisdiction then the applicable provision shall be severed and the remaining provisions of these Terms and Conditions shall survive and remain in full force and effect and continue to be binding and enforceable.

These Terms and Conditions shall: (i) be governed by and construed in accordance with the laws of the province of Alberta and you hereby submit to the exclusive jurisdiction of the Alberta courts, and (ii) ensure to the benefit of, and be binding upon, the Government of Alberta and your respective successors and assigns.

Shell Quest Carbon Capture and Storage Project

MEASUREMENT, MONITORING AND VERIFICATION PLAN

FEBRUARY 2017 VERSION

Prepared by:
Shell Canada Limited
Calgary, Alberta

Revised: May 5th, 2017

Executive Summary

The aim of the Quest Carbon Capture and Storage Project (Quest CCS Project) is to capture 1.08 million tonnes of CO_2 per annum from the Shell Scotford Upgrader where bitumen from the Alberta oil sands is processed. After capture, the CO_2 is compressed and transported towards the North along an about 65 km long pipeline to injection well sites. There, the CO_2 is injected into a 2 km deep saline aquifer, called the Basal Cambrian Sands (BCS), and securely stored within the BCS storage complex.

The Quest Project has a responsibility to carefully monitor activity within the sequestration lease area and to confirm that an acceptable risk to health, safety, and the environment is maintained. To that end, a Measurement Monitoring and Verification (MMV) plan has been developed. The two key design principles of the MMV plan are that it is risk-based and adaptive.

The goal of the MMV plan is to achieve the following objectives:

Demonstrate CO_2 Inventory Accuracy to ensure the reported CO_2 stored will comply with regulations and protocols.

Ensure Containment to demonstrate the *security* of CO_2 storage and to protect human health, groundwater resources, hydrocarbon resources, and the environment.

Ensure Conformance to indicate the *long-term effectiveness* of CO_2 storage by demonstrating actual storage performance is consistent with expectations about injectivity, capacity, and CO_2 behaviour inside the storage complex;

These objectives will be achieved:

- By measuring the composition and flow of the injection stream.
- By verifying the expected effectiveness of existing safeguards created by site selection, site characterization, and engineering designs.
- By creating additional safeguards using the same monitoring systems to provide an early warning to trigger timely control measures designed to reduce the likelihood or the consequence of any leakage from the storage site.

This version of the MMV plan, submitted 23rd of February 2017, integrates learnings from the initial injection phase monitoring. Previous versions of the MMV plan are available at the Alberta Government Carbon Capture and Storage knowledge sharing website [1].

This document focuses on addressing CO_2 inventory accuracy, containment and conformance in relation to the injection target reservoir, namely the Basal Cambrian Sands located at a depth of about 2 km below ground. It does not address monitoring of pipeline integrity within the Quest Sequestration Lease Area.

Table of Contents

1 Project Description ... 1
2 Aim and Timeframe of MMV updates ... 3
2.1 Aim ... 3
2.2 Timeframe of MMV updates ... 3
2.2.1 Alberta Energy Regulator Updates ... 3
2.2.2 Government of Alberta Energy Updates ... 3
2.2.3 General Updates ... 4
3 Risk Assessment ... 5
3.1 Containment Risks ... 5
3.1.1 Loss of Containment Definition ... 5
3.1.2 Potential Consequences Due to a Loss of Containment ... 6
3.1.3 Potential Threats to Containment ... 6
3.1.4 Safeguards to Ensure Containment ... 11
3.2 Conformance Risks ... 13
3.2.1 Loss of Conformance Definition ... 13
3.2.2 Potential Consequences Due to a Loss of Conformance ... 13
4 MMV Plan ... 14
4.1 Background ... 14
4.2 Area of Review ... 15
4.3 Monitoring Performance Targets ... 17
4.4 Monitoring Tasks ... 17
4.5 Monitoring Schedule ... 18
4.6 Monitoring Technologies ... 20
4.6.1 Injection stream composition ... 20
4.6.2 Atmosphere ... 20
4.6.3 Biosphere ... 20
4.6.4 Hydrosphere ... 20
4.6.5 Geosphere ... 22
4.7 Performance Targets for CO_2 Inventory Accuracy ... 24
4.7.1 Composition of injection stream ... 24
4.7.2 Volume of injected CO_2 ... 24
4.8 Performance Targets for Conformance Monitoring ... 24
4.8.1 Monitoring CO_2 Plume Development ... 24
4.8.2 Monitoring Pressure Development ... 24
4.9 Performance Targets for Containment Monitoring ... 25
4.9.1 Monitoring the Atmosphere ... 25
4.9.2 Monitoring the Hydrosphere ... 25
4.9.3 Monitoring Injection Well Integrity ... 26
4.9.4 Monitoring Geological Seal Integrity ... 27
4.9.5 Trigger Events and Detection Thresholds ... 28
5 Operating Procedures ... 30
5.1 Operating Procedures in Response to Monitoring Trigger Events ... 30

5.2 Response Times of Safeguards to Ensure Conformance 32
5.3 Response Times of Safeguards to Ensure Containment 33
6 Contingency Monitoring Plans 36
6.1 Measurement equipment 36
6.2 InSAR 37
6.3 Time-lapse Seismic Data 37
References 38

Abbreviations

AER .... Alberta Energy Regulator
AOR .... Area of Review of MMV activities for the Project
BCS .... Basal Cambrian Sands
BGWP .... Base of Groundwater Protection
CBL .... Cement Bond Log
CCS .... Carbon Capture and Storage
CO_2 .... Carbon Dioxide
DAS .... (Fiber-optic) Distributed Acoustic Sensing
DHMS .... Downhole Microseismic Monitoring
DHPT .... Downhole Pressure-Temperature Gauge
DMW .... Deep Monitoring Well
DTS .... (Fiber-optic) Distributed Temperature Sensing
GoA .... Government of Alberta
GPS .... Global Positioning System
HUD .... Hold-Up Depth
INJ, IW .... Injection wells
InSAR .... Interferometric Synthetic Aperture Radar
IPCC .... Intergovernmental Panel on Climate Change
IRM .... Injection Rate Metering at wellhead
LMS .... Lower Marine Sands
MCS .... Middle Cambrian Shale
MMV .... Measurement, Monitoring and Verification
MWIT .... Mechanical Well Integrity pressure Testing
Quest CCS project .... Quest Carbon Capture and Storage Project
SEIS2D .... Time-lapse surface 2D Seismic Data
SEIS3D .... Time-lapse surface 3D Seismic Data
Shell .... Shell Canada Limited
SLA .... Sequestration Lease Area for the Project
USIT .... Time-lapse Ultrasonic casing imaging
VSP .... Vertical Seismic Profiling
VSP2D .... Time-lapse 2D Vertical Seismic Profiling
WEC .... Downhole Electrical Conductivity monitoring
WHPT .... Well Head pressure-temperature gauge
WPH .... Downhole pH monitoring

1 Project Description

Shell Canada Limited, which currently holds all necessary regulatory approvals in respect of the Quest CCS Project, is the managing partner of Shell Canada Energy. Shell Canada Energy operates 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 capture, transport and permanently store CO_2 securely, 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 key components of the Quest CCS Project are:

- CO_2 capture infrastructure that is connected to the Scotford Upgrader. The method of capture is based on a licensed Shell amine system called ADIP-X.
- A CO_2 pipeline to transport the CO_2 from the Scotford Upgrader about 65 km to the injection wells north of the upgrader. Note that the CO_2 injection well locations are located in the center of the sequestration lease area.
- An approved storage scheme consisting of up to eight injection wells that can be used to inject the CO_2 into the Basal Cambrian Sands (BCS) Formation, a deep underground saline aquifer, for permanent storage at a depth of about 2 km below ground level. Although eight wells are approved as part of the D65 approval 11837C [2], only three injection wells have been drilled at this time due to site characteristics exceeding initial expectations. Please also note that only two out of the three drilled injection wells are currently used for CO_2 injection.
- A site-specific, risk-based and adaptive Measurement, Monitoring and Verification (MMV) plan. The selected storage site is believed to be inherently safe; however, it is incumbent on Shell / the Operator to manage and minimize storage risks. There are two independent storage risks: loss of containment and loss of conformance. These are reflected in two of the primary objectives of MMV for the Quest CCS Project:
    a) Ensure Containment to demonstrate the *current security* of CO_2 storage, i.e.
        - Verify containment, well integrity, and the absence of any environmental effects outside the storage complex.
        - Detect early warning signs of any unexpected loss of containment.
        - If necessary, activate additional safeguards to prevent or remediate any significant environmental impacts as defined by the Environmental Assessment.

    b) Ensure Conformance to indicate the long-term security of CO_2 storage, i.e
        - Show pressure and CO_2 development inside the storage complex are consistent with models and, if necessary, calibrate and update these models.
        - Provide the monitoring data necessary to support CO_2 inventory reporting.

The injection program consists of injecting 1.08 million tonnes of CO_2 per annum for 25 years. The maximum bottomhole injection pressure shall not exceed 30 MPa (Table 1 in Ref [2]).

Figure 1-1 shows the Quest CCS Project Sequestration Lease Area (SLA).

Further information about the Quest CCS project is available at the Alberta Government Carbon Capture and Storage knowledge sharing website [1].

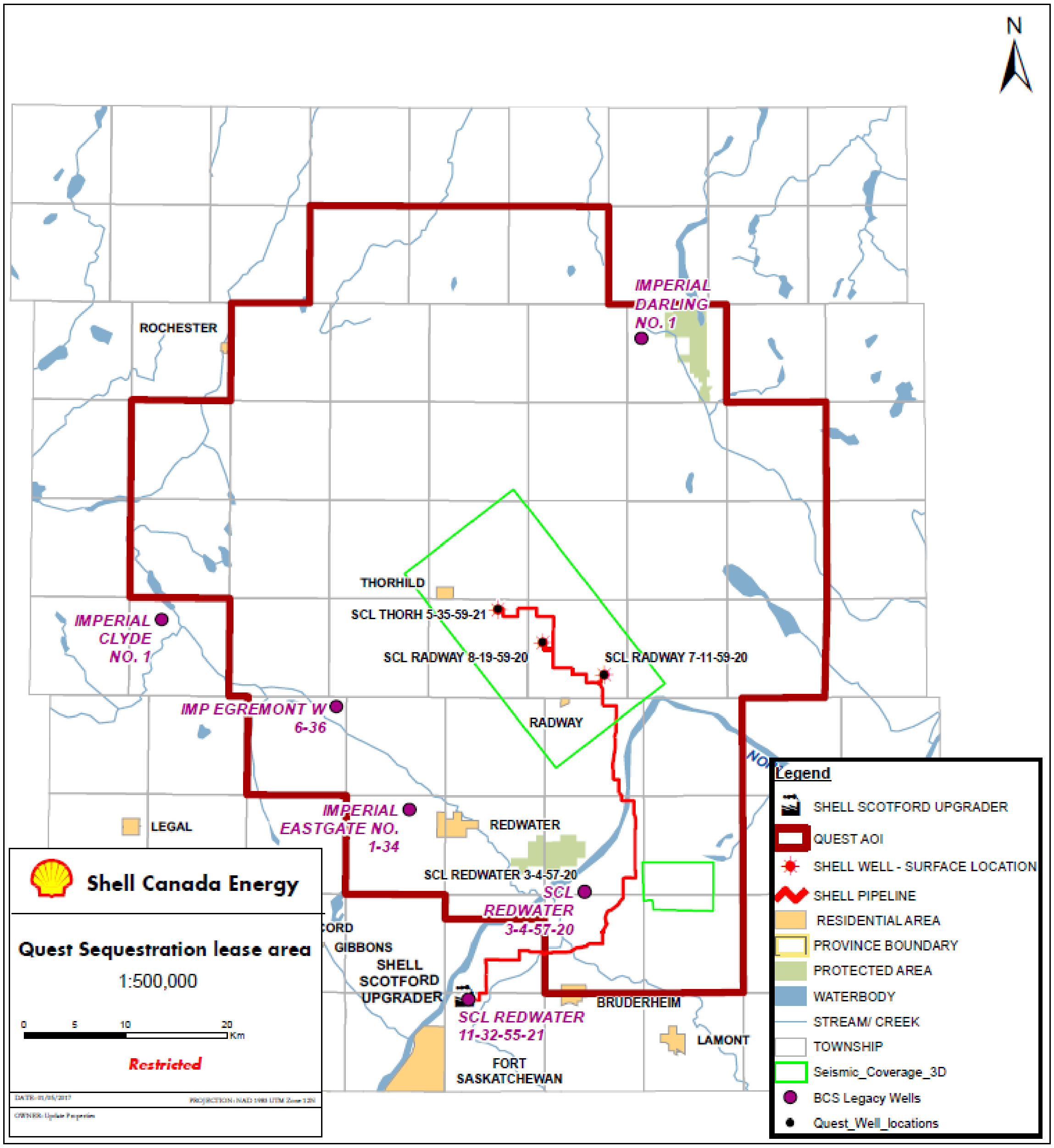

Figure 1-1: Location Map of the Quest Sequestration Lease Area (SLA). Shown: Quest pipeline (red line), Quest Project well sites, area of the 3D surface seismic survey, and legacy wells (abandoned wells that penetrate the BCS inside the SLA) within the SLA.

2 Aim and Timeframe of MMV updates

2.1 Aim

The aim of this document is to address the following objectives:

- Outline activities related to monitoring the injection stream composition.
- Outline activities that address **containment** and **conformance** in relation to the CO_2 storage within the Basal Cambrian Sands.

This document does not address monitoring of pipeline integrity within the Quest Sequestration Lease Area. This is covered within the Pipeline Integrity Management Plan as per the Alberta Regulation 91/2005 Pipeline rules section 7(1).

2.2 Timeframe of MMV updates

2.2.1 Alberta Energy Regulator Updates

MMV plan updates to AER will be submitted in accordance with the conditions of AER Approval 11837C received May 12th, 2015. Summary of AER Approval 11837C Conditions relating to MMV plan updates are summarized as follows:

- Condition 7 - Shell is required to submit MMV plan updates as required by the AER; at a minimum, updates are required at the critical milestones for commencement of injection, closure and post closure.
- Condition 8 - Shell must provide a complete pre baseline MMV plan by September 30, 2012. This condition has been completed with the final submission sent October 15, 2012 as per approved submission date change.
- Conditions 10d and 17 - Shell must provide annual operations reports that are aligned to the most current MMV plan and discuss any need for changes to the current MMV plan.
- Condition 15e – Shell must provide the MMV Plan as part of the third annual status report to be submitted January 31, 2015. This condition has been completed.
- Condition 18 – Shell must submit a closure report in 2040 that includes an MMV plan update, with specific attention to any performance problems evident in the 25 years of operations.
- Condition 19 – Shell must submit a post closure report, which includes an update of its MMV plan.
- Condition 25 – Shell must submit MMV plans referenced in Conditions 6, 7, 8, 15, 18, and 19 to Alberta Environment and Sustainable Resource Development for review – now part of AER.

2.2.2 Government of Alberta Energy Updates

According to the Carbon Sequestration Lease Approval(s) Section 2(2) (a) The Lessee (Shell) shall comply with the provisions of the Mines and Mineral Act.

In Section 9(2) of the Alberta Regulations Mines and Mineral Act 68/2011, referring to Carbon Sequestration Leases, "*The Minister may issue to an applicant an agreement under section 116 of the Act in the form of a carbon sequestration lease if the Minister receives from the applicant….*

9(2)(e) a monitoring, measurement and verification plan that meets the requirements set out in Section 15, and…

Section 15 states:

15) The Minister may approve a monitoring, measurement and verification plan received under section 9 or 11 in relation to a carbon sequestration lease if the plan
(a) sets out the monitoring, measurement and verification activities that the lessee will undertake while the plan is in effect,
(b) contains an analysis of the likelihood that the operations or activities that may be conducted under the carbon sequestration lease will interfere with mineral recovery, based on the geological interpretations and calculations the lessee is required to submit to the Regulator pursuant to Directive 65 in its application for approval of the injection scheme under the Oil and Gas Conservation Act, and
(c) contains any other information requested by the Minister

9(2)(f) a closure plan that meets the requirements set out in section 18."

Shell submitted an MMV Plan and a Closure Plan as part of the Sequestration Lease Application submitted April 28, 2011 and approved by the Minister May 27, 2011. The latest approved MMV plan was submitted in January 2015 and approved on March 27, 2015. The latest approved Closure plan was submitted in February 2014 and approved on May 22, 2014.

According to Section 16(1) and 19(1) of Act 68/2011 on Duration and Renewal of the monitoring, measurement and verification plan and the Closure plan respectively, *the plans approved by the Minister in relation to a carbon sequestration lease ceases to have effect on the earlier of*

(a) the third anniversary of the date on which the plan was approved, and
(b) the date that the lease is renewed.

As for timing, Section 16 (2) and 19(2) state that A lessee must submit a new monitoring, measurement and verification plan and closure plan for approval under section 15 no fewer than 90 days before the date on which the approved plan ceases to have effect.

Shell is required to submit an updated MMV and closure plan every three years as a stipulation of its Sequestration Lease Approval from Alberta Energy.

2.2.3 General Updates

In both of the agreements cited in Section 2.2.2, it is understood that the MMV Plan will be adapted if necessary in response to new information gained as the project progresses from:

- Well Data
- Site-specific technical feasibility assessments
- Monitoring during the injection and closure periods.

This MMV plan contains updates based on learnings from the initial phase of injection which provide a basis to optimize and streamline MMV activities, as per the design principles of the MMV plan. As well, the MMV plan's overall structure was revised to make it relevant to and focused on the on-going operating-injection phase of the project. Note that the timing of the MMV plan update was also chosen to re-align MMV and Closure Plan submissions. The next Closure Plan update was due February 27, 2017; whereas, the next MMV Plan update was due December 26, 2017.

3 Risk Assessment

This section reviews the assessment of the storage risks, historical and current to the Quest project. The scope of this assessment includes both conformance and containment risks. The methodology for risk assessment relies on an evidence-based evaluation of potential threats and consequences, and the effectiveness of safeguards in place.

It should be noted that based on the analysis of downhole fluid samples from the BCS and other overlying aquifers, there is evidence (Fig. 3-1) for seal integrity and hydraulic isolation of the BCS aquifer from all the overlying aquifers within and in close proximity to the Quest AOI.

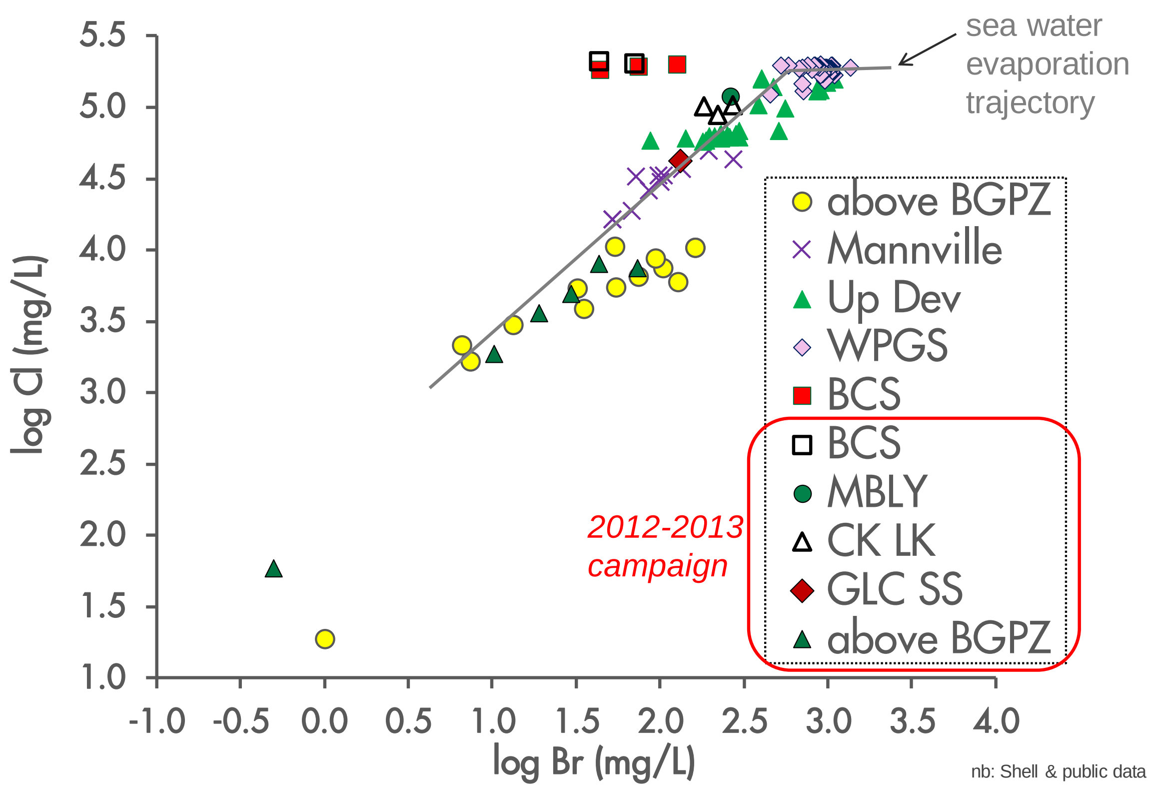

Figure 3-1: Log Cl versus log Br plot for fluid samples from different aquifers, including the BCS and overlying aquifers to the BCS. Data are from literature, as well as the Shell Quest well drilling campaigns. Nb: BGPZ: base groundwater protection zone; Up Dev: Upper Devonian; WPGS: Winnipegosis; BCS: Basal Cambrian Sands; MBLY: Moberly; CK LK: Cooking Lake; GLC SS: Glauconitic Sandstone.

3.1 Containment Risks

3.1.1 Loss of Containment Definition

Containment means that the injected CO_2 and the native BCS brine remain inside the storage complex. Consequently a loss of containment is defined as:

A migration of CO_2 or BCS brine into environmental domains above the Upper Lotsberg Salt, which is the ultimate seal of the BCS storage complex.

3.1.2 Potential Consequences Due to a Loss of Containment

A loss of containment is not expected, but if it does occur, it may result in some of the following negative consequences:

- **Hydrocarbon resources affected** due to a slight increase in the salinity or acidity of the produced fluids
- **Groundwater impacts** if sufficient quantities of CO_2 or BCS brine migrate above the base of groundwater protection to reduce groundwater quality.
- **Soil contamination** if sufficient quantities of CO_2 or BCS brine migrate into the soil to reduce soil quality.
- **CO_2 emissions into the atmosphere** will reduce the effectiveness the Project's contribution to climate change mitigation.

3.1.3 Potential Threats to Containment

Prior to commercial operation, nine potential threats to containment were identified (Fig. 3-2):

1) Migration along a legacy well, 2) Migration along an injection well, 3) Migration along a deep monitoring well, 4) Migration along a rock matrix pathway, 5) Migration along a fault, 6) Induced stress re-activates a fault, 7) Induced stress opens fractures, 8) Acidic fluids erode geological seals, and 9) Third Party activities.

Each was considered highly unlikely; but any of them are, in principle, capable of allowing CO_2 to migrate upwards out of the BCS storage complex.

Evaluation and integration of all available data-to-date (e.g. 2012-2013 drilling campaign, pre-injection phase monitoring, injection phase monitoring, Gen-5 modeling of the BCS) has confirmed that the pressure increase in the BCS will not reach a level sufficient to lift BCS brine to the base of the groundwater protection (BGWP) zone even at the injection wells [3, section 5.3.1]. Therefore, there is no risk of brine leakage impacting groundwater unless there is a severe loss of conformance. BCS pressure monitoring will be used to ascertain if there is a loss of conformance that could give rise to a potential threat related to brine leakage far in advance of any impact above the storage complex. At that time, MMV plans would be updated appropriately. Even if there was sufficient pressure, dynamic leak path modelling indicates that due to the pressure depletion of the Cooking Lake Formation, as well as flow into other deep aquifers, BCS brine cannot reach the BGWP zone unless it flows along an open migration pathway unconnected to the Cooking Lake Aquifer. In addition, considering the site characteristics of the storage complex capped by the Upper and Lower Lotsberg Salts Formations, wells that do not penetrate the storage complex pose very little to no risk to containment.

Hence, of all potential threats investigated, the key threat to containment at the Quest site is "Migration along an injection well", as such a well penetrates the storage complex. The risk of leakage, however, from the storage complex along a leakage pathway in the injection wells is considered very low, based on the following observations:

- The conceptual site model (CSM) for the Quest Project SLA does not foresee a pathway connecting the source 'CO_2 within BCS' to any receptor (e.g. overlying aquifers) (Fig. 3-3). No pathway has been identified through which CO_2 or saline brine from the BCS could reach aquifers above the BGWP zone. Furthermore, pressures are too low for BCS brine to be lifted to above the BGWP zone (Section 5.3.1 in Reference [3]).
- The evaluation of the cement bond in the injection wells (IWs), 100-08-19-059-20W4 and 103-07-11-059-20W4, which are currently used for CO_2 injection, behind both the intermediate casing and the main casing shows isolation of the BCS storage complex with a good bond across all three seals (MCS and the Lower and Upper Lotsberg Salts).

  Note that the evaluation of the cement bond log from well 102-05-35-059-20W4 (not used for injection as of Q1 2017) indicated non-ideal cement bond across part of the MCS which could potentially extend into the LMS baffle below. There is, however, good cement from the top of the BCS to the intermediate casing shoe providing an effective isolation of the BCS. Further, the good cement across the Lotsberg Salts provides significant additional isolation of the BCS storage complex. Consequently, the risk of a leakage pathway developing at the 102-05-35-059-20W4 injection well is still considered very low.

  - Surface casing vent flows (SCVFs) and gas migrations (GMs) have been detected in the IWs and are being reported on to AER on an annual basis. Analytical results ($\delta^{13}C$ values) confirm that SCVFs and GMs are independent of each other. GMs originate from a shallow zone (< 200m depth), while the SCVFs originate from just below the surface casing shoe (> ~450m depth). Due the shallow depths of the sources of the SCVFs and GMs, they are not considered a threat to containment or isolation of the BCS storage complex. The latter is assessed via analysis of future SCVF data.

Table 3-1 provides a list of causes that may lead to the threat of migration along an injection well, and the approaches used to address this threat/assess/monitor potential causes.

While the key threat to containment at the Quest site is "Migration along an injection well", the MMV plan is designed in such a way that any of the other nine threats, e.g. "Migration along a legacy well", "Migration along a deep monitoring well", or "Third Party activities", can still be addressed, as outlined below.

<u>"Migration along a legacy well"</u>: The probability of legacy wells being intersected by the CO_2 plume is very low, because:

- In the Quest SLA, there are four legacy wells that penetrate through all seals in the BCS storage complex with the closest one to an existing injection well located 18 km away. This is more than three times the distance the CO_2 plume is expected to extend.
- The status and condition of existing wells penetrating the BCS has been reviewed from multiple data sources. There are no known issues with legacy well integrity.

<u>"Migration along a deep monitoring well"</u>: This is risk is considered to be very low, because:

- All deep monitoring wells drilled to date, in the vicinity of the injection wells, terminate above the Ultimate Seal with the goal to detect fluid migrating above the BCS storage complex.

"Third Party Activities": This is risk is considered to be very low, because:

- According to the Sequestration Lease Rights Shell has the exclusive right to drill through and store within the Zone of Interest (ZOI) (below the Elk Point Group). However, there are P&NG rights held by third-parties within the SLA that extend to the basement including Shell's ZOI. As a result, the ADOE has flagged the Quest Project in their system and will not be giving out new P&NG rights within the ZOI within the SLA. In addition, Shell would be notified of any third party attempting to drill into the ZOI so risk could be assessed on an individual basis.

For additional detail on risk assessment associated with all nine potential threats to containment identified prior to commercial operation, please refer to the 2015 MMV plan [5].

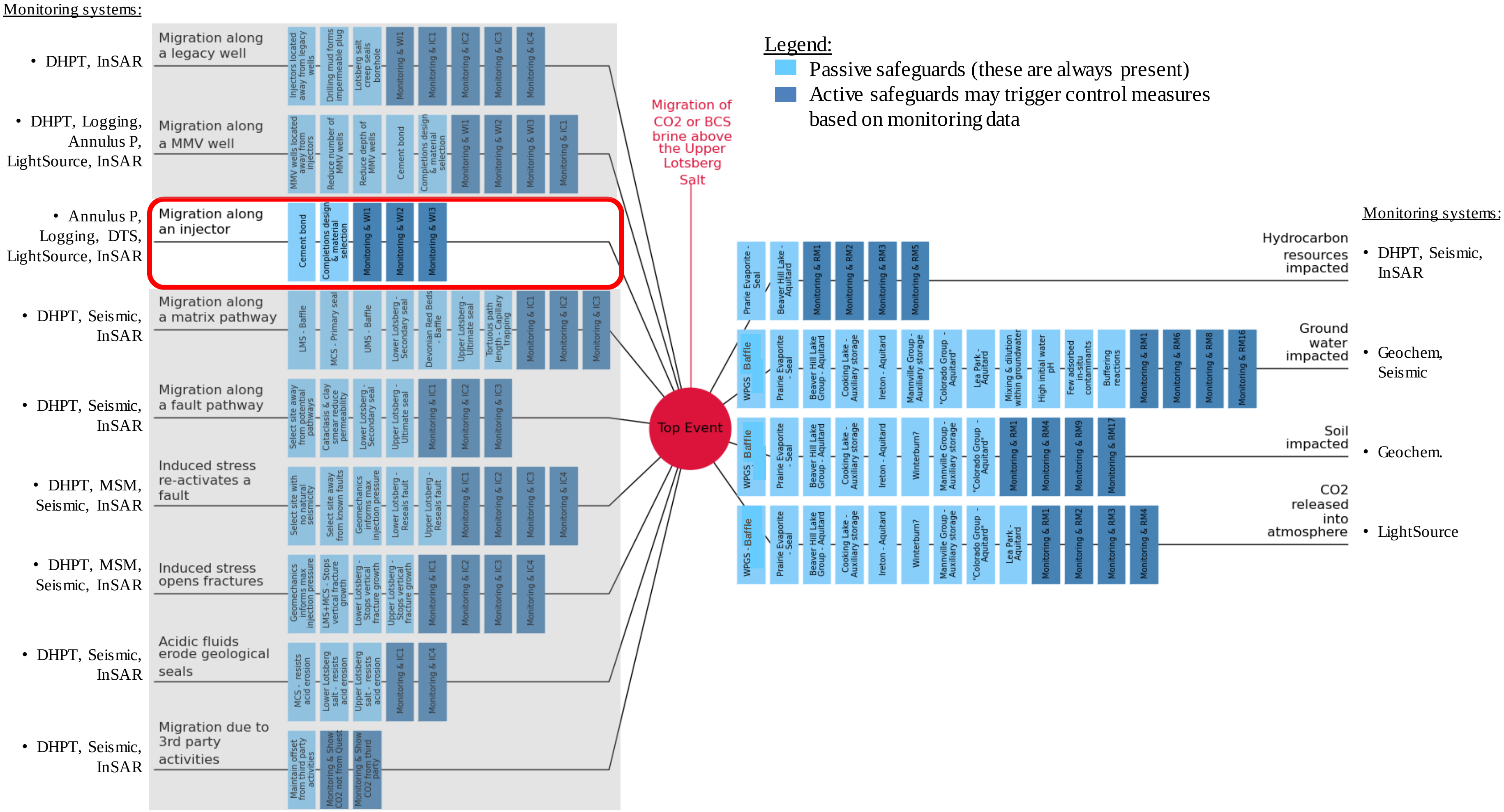

Figure 3-2: Summary of the safeguards in place to reduce the likelihood (left side) and consequence (right side) of any unexpected loss of containment. Highlighted is the remaining key risk within Quest. Note: acronyms IC1 to IC4 and WI1 to WI3 refer to control response options to prevent any unexpected migrations of fluids out of BCS storage complex (see Table 3-2 for further details); RM1 to RM17 refer to control response options to correct any unexpected migrations of fluids out of BCS storage complex (see Table 3-3 for further details). Monitoring systems listed various MMV technologies available to assess threats and consequences.

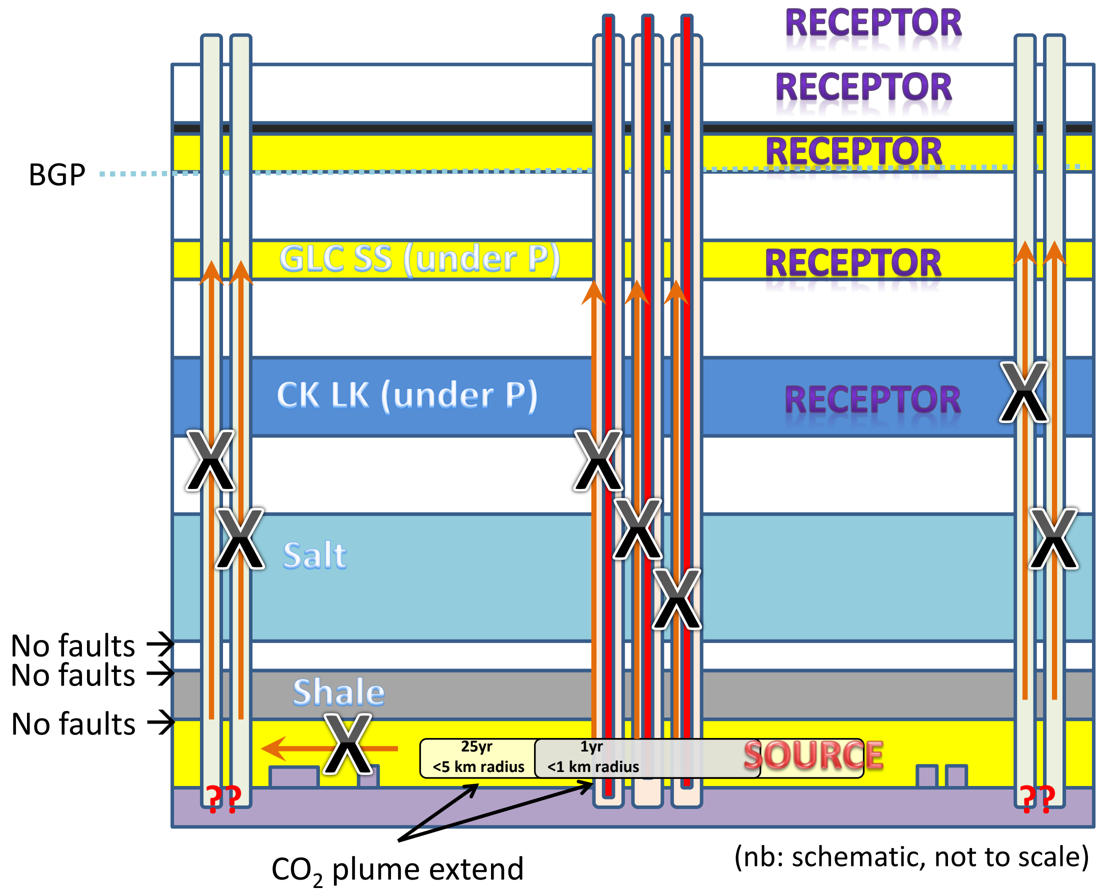

Figure 3-3: CSM for the Quest Project SLA. BGP refers to base groundwater protection; 'under P' refers to under-pressured formation.

Table 3-1: Assessment of threat 'Migration along an injection well'.

Threat causes	Description	Techniques to assess/monitor cause
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.	CBL, DTS ^
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.	Pressure monitoring, Casing inspections
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 CO_2 may allow fluids to escape through the wellbore.	WIT, Lightsource (atmospheric), Routine Wellhead inspections, DTS ^
Well interventions	During the course of normal operations, routine well interventions may result in loss of well control	Shell safety standard practices during operations, minimized interventions

Notes: ^ DTS is still considered a novel technology with regards to wellbore integrity assessment in CO_2 injection wells that needs further maturation; hence, at present it can only be used for qualitative assessment.

3.1.4 Safeguards to Ensure Containment

Following extensive site characterization, there are no known migration pathways for fluids to escape upwards out of the BCS storage complex (see CSM in Fig. 3-3). Prior to implementing any MMV, several safeguards were already in-place to reduce the risk of any unexpected loss of containment due to an unknown migration pathway.

Initial storage risk reductions are achieved through multiple independent safeguards implemented through site selection, site characterization, and engineering concept selections. These initial passive safeguards are sufficient on their own to make the loss of containment extremely unlikely. Details of these safeguards can be found in previous MMV submissions [1].

The MMV plan provides a comprehensive and reliable means to verify the effectiveness of these initial passive safeguards. In the extremely unlikely case that monitoring indicates a potential loss of containment then a wide range of control measures can be deployed in a timely fashion to effectively prevent, mitigate, or remediate any actual loss of containment (Tables 3-2 and 3-3). These additional active safeguards are triggered by monitoring and are designed to be sufficiently numerous and diverse to yield significant additional storage risk reduction.

Table 3-2: Control response options to prevent any unexpected migrations of fluids out of the BCS storage complex, including a time estimate to implement a control response.

Injection Controls:	
IC1: Redistribute injection across existing wells	minutes to hours
IC2: Drill new vertical or horizontal injectors	12 - 18 months
IC3: Extract storage formation fluids to reduce pressure	2 - 4 months
IC4: Stop injection	minutes
Well Interventions	
WI1: Repair leaking well by re-plugging with cement	1 - 3 months
WI2: Repair leaking injector by replacing completion	1 - 3 months
WI3: Plug and abandon leaking wells that cannot be repaired	1 - 3 months

Table 3-3: Control response options to correct any unexpected migrations of fluids out of the BCS storage complex, including a time estimate to implement a control response.

Well Interventions:	
RM1: Repair leaking well by re-plugging with cement	1 - 3 months
RM2: Repair leaking injector by replacing completion	1 - 3 months
RM3: Plug and abandon leaking wells that cannot be repaired	1 - 3 months
Exposure Controls	
RM4: Inject fluids to increase pressure above leak	1 - 3 months
RM5: Inject chemical sealant to block leak	1 - 3 months
RM6: Contain contaminated ground water with hydraulic barriers	1 - 3 months
RM7: Replacement of potable water supplies	Days to week
Remediation Measures	
RM8: Pump and treat	4 – 8 months
RM9: Air sparging or vapour extraction	4 – 8 months
RM10: Multi-phase extraction	4 – 8 months
RM11: Chemical oxidation	4 – 8 months
RM12: Bioremediation	4 – 8 months
RM13: Electrokinetic remediation	4 – 8 months
RM14: Phytoremediation	4 – 8 months
RM15: Monitored natural attenuation	1 - 3 months
RM16: Permeable reactive barriers	4 – 8 months
RM17: Treat acidified soils with alkaline supplements	1 - 3 months

3.2 Conformance Risks

3.2.1 Loss of Conformance Definition

A loss of conformance exists if:

- The observed distribution of CO_2 and pressure build-up inside the storage complex does not agree with model-based predictions within the range of uncertainty; or
- Knowledge of the actual storage performance is insufficient to provide confidence in the long-term effectiveness of CO_2 storage within the storage complex.

3.2.2 Potential Consequences Due to a Loss of Conformance

A loss of conformance is not expected but if it does occur it may result in some of the following negative consequences:

- **Cost of additional monitoring** activities required to collect data to improve modeling in order to establish conformance.
- **Delay in site closure** until long-term storage risks are understood to be acceptable.
- **Reduction in storage efficiency** if CO_2 plumes spread further than expected.

4 MMV Plan

4.1 Background

MMV operates within the AOR (Section 4.2) of the Quest SLA (Figure 1-1). The SLA for the Quest Project extends from the Precambrian basement up to top of Elk Point Group, located just above the Prairie Evaporite.

MMV to assess containment and conformance within the BCS storage complex spans four key domains:

- **Atmosphere:** The air mass above the ground surface.
- **Biosphere:** The domain containing ecosystems where living organisms exist.
- **Hydrosphere:** The subsurface domain from ground surface to the base of groundwater protection (BGWP) zone. In essence, this domain covers the subsurface from ground surface to top of the Lea Park Formation.
- **Geosphere:** The subsurface domain below the BGWP zone including the Basal Cambrian Sands (BCS) storage complex). The BCS storage complex comprises a primary storage formation (BCS), the first major seal (Middle Cambrian Shale, MCS), the second major seal (Lower Lotsberg Salt), and the ultimate seal (Upper Lotsberg Salt). Above the storage complex, the geosphere also contains additional deep saline aquifers, e.g. the Cooking Lake Formation which provides opportunities for MMV. Proven oil resources exist within the Leduc, Nisku, and Wabamun formations and proven gas resources exist within the Nisku, Mannville Group, and Colorado Group.

The MMV Plan is designed on the basis of the following principles: Regulatory-Compliance; Risk-Based; Site-Specific; and Adaptive.

Monitoring tasks are designed to verify the effectiveness of the passive safeguards described previously and, if necessary, to trigger the timely deployment of active control measures, such as reducing or stopping injection, in order to reduce the risk and / or consequence of a loss of conformance or containment. Established industry practices and regulations for well and reservoir management and environmental monitoring provide guidance on steps that can be taken to fulfill the monitoring tasks.

MMV activities are scheduled to streamline interfaces with on-site activities at Scotford to maximize operational efficiency and minimize downtime of Quest capture facilities.

As necessary, the MMV Plan has been and will be adapted in response to new information gained from:

- Well data;
- Site-specific technical feasibility assessments;
- Findings from on-going monitoring activities.

Adaptations to the MMV plan may entail changes in the frequency and / or number of techniques being deployed, after review with appropriate agencies. The need for changes to the MMV plan are discussed within the Annual Status Reports submitted to the AER, as per condition 10 d) vi) of the approval No. 11837C [2].

4.2 Area of Review

MMV operates within an area of review (AOR) based on expected volumes of CO_2 to be injected during the course of the project (Figure 4-1). The Quest AOR extends 10 km radially outwards from an active injection well.

The AOR is based on the perceived risks of having CO_2 in the BCS reservoir at some future time, including the Closure and Post-Closure periods. It takes into account potential uncertainty in the plume radius and represents a conservative estimate. The current dynamic model incorporates injection well rates & pressure data to the end of 2016, and the 1st monitor VSP results. Assuming IW 8-19 and IW 7-11 are only used for injection (as per 2016 operations), the modelling shows maximum plume lengths in 2040 of 2 to 4 km. The resulting end-of-life plumes are illustrated in Figure 4-2a. The most significant impact on CO_2 plume size will be whether or not IW 5-35 is required for injection.

The pressure in the BCS is not expected to reach a level that could displace BCS brine up to the ground water zone over the life of the project. On this basis, the limited pressure increase in the BCS due to injection does not create any risk of potential adverse effects. By the end of project life, the pressure build-up in the BCS is forecasted to be less than 2 MPa of differential pressure (DeltaP) at the injection wells (Figure 4-2b). This pressure increase represents less than 12% of the delta pressure required to exceed the BCS fracture extension pressure and less than 25% of the pressure increase required to exceed the AER Approval operating constraint on bottom hole pressure. The assumption for the pressure build forecast (Figure 4-2b) is that from 2017 onward an equal amount of CO_2 will be injected in each well for the remainder of the life of the project. Note that the pressure incline observed at IW 5-35 is responding to the injection at IW 8-19.

Observed storage performance and specific injection well volumetric assumptions will be used to verify the size and shape of the AOR and, if necessary, the AOR will be updated as needed.

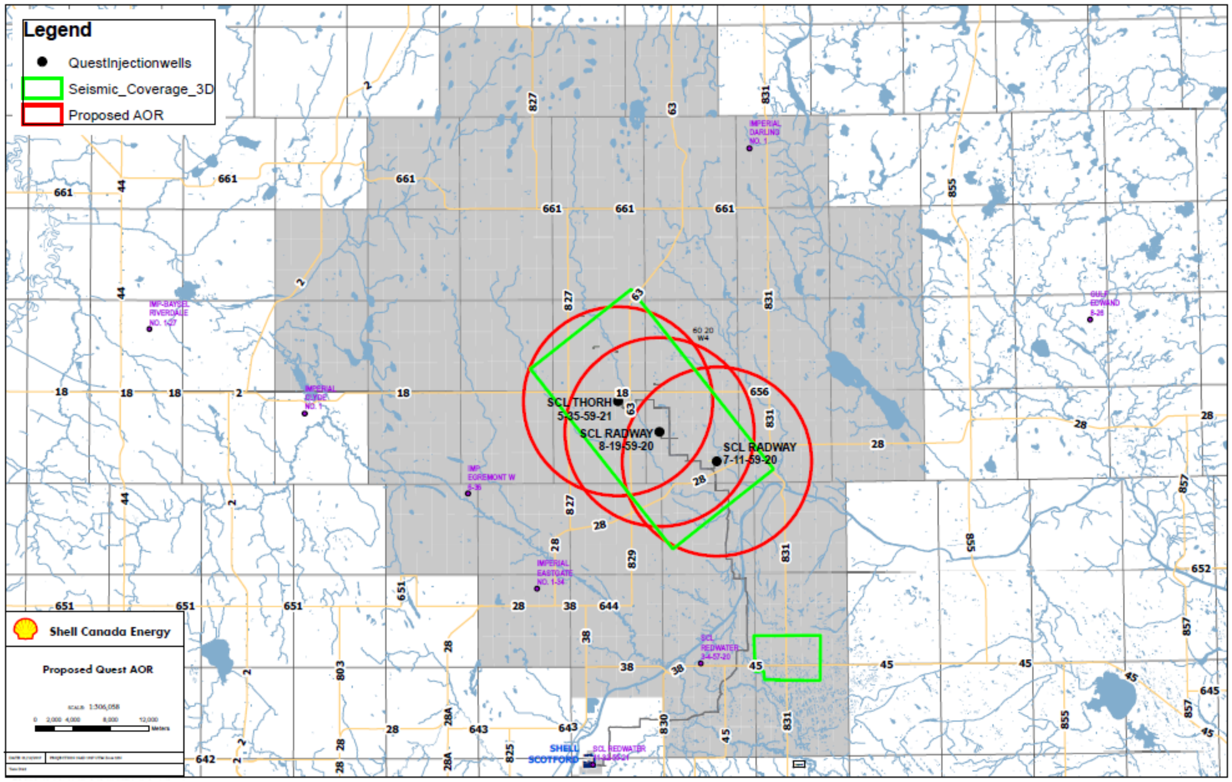

Figure 4-1: QUEST AOR (red circles).

a) b)

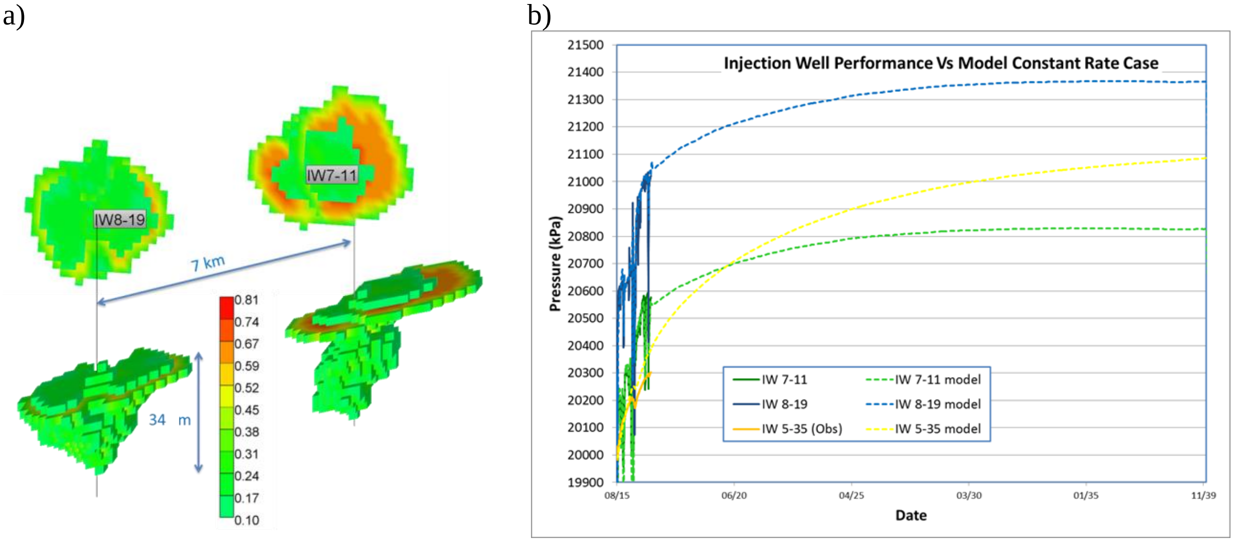

Figure 4-2: a) Map view and 3D views of the CO_2 plume in 2040; b) Well by well expected pressure build forecast.

4.3 Monitoring Performance Targets

In accordance with the Closure Plan, the monitoring performance targets are defined as follows:

CO_2 Inventory Accuracy Target

1) *The accuracy of the reported CO_2 stored will comply with regulations and protocols.*

Conformance Monitoring Targets

1) *Observed storage performance conforms to predicted storage performance within the range of uncertainty.*
2) *Knowledge of the actual storage performance is sufficient to provide confidence in the long-term effectiveness of CO2 storage within the storage complex.*

Containment Monitoring Targets

1) *Measurements of any changes within the MMV datasets caused by CO_2 injection are sufficient to demonstrate the absence of any significant impacts as defined in the Environmental Assessment.*
2) *Measurements of any changes within the MMV datasets caused by CO_2 injection are sufficient to trigger effective control measures to protect human health and the environment.*

4.4 Monitoring Tasks

The monitoring tasks identified to fulfill these monitoring targets are:

- Monitor the composition and flow of the injection stream.
- Monitor CO_2 plume development inside the storage complex.
- Monitor pressure development inside the storage complex.
- Monitor injection well integrity.
- Monitor geological seal integrity.
- Monitor for any hydrosphere impacts.
- Monitor for any CO_2 emissions into the atmosphere.

4.5 Monitoring Schedule

The monitoring schedule to address conformance and containment allows for multiple independent monitoring systems with comprehensive coverage through time and across the AOR within each of the domains considered (Fig. 4-2, Table 4-1). The diversity of monitoring technologies mitigates the risk of any one particular technology failing to work at optimal levels for the project. The monitoring systems are continually assessed for their value and required continuance, with changes communicated to the GoA and AER as required..

The monitoring schedule is aligned with activities at Scotford. For example, to optimize execution of well activities during periods of less CO_2 availability such as turnarounds or maintenance activities. Specific dates for acquisition and frequency of certain monitoring activities are determined on an ongoing basis and communicated in annual Quest reporting.

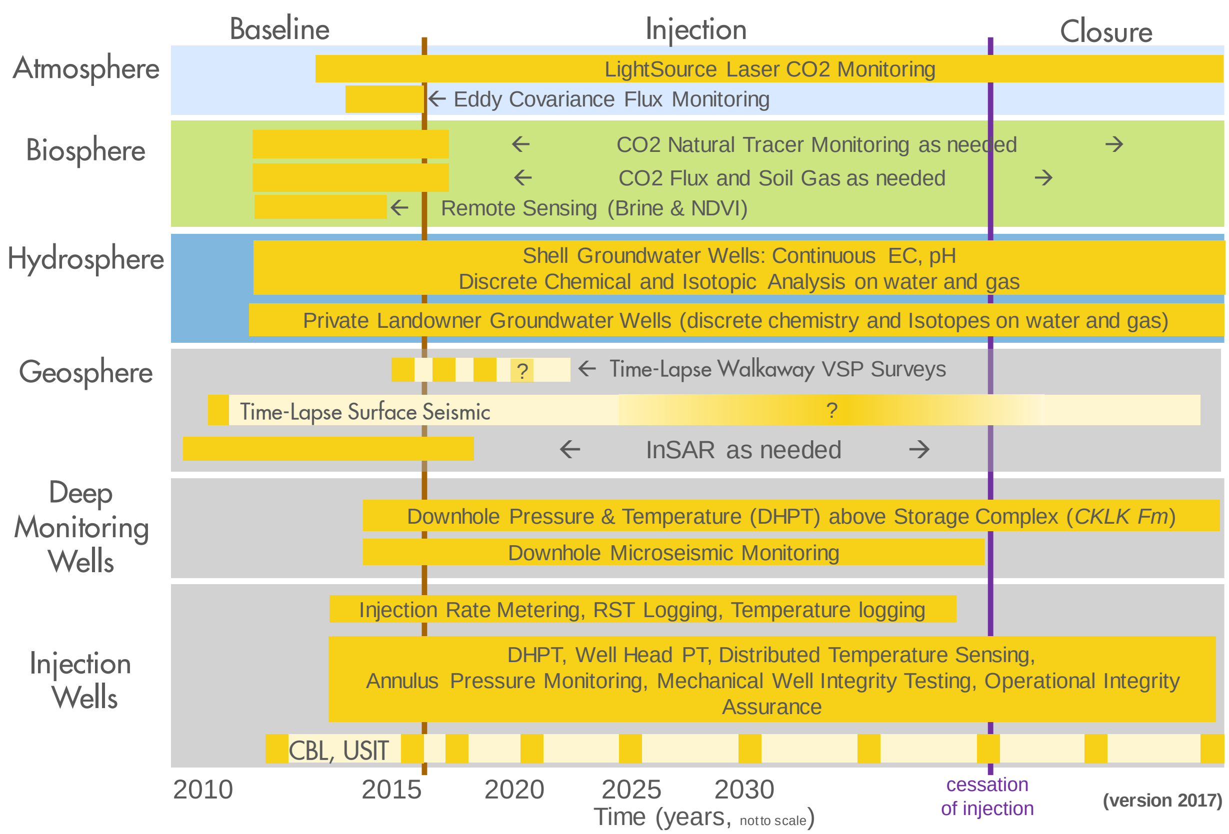

Figure 4-2: Schematic of Quest's diversified monitoring program.

Table 4-1: Summary of Quest monitoring.

Domain	Monitoring technology	Areal coverage	Frequency
Atmosphere	LightSource (line-of-sight atmospheric CO_2 monitoring)	at each injection well pad	continuous
Biosphere	CO_2 flux and soil gas	on as needed basis	on as needed basis
Hydrosphere	water & gas geochemical analyses	GWWs and Private landowner groundwater wells	discrete sampling events [a]
	Downhole pH and WEC monitoring above BGPW	GWWs	continuous
Geosphere	Down-hole pressure-temperature monitoring in the Cooking Lake Formation	DMWs	continuous
	Downhole microseismic monitoring	DMW 8-19 (only)	continuous
	SCVF testing as per AER ID 2003-01 [b]	DMWs and IWs, as required	annually by June 30th
	Gas migration testing as per AER Directive 020 [c]	DMWs and IWs, as required	annually by June 30th
	Wellhead pressure-temperature monitoring	IWs	continuous
	Downhole pressure-temperature monitoring	IWs	continuous
	Annulus pressure monitoring	IWs	continuous
	Time-lapse ultrasonic casing imaging	active IWs	every 5 years
	Time-lapse electromagnetic casing imaging	active IWs	every 5 years
	Time-lapse cement bond log	active IWs	every 5 years
	Mechanical well integrity testing (packer isolation test) and tubing caliper log	*DMW and IWs*	every 5 years
	Injection rate monitoring	IWs	continuous
	Temperature and RST logs	active IWs	as per AER Approval No. 11837C condition 5c and associated logging extension request as granted on March 22, 2016
	Time-lapse walkaway VSP surveys [d]	within 600 m radius of every injector	next monitor planned for Q1 2017; post-2017 to be determined [e]
	Time-lapse surface seismic surveys	area covering expected CO_2 plume extent	to be determined [e]
	Distributed temperature sensing	IWs	continuous
	InSAR	AOR plus buffer zone	contingency monitoring technology [f]

NOTES:

[a] sampling schedule described in section 4.6.2. Note that there will be an on-going assessment of available data to optimize groundwater well sampling campaigns, which may lead to changes in the proposed sampling plan.

[b] Annual SCVF testing as per AER ID 2003-01 for non-serious SCVF, until time of well abandonment or until SCVF dies out. Annual reporting to AER is required. See AER letter from December 3rd 2013 regarding approval of the MMV plan for full details.

[c] Annual Gas Migration testing as per procedure given in AER Directive 020 until time of well abandonment or until the GM disappears. Annual reporting to AER is required. See AER letter from December 3rd 2013 regarding approval of the MMV plan for full details.

[d] Data acquired using DAS system; baseline survey executed in Q1 2015, 1st monitor executed in Q1 2016.

[e] Timing of subsequent time lapse seismic surveys will be determined based on plume growth, reservoir performance, and findings from the 2017 VSP survey

[f] InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). In other words, InSAR will be used in the event of another MMV technology or observation indicating the need for further investigation [6]. Note though that satellite image programming and acquisition is planned to continue over the next three years using a single frame centered over the 3 injection well pads.

4.6 Monitoring Technologies

4.6.1 Injection stream composition

The composition of the injection stream is continuously measured using an online GC analyzer at the Quest capture facility located at stage 7 of the compressor. In addition, regular samples of the injection stream from stage 7 at the compressor are taken for laboratory analysis. Coriolis-type mass flow meters at the Shell Scotford boundary limit and at the injection well skids continuously measure the injection stream flow to determine mass of CO_2 injected.

4.6.2 Atmosphere

Above-ground CO_2 levels are monitored using a technique called 'LightSource', deployed on each injection well pad. It is comprised of a Boreal Laser GasFinder sensor located in one corner of each injection well pad and three reflectors positioned at the opposite corners of the injection well pad. The system also includes a number of weather station equipment (e.g. anemometer) that record wind direction, speed, etc. on a continuous basis.

4.6.3 Biosphere

CO_2 flux, soil gas, and soil sampling and analysis will be conducted on an as needed basis. For instance, in the event other monitoring technologies indicate the need to take samples within the biosphere. Note that monitoring the biosphere is challenging due to natural variability in soil gas and flux, as described in the special report on baseline data and analysis of biogenic flux of CO_2 submitted in fulfillment of condition 15) of the Approval 11837C [2].

4.6.4 Hydrosphere

4.6.4.1 Project Groundwater Wells

Shallow groundwater wells (GWW, < 200 m below ground surface) on each injection well pad were drilled and completed within different aquifers above the BGWP zone.

On each pad one of the groundwater wells is completed as close as possible to the BGWP zone. The other well(s) are completed at a typical depth of most local private landowner groundwater wells in the area.

Each GWW is equipped with a downhole multi-parameter water quality probe for continuous measurement of pH and WEC.

During 2017, it is expected that discrete sampling of the GWWs will take place on a quarterly basis. Note that there will be an on-going assessment of available data to optimize sampling campaigns, which may lead to changes in the above proposed sampling plan. The sampling plan for 2018 and 2019 will be based upon evaluation of the data collected during 2017.

4.6.4.2 Landowner Groundwater Wells

Besides the GWWs, a number of private landowner groundwater wells are also being monitored via discrete sampling events. The categories of private landowner groundwater wells include:

- Landowner wells within a 1 km radius of the injection wells (referred to as LIW).
- Landowner wells selected in accordance to plume size for assurance monitoring, and as such the number of wells will change over time (referred to as LAM). Modelling indicates that average CO_2 plume extent is not expected to exceed a radius of 1km from the injection wells until 2018-2019.
- Landowner wells associated with VSP surveys (referred to as LVSP).

The sampling schedule for the private landowner groundwater wells will vary depending on the groundwater well category.

During 2017, the sampling schedule includes the following (see Table 4-1):

- LIW: bi-annual or quarterly basis depending on well. Bi-annual or quarterly sampling frequency of a particular well is based on analyte concentration trend analysis of available data from Q4-2012 to Q4-2016
- LAM: part of LIW based on expected plume extent
- LVSP: pre- and post-VSP survey campaigns

The sampling plan for 2018 and 2019 will be based upon evaluation of the data collected during 2017 using analyte concentration trend analysis.

Notes:

- Any additional landowner water wells for which landowners have made a reasonable request to participate in the program will be included in the sampling program as per AER Approval 11837C [2]. Note that future sampling of those wells will depend upon their location relative to the sampling strategy discussed above.
- There will be an on-going assessment of available data to optimize all groundwater well sampling campaigns, which may lead to changes in the above proposed sampling plan with approval by AER.

4.6.4.3 Laboratory analysis for discrete samples

Table 4-2 provides the list of key analytes for which the discrete water samples collected from the project and landowner groundwater wells will be analyzed for. Well gas samples will be collected using a flow-through cell, if possible, for well gas compositional (CO_2, N_2, O_2, C_n) and isotopic ($\delta^{13}C\text{-}CO_2$, $\delta^{13}C\text{-}C_1$) analyses.

Table 4-2: List parameters considered important for ongoing monitoring.

Parameter	Reason to Monitor
Alkalinity / Dissolved Inorganic Carbon (DIC)	Water type and water quality
As	Aquifer acidification
Ca	Water type and water quality
Cl	Potential brine indicator
$\delta^{13}C$	CO_2 isotopic fingerprint
Water Electrical Conductivity (WEC)	Potential brine indicator
K	Water type and water quality
Mg	Water type and water quality
Na	Potential brine indicator
pH	Water quality, CO_2 impact
SO_4	Water type and water quality
TDS	Potential brine indicator

4.6.5 Geosphere

4.6.5.1 Time-lapse Seismic Surveys

Time-lapse seismic data (VSP2D, SEIS2D, SEIS3D) are used to monitor the development of the CO_2 plume inside the BCS storage complex. Time-lapse seismic surveys are expected to yield an image of the CO_2 plume geometry around each CO_2 injector.

A baseline 3D seismic survey was acquired in the winter months of 2010 and 2011 and covers an area of 435 km^2 (Figure 1-1). It is expected this areal coverage will be adequate to monitor the CO_2 plumes over the lifespan of the project to the closure period.

Eight baseline walkaway VSP surveys were acquired at each injection well using the Distributed Acoustic Sensors (DAS) fibers in Q1 2015. The survey lines are separated by roughly 45^{o} to provide multi-azimuthal coverage at the each injection site. The maximum source offset for each line is approximately 2400 m, and the expected maximum imaging offset at the BCS is approximately 800 m based on results from the 2015 and 2016 VSP surveys.

Time-lapse seismic surveys include the utilization of VSP2D, SEIS2D, and SEIS3D technologies. The footprint of future time-lapse surveys will be adjusted to cover the expected plume size growth with continued injection.

The timing and deployment of time-lapse seismic surveys are continually assessed to manage containment and conformance risk and to ensure monitoring compliance.

This is a function of:
- Measured plume growth and shape from previous measurements.
- Predicted plume growth and shape based on conformance modelling.
- Increased containment risk.
- Increased conformance risk.

4.6.5.2 InSAR

InSAR is a satellite remote sensing method designed to map displacements of the Earth's surface that may be related to displacements at depth. InSAR was evaluated as a technique to be used within the Quest MMV program. Based on the outcome of the special report on InSAR efficacy [6], the InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). It will be used in the event of another MMV technology or observation indicating the need for further investigation. Satellite image programming and acquisition is planned to continue over the next three years using a single frame centered over the 3 injection well pads.

4.6.5.3 Observation Wells within the Basal Cambrian Sands Formation

As of Q1 2017, IW 5-35 is currently being utilized as a BCS monitoring well.

The BCS pressures are being monitored continuously at wells IW 8-19, IW 7-11 and IW 5-35). Long-term continuous pressure monitoring is the basis for history matching dynamic reservoir models.

The wells IW 8-19, IW 7-11 and IW 5-35 are currently the only direct observation points within the BCS. In accordance with AER Condition 10i, the potential need for installing additional monitoring wells will be re-assessed on an annual basis.

4.6.5.4 Deep Monitoring Wells (Above BCS Storage Complex)

There is one deep monitoring well (DMW) on each injection well pad which is completed in the Cooking Lake Formation with downhole pressure and temperature gauges.

AER Approval 11837A Conditions 10i and 10j require the consideration of the potential need for installing additional monitoring wells towards the periphery of the area of pressure increase. This would occur later in the project life and includes an evaluation of the need for additional deep monitoring wells adjacent to the four legacy wells in the approval area. The current pressure monitoring program is adequate.

Three regional aquifers (Winnipegosis Formation, Beaverhill Lake Group, and Cooking Lake Formation) were evaluated in the 2012 – 2013 drilling campaign and it was determined that the Winnipegosis/ Contact Rapids Formations were tight and that the Cooking Lake Formation is the best monitoring interval. As such, an application was submitted and approval to monitor in the Cooking Lake was granted from Alberta Energy in May 2012.

Due to regional third party activities in the Leduc and Cooking Lake, pressure monitoring is complicated. To aid in the interpretation of pressures observed in the Cooking Lake Formation, the Redwater 3-4 well was completed in 2015 to monitor far field pressures responses to non-Quest activities.

In addition to the DMW pressure monitoring, DMW 8-19 is instrumented with a conventional permanent eight level downhole geophone array to support microseismic monitoring. The IW 8-19 pad was selected as it is at the centre of the development.

4.7 Performance Targets for CO_2 Inventory Accuracy

4.7.1 Composition of injection stream

As per AER Approval No 11837C Condition 5e): *The injectant must contain no less than 95 per cent of CO_2 by volume.*

4.7.2 Volume of injected CO_2

As per AER Approval No 11837C Condition 5d): *the cumulative injection volume for all approved scheme wells must not exceed 14 500 million cubic metres of CO_2 at standard conditions (15^{o}C, 101.325 kPa), which is an equivalent mass of 27 million tonnes*.

4.8 Performance Targets for Conformance Monitoring

4.8.1 Monitoring CO_2 Plume Development

Time-lapse seismic data (VSP2D, SEIS2D, SEIS3D) are being used to monitor the development of the CO_2 plume inside the BCS storage complex. Time-lapse seismic methods are able to identify the replacement of brine with CO_2 in the BCS, and are expected to yield an image of the CO_2 plume geometry around each CO_2 injector, but not the distribution of CO_2 saturations inside the pore space.

Feasibility studies and baseline data acquisition indicate that seismic methods have an expected lateral and vertical resolution of 25 m and 10 m, respectively. Increases in CO_2 saturation of above 5% should be detectable in layers of 5-10m thickness. This resolution is sensitive to non-repeatable noise and signal repeatability.

4.8.2 Monitoring Pressure Development

4.8.2.1 Downhole Pressure Temperature Gauges

Downhole Pressure Temperature (DHPT) gauges in the injection wells are being used to monitor the development of fluid pressure inside the BCS storage complex. The DHPT gauges provide direct continuous measurements of pressure changes at these discrete locations.

As per AER Conditions 4d, 5b, 6a, 10b, 11c, and 17g, collection and analysis of shut-in stabilized pressure fall-off tests (or analytical equivalent) and pressure transient analyses are reported on an annual basis. The initial baseline BCS pressure transient analyses for all three injection wells were submitted as part of the second annual status report submitted to AER January 31, 2014 [4].

4.8.2.2 InSAR

Based on the outcome of the special report on InSAR efficacy [6], the InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). It will be used in the event of another MMV technology or observation indicating the need for further investigation..

4.8.2.3 Modelling

Models are run on a regular basis to provide an ongoing assessment of well and reservoir performance. These models allow for trending information on storage performance.

Models are updated in accordance with AER conditions 4, 6, 10c, 17f. For instance, Condition 6 of Approval 11837C states that "*If monitoring shows loss of containment or unexpected surface heave the Approval Holder is required to conduct and submit results of more comprehensive project modeling using site-specific parameters to re-evaluate the issue of deformations caused by pressure changes.*". In addition, model updates will be submitted to the Minister of Energy as per of Regulation 19 3) c in accordance with the Mines and Mineral Act Carbon Sequestration Tenure Regulation 68/2011.

4.9 Performance Targets for Containment Monitoring

4.9.1 Monitoring the Atmosphere

The sensitivity and resolution of detecting and mapping CO_2 emission depends on distance from the sensor system:

- **On Well Pad**: A sustained 45 kg/ hour (1 tonne/day) release rate of CO_2 from a localized source would be detectable and locatable from a range of 100 m, and its location mapped within a resolution of about 10 m under moderate windspeed conditions. This is for daytime acquired data and is subject to the variety of wind directions sampled.
- **Within 1 km radius of a well pad**: A release rate of 800 kg/hr (200 tonnes/day) would be detectable and the direction to the source well defined; however the inferred distance to the source will be less well defined (depending on its actual range and weather conditions).

4.9.2 Monitoring the Hydrosphere

There are three key approaches used to monitor the hydrosphere:

- **Continuous water electrical conductivity (WEC) monitoring** at each of the project groundwater monitoring wells for detection of changes in water salinity. WEC may be impacted due to potential increase in ionic strength associated with acidification of groundwater that could be caused by CO_2 intrusion. It can also indicate an influx of brine from formations below the base of groundwater protection zone. There is no risk of brine leakage from the BCS storage complex above the BGWP (Section 3.1.3).
- **Continuous water pH (WpH) monitoring** at each of the project groundwater monitoring wells. This enables the detection of changes in pH that could potentially be associated with increased levels of dissolved CO_2 within the groundwater.
- **Discrete water/ gas sampling and analysis** within the project groundwater monitoring wells and a selection of accessible/active landowner groundwater wells are used to verify the absence of any impact upon water quality due to CO_2 injection.

Continuous WpH and WEC data are assessed relative to the data collected during the pre-injection phase in order to check whether or not values fall within expected range(s).

Results from the discrete sampling events are assessed using project specific triggers. For further details please refer to Section 7.2.3.3 of the 2015 MMV plan [5].

4.9.3 Monitoring Injection Well Integrity

4.9.3.1 Mechanical Well Integrity Testing

Mechanical Well Integrity Testing consists of annually pressure testing according to the AER D51 as it was in effect at the time of application approval.

4.9.3.2 Time-lapse Logging and corrosion monitoring

Cement Bond Logs, Ultrasonic Casing Logs, Casing Caliper and Electromagnetic Casing Logs verified the initial integrity of the cement bond and well completion along the entire length of each injector. These are re-acquired every five years to verify continuing cement bond and casing integrity.

Hydraulic isolation testing was performed using temperature logs and pulsed neutron logs after 8 months of injection to prove the initial integrity of the cement bond. A second set of hydraulic isolation logs will be performed during the second year of injection. Thereafter, the need will be determined by the annual reporting process as per AER Approval Condition 5c. Pulsed neutron logging has been used on a large number of CCS Projects to identify CO_2 accumulations behind casing. Log interpretations are included in the annual status reports to AER, and raw logs will be submitted through the standard log submission process.

4.9.3.3 Hold-Up Depths

Hold-up Depths (HUD) are measured in conjunction with the CBL / MWIT / USIT / EMIT logs to ensure no plugging exists across the perforation interval.

4.9.3.4 Distributed Temperature Sensing

Continuous Distributed Temperature Sensing (DTS) is being recorded along an optical fiber permanently installed in each injection well. All fiber optic cables are clamped to the outside of the production casing and cemented in place.

DTS is currently considered a novel technology with regards to wellbore integrity assessment in CO_2 injection wells and needs further maturation. At present, it can only be used for a qualitative assessment primarily by observing rates of change in temperature over time, and the integration of temporal data on CO_2 flow into the injection wells.

4.9.3.5 Distributed Acoustic Sensing

The 2015 approved MMV Plan [5] referred to the evaluation of potential applications of DAS monitoring based on the optical fibers installed within the injection wells including:

- acoustic monitoring for leak detection;
- detection of small temperature changes;
- continuous microseismic acquisition and data analysis;
- determine mechanical integrity of cement.

Assessment of these potential applications has ceased, as existing and implemented technologies in the current MMV plan have demonstrated sufficient monitoring and risk mitigation.

There are also no additional feasibility studies which currently support additional DAS applications for monitoring well bore integrity of the Quest wells. DAS technology continues to evolve and develop, and the opportunity for future DAS deployment will be assessed as required.

4.9.4 Monitoring Geological Seal Integrity

4.9.4.1 Continuous Pressure Measurements

Continuous pressure measurements (DHPT) within the deep monitoring wells provide a means of detecting material migration of injected CO_2 or brine out of the BCS storage complex. The Cooking Lake is the interval that is monitored at all three injection sites.

An induced, detectable and sustained pressure rise into the Cooking Lake has been assessed with the baseline pressure data available and included in Table 4-3.

4.9.4.2 Time-lapse Seismic Data

Time-lapse seismic data (VSP2D, SEIS2D, SEIS3D) are used to verify the absence of CO_2 above the ultimate seal of the BCS storage complex. In the vicinity of the wells, it is the permeable and under-pressured Cooking Lake Formation that is being used to verify the absence of CO_2 above the storage complex (Section 4.1).

Any CO_2 unexpectedly entering an overlying formation will affect the seismic image due to the same fluid substitution effects demonstrated in the BCS. Due to different formation properties and different in-situ temperature and pressure conditions affecting the properties of CO_2, the magnitude of anticipated time-lapse seismic changes in the unexpected event of CO_2 entering these formations will vary. Feasibility studies indicate that time-lapse effects will likely be detectable from the seismic images for a contiguous CO_2 plume in the Cooking Lake Formation.

4.9.4.3 Microseismic Monitoring

Induced microseismicity results from fracture propagation, fault slippage, fluid movement, and pressure relaxation in a formation caused by pressure changes and associated stress states within the subsurface. A microseismic array is being used to monitor microseismic activity within the storage complex that may be indicative of potential fracture propagation into the Lotsberg Salts.

Microseismic (DHMS) monitoring using an eight level conventional downhole geophone array with three-component retrievable geophones was deployed in DMW 8-19 in November 2014. The microseismic monitoring performance of a conventional downhole geophone array is well established through observed field performance elsewhere. Similar downhole geophone arrays have operated elsewhere for more than ten years.

The array began recording pre-injection data in November 2014 in order to verify the amount of microseismic activity within the vicinity of this injector prior to CO_2 injection. In the pre-injection period, no ambient microseismic events were detected within the monitoring range of the array.

Feasibility modelling predicts that microseismic events with M_o of –2 should be detectable out to 800 m, events with M_o = -1 should be detectable out to a distance of 3000 m and events with M_o = 0 should be detectable out to a distance of 10,000 m from the geophone array. Observed monitoring performance has confirmed this sensitivity.

4.9.4.4 Injection Pressure and Rate Monitoring

Well injection pressure and associated rates provide a continuous means to verify the absence of injection induced fracturing within the BCS:

- The flow rate at Scotford and on well sites is measured with a Coriolis mass flow meter with a minimum accuracy of +/ -0.5% of reading (typical ± 0.1%).
- The pressure is measured with gauges with +/- 0.1% accuracy.
- The temperature is measured with gauges with +/- 0.5 ºC accuracy.

These estimates are based on the technical specifications of the flow rate, pressure, and temperature monitoring systems. This is a mature, industry standard technology and any failed gauge will be replaced during a scheduled well work-over.

Downhole pressure temperature gauges are used to ensure downhole injection pressures do not exceed the approved maximum value of 30 MPa [1]. The injection pressures based on current operations and modelling are considerably lower than this threshold over the life of the project.

Additionally, when injection is halted at a well, the gauges record the pressure fall. Analysis of this shut-in period can be used to further validate the absence of induced fracturing.

4.9.4.5 InSAR

Based on the outcome of the special report on InSAR efficacy, the InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). It will be used in the event of another MMV technology or observation indicating the need for further investigation.

4.9.5 Trigger Events and Detection Thresholds

Assessment of loss of containment is based on a tiered system of the various technologies deployed as part of the MMV Plan. Table 4-3 provides a list of the technologies and their assigned tier. Trigger events will be used to initiate any control responses if required to safeguard containment.

Tier 1 technologies are focused on a) addressing the key threat of containment which is “Migration along an injection well” and b) monitoring as close as possible to the storage complex. Tier 1 technologies form the basis for assessing whether or not there is an indication of loss of containment. Depending on the outcome, further analysis or investigation of the Tier 2 technologies will be undertaken, and then if needed Tier 3 technologies will be assessed. The Tier 3 water and gas geochemical analyses from private landowner groundwater wells will support engagement with those stakeholders.

Table 4-3: Technologies used to assess loss of containment at Quest including trigger events considered.

Tier	Technology	Indicator	Surveillance Frequency	Trigger	Magnitude of CO_2 Detection Capability
Tier 1	IW DHP	Pressure	Continuous	Measuring greater than 26 Mpa	N/A
	DMW DHP	Pressure	Daily	Anomalous pressure increase above background levels	deca tonne/day
	MSM	Locatable MS events	Daily	Sustained clustering of events with a spatial pattern indicative of fracturing upwards	N/A
	DTS	Temperature outside of casing	Daily	Sustained temperature anomaly outside casing	Qualitative
Tier 1 - when available	Pulsed Neutron log	Log Response	As per AER directive, every 5 years	Indication of CO_2 out of zone	Qualitative
	SCVF	Geochemical composition	Annually	Change in geochemical composition indicating presence of project CO_2	Qualitative
	VSP2D	Seismic amplitude	Yearly to bi-yearly, after the start of injection [i]	Identification of a coherent and continuous amplitude anomaly above the storage complex	kilo tonne/day
	SEIS3D, SEIS2D	Seismic amplitude	As required [i]	Identification of a coherent and continuous amplitude anomaly above the storage complex	kilo tonne/day
Tier 2	WPH [ii]	Water pH	Daily	Sustained decrease in baseline pH values	Qualitative
	WEC [ii]	Water Salinity (electrical conductivity)	Daily	Sustained increase in baseline WEC values	Qualitative
	LightSource	CO_2 emission rate	Daily	Sustained locatable anomaly above background levels	tonne/day (well pad)
Tier 3	Shallow groundwater wells: water / gas geochemical analyses	Table 4-2	variable dependent upon groundwater well type (see section 4.6.2)	Outside expected range	Qualitative
Feasibility stage	InSAR [iii]	Surface heave	to be defined	Unexpected localized surface heave	Qualitative

Notes:

N/A: not applicable

Continued performance monitoring of these technologies and data will be used to verify, and if necessary, update these events

i - The time-lapse seismic deployment and timing will be based on the observed and predicted CO_2 plume growth rate and risk assessments, rather than preset dates.

ii – gauges in GWW project wells only (see section 4.6.2.1)

iii - Continuation of acquisiton will be revisited in 2017 after completion of InSAR Efficacy Report (Condition 16 of AER Approval 11837C)

5 Operating Procedures

Shell will operate the Project in accordance with AER Approval 11837C Conditions [2]. The following AER Approval Conditions specifically relate to operation procedures and are adhered to as follows:

1) Condition 5f – inform WellOperations@aer.ca if leak or potential leak detected in the tubing/casing annulus or packer in the injection well.
2) Condition 5g – immediately suspend injection and notify WellOperations@aer.ca if fluid movement above BGWP or any zone outside the BCS storage complex.
3) Condition 5h – immediately suspend injection operations if failure of any systems that compromise safe operations of the scheme occur.
4) Condition 5i – immediately report any movement of fluids into or above the MCS, or anomalous pressure changes occurring anywhere within the CO_2 disposal approval area to ResourceCompliance@aer.ca and WellOperations@aer.ca.
5) Condition 6 and 25 – provide written incident report within 90 days to ResourceCompliance@aer.ca, WellOperations@aer.ca and AEP Water Policy Branch for the following:
    a. Any movement of fluid out of BCS Formation or above MCS
    b. Any anomalies that indicate fracturing out of the BCS formation
    c. Any indications of loss of containment
    d. Unexpected surface heave, and
    e. Appropriate mitigative measures taken.
6) Condition 26 – immediately notify the Ministry of Environment and Parks at 1-800-222-6514 regarding any loss of CO_2 to the atmosphere, soils or shallow (non-saline) aquifers and provide an incident report as per Condition 6 and 25 above.

5.1 Operating Procedures in Response to Monitoring Trigger Events

Continuous or discrete monitoring systems may trigger alarms that require an initial prompt response such as:

Down-hole pressure and temperature gauge trigger event

- **Alarm indicates**: down-hole injection pressure trends towards maximum injection pressure.
- **Alarm response**: Quest Storage team to evaluate and make recommendation to reduce the pressure escalation including but not limited to: bringing on additional injection well or reducing injection rate.

LightSource

- **Trigger event indicates:** Localized CO_2 flux exceeds excepted values.
- **Alarm response:** investigate location and under-take site specific study as deemed necessary.

Hydrosphere trigger event

- **Trigger event indicates:** Water electrical conductivity above expected threshold/ trigger values, water pH below expected threshold/ trigger values, and/or project trigger greater than 1 for hydrosphere.
- **Alarm response:** investigate using an integrated response plan-IRP (Figure 5-1) with primary (e.g. misidentified well name, wrong sample number, transcription error) and secondary checks (e.g. assess historical information, review data for other parts of AOR, review findings from other MMV monitoring technologies).

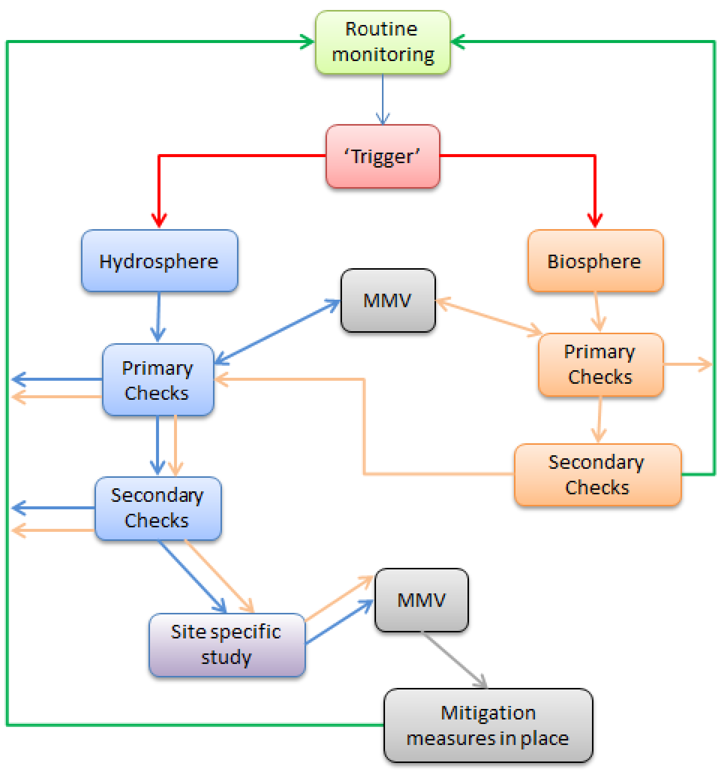

Figure 5-1: Schematic overview of Integrated Response Plan.

Distributed temperature sensing alarm

- **Trigger event indicates:** anomalous rate of change in temperature versus time.
- **Alarm response:** investigate and, if necessary stop injection into the well being investigated and plan additional logging or an appropriate well work-over, before re-starting injection in that well.

Down-hole microseismic monitoring alarm

- **Alarm indicates:** Abnormal microseismic activity.
- **Alarm response**: Review with other monitoring data and potentially reduce injection pressures at wells when appropriate. If investigation discovers an increased risk to containment, Shell will submit an incident report.

5.2 Response Times of Safeguards to Ensure Conformance

The following monitoring-supported safeguards are planned to prevent or correct a situation where the lateral extent of the CO_2 plumes or pressure build-up exceeds their model-based predictions.

CO_2 plume development

- **Monitoring:** Time-lapse seismic data
- **Intervention Indicator:** The observed CO_2 plume is larger than baseline seismic area, or there is a clear temporal trend towards this state.
- **Control Options:** Update models and rely on only model based predictions. If necessary increase the areal extent of the baseline seismic survey. Consider re-distributing injection across existing wells or drilling additional injection wells to keep the plume within the footprint of the baseline seismic area.
- **Response Time:** 3 – 6 months for model updates. 12 months for additional seismic surveys due to seasonality. Re-distribution of injection between existing wells is available on demand. Drilling additional injection wells will take 12 – 18 months and are subject to additional regulatory approvals and land access consents.

Pressure development

- **Monitoring:** BCS pressure gauges and supplemented by InSAR when necessary.
- **Intervention Indicator:** The observed lateral extent of pressure rise sufficient to lift BCS brine above the base of groundwater protection is larger than the current monitoring area or there is a clear temporal trend towards this state.
- **Control Options:** Update models and rely on only model based predictions..
- **Response Time:** 3 – 6 months for model updates. 1-3 months to schedule additional InSAR data acquisition.

The following additional safeguards are planned to ensure accurate CO_2 inventory measurements are available and that the target CO_2 inventory is achieved.

Injected mass of CO_2

- **Monitoring:** Wellhead injection rate metering on each injector and rate metering at the compressor outlet in Scotford, minimum technical accuracy of 0.5%

- **Intervention Indicator:** Based on existing acid gas disposal regulations, a difference greater than 5% between the sum of monthly CO_2 injection volumes for all injection wells and the Scotford fence-line meter. This is subject to revision as the regulatory framework assessment is ongoing.
- **Control Options:** Recalibrate or, if necessary, replace meters or revise the performance target.
- **Response Time:** 1 – 3 months.

Target inventory of CO2

- **Monitoring:** Down-hole pressure monitoring for each injector.
- **Intervention Indicator:** The rate of pressure increase on each injector is large enough to reach the maximum down-hole injection pressure (30 MPa) before cessation of injection.
- **Control Options:** Drill additional injection wells.
- **Response Time:** 12-18 months are likely required to drill an additional injector in one of the remaining pre-selected locations.

Each aspect of conformance is managed by a single monitoring system designed to trigger one of several possible control measures. This collection of control measures is expected to be effective at ensuring conformance provided the monitoring systems perform as expected. In the unlikely event of poor monitoring performance, contingency monitoring plans are in place that will provide timely alternative systems to monitor conformance (Section 6). The likelihood of an unexpected loss of conformance despite the control measures in-place is low.

5.3 Response Times of Safeguards to Ensure Containment

The following monitoring supported safeguards are planned to prevent or correct any potential loss of containment.

Safeguards supported by Pressure Monitoring

- **Monitoring:** BCS pressure gauges and supplemented by InSAR when necessary
- **Intervention Indicator:** BCS pressure increase at a legacy well is sufficient to lift brine above BGP or there is a clear temporal trend towards this state.
- **Control Options:** Re-distributing injection across existing wells, increase frequency of groundwater fluid/soil sampling and analysis next to the legacy well, consider drilling a deep monitoring well and/or a project groundwater well at this location.
- **Response Time:** Injection rates can be re-distributed immediately. Additional groundwater fluid samples and soil and vegetation data can be acquired within 2 weeks. 6 months are likely required to drill a project groundwater well and 12-18 months to drill an additional deep monitoring well at the legacy well locations.

Safeguards supported by injection well integrity monitoring

- **Monitoring:** Cement bond logging, tubing-casing annulus pressure monitoring, casings annuli pressure monitoring, mechanical well integrity monitoring, corrosion coupons, distributed temperature sensing, distributed acoustic sensing, Cooking Lake Formation pressure monitoring, time-lapse seismic data

- **Intervention Indicators:** significant deterioration of cement bond, increase in sustained annulus pressure above expectation, failed well integrity test, sustained temperature or noise anomaly outside casing, sustained Cooking Lake Formation pressure, or a time-lapse seismic anomaly around the injection well within the Winnipegosis Formation or shallower.
- **Control Options:** Cross-check information with other monitoring data. If data indicative of loss of containment re-distribute injection away from this well, repair the well by changing the failed completion component(s) or re-plugging with cement, or plug and abandon an injector that cannot be repaired, and drill a replacement well.
- **Response Time:** Continuous pressure monitoring supports an automated instant control response to re-distribute injection (Section 0). 1 – 3 months are likely required to plan and execute a well intervention. 12-18 months are likely required to drill an additional injector in one of the remaining pre-selected locations.

Safeguards supported by geological seal integrity monitoring

- **Monitoring:** BCS pressure monitoring, Cooking Lake Formation pressure monitoring, time-lapse seismic data, downhole microseismic monitoring, and supplemented by InSAR when necessary
- **Intervention Indicator:** BCS injector pressure exceeds agreed limits, sustained Cooking Lake Formation pressure, time-lapse seismic anomaly above BCS storage complex, InSAR anomaly due to volume changes above the ultimate seal or within a sustained clustering of microseismic events with an upward spatial pattern indicative of fracturing above the base of the Lower Lotsberg Salt.
- **Control Options:** Re-distribute injection across existing wells, drill an additional injector, or stop injection. Consider reservoir fluid extraction to reduce pressures inside the BCS storage complex.
- **Response Time:** Continuous pressure monitoring supports an automated instant control response to re-distribute injection. Microseismic monitoring requires 1 month for processing and interpretation. Time-lapse seismic data and InSAR monitoring requires 6-12 months for processing and interpretation. 12-18 months are likely required to drill an additional injector in one of the remaining pre-selected locations. Implementing a scheme for reservoir fluid extraction and re-disposal will take at least 24 months.

Safeguards supported by hydrosphere monitoring

- **Monitoring:** Project groundwater wells with continuous water electrical conductivity and pH measurements, regular groundwater sampling and geochemical analyses of all project groundwater wells and a selection of private landowner groundwater wells.
- **Intervention Indicator:** Sustained increase in water electrical conductivity, sustained decrease in pH, presence of project-specific tracers within groundwater samples.

- **Control Options:** Conduct groundwater and biosphere investigations, implement exposure controls and remediation measures. If required, stop injection at the well(s) suspected to be the source of these impacts.
- **Response Time:** 1 – 3 months are likely required to conduct these investigations and deploy the appropriate control measures.

Safeguards supported by biosphere monitoring

- **Monitoring:** Soil gas flux and tracer analysis at well locations if deemed necessary.
- **Intervention Indicator**: Soil gas flux and /or project-specific tracers measured outside of expected range.
- **Control Options:** Conduct groundwater and biosphere investigations, implement exposure controls and remediation measures. If required, stop injection at the well suspected to be the source of these impacts.
- **Response Time:** 1 – 3 months are likely required to conduct these investigations and deploy the appropriate control measures.

Safeguards supported by atmosphere monitoring

- **Monitoring:** LightSource
- **Intervention Indicator:** Sustained localized anomalous concentrations detected using a statistical process control model followed by an assessment to locate and to quantify an anomaly using a dynamic linear model.
- **Control Options:** Conduct soil and groundwater investigations at the site of the indicated anomaly. Implement exposure controls. If required, stop injection at all wells suspected to be the source of these emissions.
- **Response Time:** 1 –3 months are likely required to conduct these investigations and deploy the appropriate controls measures.

6 Contingency Monitoring Plans

This section describes how the monitoring plan will be adapted in response to a range of unexpected but possible scenarios for under-performance of the monitoring systems. The monitoring plan comprises many diverse monitoring technologies. Each was selected on the basis of site-specific technical feasibility evaluations indicating its likely suitability for the task. Because containment monitoring is a safety-critical task, multiple independent monitoring systems are designed to fulfill each task. This multiple-redundancy is designed to mitigate the risk of unexpected under-performance of an individual monitoring system – this form of contingency is built into the monitoring plan.

The same approach is not required for conformance monitoring systems as any unexpected under-performance in this domain is not immediately safety-critical. The risk of failed conformance monitoring, hence, may be mitigated by developing alternative monitoring systems that are ready to be deployed only in the unexpected event that they are required.

The following sections describe the contingency plans for conformance monitoring and for selected containment monitoring systems which would require adaptation or replacement should they under-perform.

6.1 Measurement equipment

The equipment used for continuous measurement of certain parameters to address the targets of CO_2 Inventory Accuracy, Conformance Monitoring, and Containment Monitoring is unavailable.

- **Reason**: equipment failure or off-line for QA/QC and/or maintenance.
- **Indicator:** no data being transmitted, or data drift.
- **Mitigation:** scheduled QA/QC and maintenance checks of measurement equipment; redundant measurement system (e.g. collection and analysis of regular discrete samples in addition to continuous measurements; more than one technology available to address a specific threat (see Fig. 3-2); adjust collection and analysis of regular discrete samples; potential sample collection for third party off-site laboratory analysis).

Note that in case safe operation of the scheme is compromised due to failure of equipment, injection operations will be suspended as per Approval 11837C condition 5) h) "*immediately suspend injection operations if any injection equipment, monitoring equipment, or safety devices fail that could compromise the safe operation of the scheme*".

6.2 InSAR

There are a number of potential shortcomings regarding the usage of InSAR for MMV:

- *Surface displacements are too small to support reliable imaging of volume changes inside the BCS storage complex*
- *Unexpected surface uplift cannot be reconciled by volume changes inside the storage complex*

The special report on the efficacy of the InSAR program [6] highlighted the following:

InSAR is a viable technology for assessing unexpected surface heave. Its value, however, is limited for continuous monitoring given the site specific characteristics of the Quest site. Based on the observed and modelled pressure build-up within the BCS, expected to be less than 1.5 MPa after 25 years of injection (using a two well injection scenario), dilation within the BCS storage complex will be small. The resulting surface uplift will likely fall within the noise levels of the measured ground displacement. As a result, InSAR has limited value as a continuous monitoring technology for unexpected containment issues. As injected volumes increase, it may have some value from a conformance perspective. Hence, The InSAR technology will be considered a contingency monitoring technology with a focus on the AOR (area of review) of the Quest SLA (sequestration lease area). It will be used in the event of another MMV technology or observation indicating the need for further investigation.

6.3 Time-lapse Seismic Data

The potential shortcoming regarding the usage of time-lapse seismic data for MMV is:

The rate of CO_2 plume growth is different than expected.

- **Reason**: Uncertainty about reservoir properties such as relative permeability result in a CO_2 plume growing at a rate substantially different from the median predicted rate.
- **Indicator:** Time-lapse seismic methods show that at least half of the CO_2 plume is reaching the imageable limit.
- **Mitigation:** Switch from VSP to surface seismic for monitoring the CO_2 plume.

References

[1] Alberta Government Carbon Capture and Storage knowledge sharing website, http://www.energy.alberta.ca/CCS/3845.asp, last accessed 5 Dec 2016.
[2] Alberta Energy Regulator Carbon Dioxide Disposal & Containment Approval No. 11837C. Issued to Shell Canada Limited May 12th, 2015.
[3] AER Third Annual Status Report, available at Alberta Government Carbon Capture and Storage knowledge sharing website, http://www.energy.alberta.ca/CCS/3845.asp, last accessed 5 Dec 2016.
[4] AER Second Annual Status Report, available at Alberta Government Carbon Capture and Storage knowledge sharing website, http://www.energy.alberta.ca/CCS/3845.asp, last accessed 5 Dec 2016.
[5] 2015 MMV plan, , available at Alberta Government Carbon Capture and Storage knowledge sharing website, http://www.energy.alberta.ca/CCS/3845.asp, last accessed 5 Dec 2016.
[6] Special report on the efficacy of the InSAR program submitted to the AER on 31 March-2017 in response to Condition 16 of the Carbon Dioxide Disposal Approval No. 11837C.