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Quest CCS Project

Independent Project Review (IPR) of Storage Component of the QUEST Carbon Capture and Storage Project

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Signatures for this revision

Date	Role	Name	Signature or electronic reference (email)
	Originator	Jorg Aarnes (DNV)	
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Summary

The Independent Project Review (IPR) of the storage component of the QUEST Carbon Capture and Storage (CCS) project was managed and facilitated by DNV with the onsite review with the expert panel taking place in the week from 4-8 Oct 2010. The overall objective of the IPR was to prepare an independent assessment of the suitability of the targeted storage site for sequestration of 1.2 Megatons (Mt) CO2 per annum for a minimum of 10 years, with possible extension of the injection period to a total of 25 years.

Keywords

Quest, CCS, CO2 sequestration, External review, Independent Assessment, Expert panel, Risk review

DET NORSKE VERITAS

Independent Project Review (IPR) of Storage Component of the QUEST Carbon Capture and Storage Project

Shell Canada Energy

2010-9343

Revision 2, 2010-11-19

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Report No.:	2010-9343	Subject Group:	Technical paper
Summary:	The current report represents the results and conclusions of an independent project review (IPR) of the storage component of the QUEST CCS project. The IPR was managed and facilitated by DNV, and performed by an expert panel contracted by DNV. The objective of the IPR was to prepare an independent assessment of the suitability of the targeted storage site for sequestration of 1.2 Megatons CO_2 per annum for a minimum of 10 years, with possible extension of the injection period to a total of 25 years. To this end, the expert panel was tasked to do a "critical review of the project's risk assessment work performed."		
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Executive Summary

The current report represents the conclusions of an independent project review (IPR) of the storage component of the QUEST Carbon Capture and Storage (CCS) project. The IPR was managed and facilitated by DNV, and performed by a DNV contracted expert panel (Panel). The overall objective of the IPR was to prepare an independent assessment of the suitability of the targeted storage site for sequestration of 1.2 Megatons (Mt) CO_2 per annum for a minimum of 10 years, with possible extension of the injection period to a total of 25 years. The review was performed Sept.-Nov. 2010.

Extensive work has been performed by QUEST to identify, select and characterize a site suitable for geological storage of the required volumes of CO_2 for the CCS project. The Panel agrees that ample evidence has been provided to demonstrate that the selected site is naturally suited for geological storage of CO_2. The results of site characterization give confidence in the following statements:

- There is sufficient pore space for the required 27 Mt of CO_2.
- Injectivity can be sustained for the planned duration of CO_2 injection operations, i.e., 25 years.
- Any migration of injected or displaced reservoir fluid out of the containment complex is extremely unlikely.

DNV and the Panel further agree that a risk and uncertainty management framework appropriate for the storage site is in place. In particular, the risk management framework should ensure that any signs of migration of injected or displaced reservoir fluid out of the containment complex are detected sufficiently early to allow corrective actions to be implemented before adverse impacts can occur.

The risk assessment activities have been carried out in a very comprehensive and systematic manner. In the opinion of DNV, particularly two elements represent pioneering work within risk management: The systematic way that identification and management of uncertainty is integrated with the risk assessment, and the development of a risk-based Monitoring, Measurement and Verification (MMV) plan that may set a precedent for design of MMV programs for CCS projects world-wide.

Disclaimer note:
The Panel members were asked to commit a total of 10 days for the IPR. Due to the relative limited time devoted to the IPR, it should be recognized that the opinions of the review panel expressed in this report should be considered in the context of the amount of information that the experts were able to adequately assess during the allocated time. For instance, there was limited time to review the full basis for assessment and ranking of each individual identified risk. There are therefore technical details that the Panel has not had opportunity to review that limit the extent to which they could form specific opinions.

Also, the Panel found it difficult to judge the amount of risk reduction from planned risk mitigating actions that were yet to be implemented. The opinions expressed with regards to the appropriateness of assessed target risk levels should therefore be considered in the context of the level of uncertainty attached to the effect of the planned actions to reduce current risk levels.

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1 INTRODUCTION

The current report represents the conclusions of an IPR of the storage component of the QUEST CCS project. The IPR was managed and facilitated by DNV, and performed by a DNV contracted expert panel (Panel). The Panel was put together to ensure that expertise covering all discipline areas relevant for performing an independent assessment of the storage project was adequately covered.

The overall objective of the IPR was to do an independent assessment of the suitability of the targeted storage site for sequestration of 1.2 Mt CO_2 per annum for a minimum of 10 years, with possible extension of the injection period to a total of 25 years. To this end, the Panel was tasked to do a "critical review of the project's risk assessment work performed." As part of this task, the Panel members were asked to answer the following questions related to the suitability of the targeted storage site based on their individual judgment:

A. Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity and containment (and conformance[1])?
B. Are plans for future characterization work suitable to enable a decision on a final injection plan?
C. Is there an appropriate risk and uncertainty management framework in place for the storage site?
D. Are the risks and uncertainties related to the storage project adequately understood and classified in terms of probability and consequences?
E. Are the right plans in place in the next phase to ensure that risks and uncertainties of CO_2 storage reach acceptable levels?
F. Are there any additional risks within the scope of the project have not been identified?

Here, "this stage" refers to the expected level of maturity of site characterization and appraisal activities given the timeline to make the Financial Investment Decision during Q1 2012. This implies that the characterization and appraisal activities should demonstrate a level of maturity that would allow the final concept selection for the site development plan to be made. The target date for concept selection is July 2011. The next stage of the project is therefore defined as the period October 2010 – July 2011.

Prior to the concept selection, which includes finalizing plans for preferred injector locations and development of a Monitoring, Measurement and Verification (MMV) plan and concept, further appraisal activities will be carried out. In particular, an additional seismic survey, a water injection test and a potential CO_2 injection test at the Radway 8-19-59-20W4 well are still outstanding. Activities to establish an environmental baseline have started, but many baselining activities are yet to be initiated.

Thus, the results of this IPR need to be considered in the context that the injection plan and the MMV plan are not yet finalized. A follow-up IPR is planned in 2011 when updated plans are available.

[1] Conformance was not part of the initial scope, but was added during the review process. The reason for including it was that part of the objective of the review was to do a critical review of the risk assessment work carried out by the QUEST subsurface team, and that the risks associated with the subsurface component of the QUEST project was split into four subcategories: capacity, injectivity, containment and conformance. The risks in each category were associated with a hypothesis that would support the statement that "the injection site has been adequately characterized at this stage of the project in terms of the corresponding characteristic". It was therefore natural to also consider the level of characterization in terms of conformance. It should be recognized, however, that this work is at an early stage and that many of the activities that are intended to manage conformance issues have not yet been initiated.

2 SYNOPSIS OF PANEL RESPONSE TO IPR QUESTIONS

Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity and containment (and conformance)?

Yes, the Panel agrees that ample evidence has been provided to demonstrate that the injection site has been adequately characterized at this stage of the project to give confidence that:

- There is sufficient pore space for the full life cycle (25 years) of the required volumes of CO_2.
- Injectivity can be sustained for the full life cycle.
- Injected reactive fluids will not leak significantly from the containment complex.

The Panel also agrees that the plans for further work should be adequate to build confidence in the following conformance criteria:

- Domains are mapped; current levels/fluxes of CO_2 are established and can be differentiated from project emissions; tolerances are understood.
- Likely and high risk (consequence) movements of injected CO_2 in the container and between each domain can be detected by proposed technology.

Are plans for future characterization work suitable to enable a decision on a final injection plan?

Yes, plans for future characterization work are suitable to enable a decision on a final injection plan.

Is there an appropriate risk and uncertainty management framework in place for the storage site?

Yes, the risk and uncertainty management plan is appropriate for the storage site.

Are the risks and uncertainties related to the storage project adequately understood and classified in terms of probability and consequences?

Yes, the modifications proposed to the assessed levels of risk by the Panel, applying the principle to account for uncertainty conservatively, are relatively minor. This indicates that the assessed levels of risks recorded in the risk register are generally representative of the risk significance.

Are the right plans in place in the next phase to ensure that risks and uncertainties of CO_2 storage reach acceptable levels?

Yes, contingent upon execution of studies listed in Section 3 and design and implementation of an appropriate risk-based MMV program for the storage site, the Panel agrees that the right plans are in place to ensure that risks and uncertainties reach acceptable levels.

Are there any additional risks within the scope of the project have not been identified?

No, the Panel agrees that the risk register contains all major *technical risks* that should be considered in a regulatory application for a storage injection license within the area of interest (AOI).

3 TECHNICAL RECOMMENDATIONS OF THE PANEL

The recommendations in Table 1 below are compiled from the assessments of the respective Panel members to capture a single and consistent set of recommendations. An observation is attached to each recommendation to give a brief justification and context for why the recommendation is made.

The recommendations do not necessarily represent studies or other work that should have been done at "this stage of the project". Rather the recommendations reflect work that the Panel considers should be done to continue to mature the project to the point of concept selection and beyond[2].

Table 1: Technical recommendations of the Panel

Observation	Recommendation
Questions concerning the potential for injecting volumes beyond the project design requirements of approximately 27 Mt may be relevant for optimizing pore space use. There seemed to be a mismatch between the static and material balance capacity estimates presented.	**Capacity:** 1. The QUEST subsurface team is advised to look beyond the 10 and 25 year periods of assessment to ensure that questions regarding potential future injection scenarios will be possible. 2. Reported capacity estimates should be consistent.
Proposed candidate monitoring technologies in the draft MMV plan may not provide the necessary information for verification of simulation models to determine the storage mechanism that can be a part of requirements during the regulatory application review process. Ultimately, it will likely be a requirement to demonstrate "how" the CO_2 is stored within the BCS. This might place additional demands on the MMV plan beyond what is currently anticipated, possibly including partitioning of capacity estimates with respect to solubility trapping, residual gas trapping and hydrodynamic trapping (mineral trapping is accepted to be negligible within the QUEST project).	**Capacity and Conformance:** 3. Potential techniques for monitoring the respective contribution of different storage mechanisms to ensure containment of injected CO_2 during the lifecycle of the project should be investigated. 4. Capacity estimates should be partitioned with respect to solubility trapping, residual gas trapping, and hydrodynamic trapping.
There was no study of the effect of non-isothermal injection of CO_2 on formation and injectivity. An inconsistency in the fracturing conditions within the BCS was identified in the text. For the risk "injection induced stress fractures geological seals" it is assumed that the BHP constraint of 28 MPa provides a sufficient margin (it is approximately 4 MPa below the interpreted fracture propagation pressure of the LMS) to be robust against the risk of fracture propagation out of the BCS. For the cooling conditions expected (and reported), it is	**Injectivity and Containment:** 5. A simulation study to investigate for the non-isothermal effect on CO_2 injection into the formation and its potential impacts on formation and CO_2 injectivity should be performed. 6. The risk "Injection induced stress fractures geological seals" should be subdivided into the following two elements: "Injection fractures BCS" and "Injection fractures geological seals".

[2] While the scope of the project was to consider additional site characterization and appraisal activities that the QUEST subsurface team should perform to mature the site up until the point of concept selection, it is recognized that some of the recommendations reflect activities that Shell may choose to perform after FID and regulatory approval. Hence, not all recommended studies in Table 1 would need to be performed to establish a sufficient basis for the concept selection, FID and regulatory approval. For instance, baselining activities that primarily serve to limit Shell's liability exposure could be performed after FID, at Shell's discretion.

possible that fracture conditions within BCS will be reached for pressures of 28 MPa because even modest assumptions of thermal properties for the BCS can result in predicted stress reductions that exceed 4 MPa.	
Modeling is performed with "synthetic relative permeability curves" obtained using the Shell Analogue Relative Permeability Database and derived from mineral-oil relative permeability measurements. The Panel feels that conducting relative permeability measurements for CO_2-brine systems for relevant temperature and pressure ranges would be a cost effective way to reduce uncertainty and mitigate injectivity and conformance risk associated with using inappropriate relative permeability curves.	**Injectivity and Conformance:** 7. Relative permeability measurements for CO_2-brine systems under expected temperature and pressure conditions should be performed.
Activities to establish a geochemical baseline for overlying aquifers is underway with ground water sampling, but it was not clear from the presentations if existing fluid compositional data bases were used. No numerical modeling was performed to characterize the potential impact of CO_2 or brine migration on shallow aquifer geochemistry. Documentation of potential geochemical reactions which could occur in the reservoir due to interactions of injected CO_2, formation water and formation minerals was insufficient to support conclusions in risk register. Statements about the potential reactions that may affect the geochemical stability of the seals were not validated by numerical analysis or by documentation.	**Injectivity, Containment and Conformance:** 8. It should be ensured that existing fluid compositional data bases for overlying aquifers are used to establish regional trends to be evaluated and incorporated into the shallow groundwater investigation and baseline water-chemistry monitoring program. Baseline chemical characterization of the formation fluids (water, gas) should be performed in as many units in the stratigraphic succession as possible. In particular, to characterize the impact of potential CO_2 and brine migration on shallow aquifer geochemistry it will be beneficial to set up a numerical model for shallow aquifer that incorporates results of mineralogical characterization as well as laboratory experiments on CO_2-water-rock interactions. 9. Further studies should be performed to characterize the potential geochemical reactions which could occur in the reservoir due to interactions of injected CO_2, formation water and formation minerals. These studies should include characterization and sensitivity analysis of the spatial and temporal variation in the mineralogy and fluid composition of the BCS. 10. Analysis to support statements about the potential reactions that may affect the geochemical stability of the seals should be prepared/made available.
The risks "Injection induced stress fractures geological seals" and "Injection stress reactivates fault" both depend on detailed measurements of stress states, hydraulic and elastic properties, and temperature fields, etc. Some of these have been measured, other measurements are planned, but the Panel was not shown	**Containment:** 11. Complete and integrate measurements of the elastic and hydraulic properties (porosity, permeability, compressibility, etc) of the sealing layers within and (at least) immediately above the storage complex, as well as of the stress state

a model of how they all fit together and interact.	within, and above, the storage complex.
No modeling has been performed to quantitatively assess the possibility of migration of brine along legacy wells under different scenarios. However, it is indicated that this is planned for the next stage.	**Containment:** 12. Modeling and simulation studies to investigate the possibility of migration of brine along legacy wells under different scenarios should be performed.
Reactivation of faults due to injection and possible injection-induced fractures were issues that were raised by the Panel for further consideration.	**Containment:** 13. A more detailed study of regional and local seismicity should be conducted.
The suite of monitoring technologies suggested and assessed for the storage site are comprehensive and the implementation strategy is well-founded. However, the description is very high-level and the efficacy of the techniques to be employed will depend significantly on how the monitoring surveys are designed. Numerical seismic modelling suggests that significant volumes of CO_2 will need to be injected for the plume to be detectable using 4D seismic surveys. It is proposed to map the extent of the plume initially using 3D VSP surveys. Again, this will depend on the survey design as VSP surveys are not ideal for imaging purposes due to the limited migration aperture.	**Conformance:** 14. The 3D VSP surveys should employ multicomponent geophones and pure modes as well as converted waves should be used to image CO_2 plume. Attribute studies, such as amplitude versus offset (AVO) should be fully exploited to match petrophysical data extracted with time-lapse logging data from the injection wells.
Considerable uncertainty is attached to the ability to monitor movements of the CO_2 within the storage complex with the technology proposed in the draft MMV plan. Although cross-well surveys provide information only in the local plane that contains the injection and observation wells, such surveys may provide local information about the vertical and lateral distribution of CO_2 (i.e. saturation profiles) that could be used to calibrate the interpretation of 3D VSP and surface seismic surveys; i.e. to match seismic response to a particular thickness/saturation model. The BCS facies model could then be used to propagate a possible realization of the saturation model elsewhere in the BCS. This would provide confidence in the ability of the seismic data to map the full extent of the CO_2 plume.	**Conformance:** 15. Consideration should be given to the option to augment the MMV plan by drilling an observation well to conduct cross-well surveys (seismic, ERT or EM) in the BCS.
It was unclear what boundary-conditions were used in the hydrogeology modeling. Different values for the density of the brine in the BCS were presented. It was also unclear what vertical pressure gradient in the BCS was used for modeling. It is stated that "DST data (supported by the sonic data) indicates that the Winnipegosis has pressures 3-5 MPa above the BCS". It is not clear if that data is reflected in the hydrogeology P-Z plots? It is also unclear what the pressure profile at the AOI is.	**Containment and Conformance:** 16. The hydrogeological characterization of the BCS aquifer should be completed, paying particular attention to mapping the lateral hydraulic gradients, including the effects of density-dependent flow on lateral flow rates, and flow directions, and calculating the formation-fluid flow rates. 17. If Pressure-Depth hydrogeological analysis has

It was not clear if a Pressure-Depth analysis had been undertaken. This would help build a stronger case for confined lateral flow in the BCS. It was not clear what the relationship is between the hydrogeology of the AOI and the hydrogeology of other mapped flow patterns in the Western Canadian Sedimentary Basin. In particular if the flow directions in the aquifers overlying Cooking Lake had been mapped (Upper Devonian, Mannville, Viking, etc.). These will have a direct input into the migration pathways for CO_2 from the BCS to the surface. No modeling has been performed to predict potential flow-paths for CO_2 or brine above the containment complex.	not been undertaken, it is recommended to do so. 18. The relationship between the hydrogeology in the AOI and the other mapped hydrogeological flow patterns in the Western Canadian Sedimentary Basin should be investigated in more detail. Should also look at mapped flow directions in aquifers above Cooking Lake. 19. The QUEST subsurface team is urged to undertake a three-dimensional "flow-path" groundwater modeling project to predict pathways of CO_2 or brine from the BCS to surface.
The results presented during the IPR appeared to have some ambiguity with respect to grid refinement.	**Containment and Conformance:** 20. The effect of numerical grid resolution on calculation results, especially on CO_2 plume migration, should be carefully reviewed.
Numerical modelling results using various ranges of reservoir and fluid properties were presented, but not for some of the more extreme combinations of values as they were believed to be unrealistic. In a CCS environment it is suggested that the proponent should show that the extreme data combinations are not appropriate or significant.	**Containment and Conformance:** 21. Additional numerical simulations with extreme or unlikely ranges of reservoir and fluid properties should be performed, primarily to establish that all bounding cases have been considered.

4 EXPERT PANEL REVIEW OF RISK REGISTER

The following principles formed the basis for the review of the risk register:

1. HSE risks should be reduced as low as reasonably practicable (ALARP).
2. Risks should not be disproportionate to the expected benefits.
3. Performance target should be defined: Target risk level and associated risk mitigative actions.
4. Risks should be assessed conservatively in light of uncertainty.

The ALARP principle does not relieve a risk owner from the need to evaluate acceptance criteria for risk significance, but it recognizes that there is a "grey-zone" between the unacceptable cut-off and the threshold for entering the region where risks are commonly agreed to be acceptable.

To evaluate if QUEST's indicative evaluation of risk significance is appropriate, the Panel members were asked to invoke the guiding principle that "risks posed by an activity should not outweigh the expected benefits". This principle formed the basis for evaluating if the target risk levels indicated by the QUEST subsurface team are achievable contingent upon implementation of defined risk mitigative actions, and, for HSE and reputation risks, were reduced ALARP.

Assessing risks conservatively in light of uncertainty without unduly exaggerating risk implies that the probability of a particular feature, event or process with potential for negative impacts should be assessed at the pessimistic end of the probability scale, but without taking the "end-points" of the probability distribution. Similarly, credible, but relatively unlikely consequences should be considered among the potential consequences that form the basis for assigning the significance of impacts.

4.1 Capacity risk and uncertainty review

The Panel agrees that the risks related to the potential for lack of adequate capacity for storage of 27 Mt CO_2 are properly assessed and ranked. However, caution is advised regarding the degree of understanding of "residual dissolution" due to the uncertainty surrounding preliminary fluid-rock interaction experiments related to salt precipitation from drying out of the near well region. The Panel further agrees that there is sufficient evidence to give confidence in the hypothesis for capacity: *There is sufficient pore space for full life cycle (25 years) of the required CO_2 volumes.*

4.2 Injectivity risk and uncertainty review

The Panel agrees that ample evidence has been provided to support the hypothesis for injectivity: *Injectivity can be sustained for the full project life-cycle.* There was some confusion about what time-frame that should be applied to injectivity assessments. The injectivity risks relate to the ability to meet their contractual "obligation" under the funding agreement with the Albertan government, which requires 10 years of injection. The TESLA hypotheses that relate to injectivity, on the other hand, refer to sustained injectivity for the full life cycle, i.e., 25 years. The Panel recommends that the time-frames for risks (risk register) and uncertainties (TESLA database) be made consistent.

The Panel further agrees that the injectivity risks are generally accurately assessed, but has the following additional remarks and/or recommendations for modifications:

- HSSE impacts (post-mitigation) for all injectivity risks should be recorded as minor effect. HSSE impacts are currently assessed as either minor effect or slight effect. The implication of operational upsets due to injectivity problems is generally the same for all risks. The HSSE impact should therefore be ranked consistently across the range of injectivity risks.
- CO_2 injectivity overestimated from water injectivity test (rel-perm and non-Darcy skin). Post mitigation probability is currently assessed to be "Extremely unlikely". This should be raised to Low, but not impossible. Conducting relative permeability measurements for expected temperature and pressure ranges for CO_2-brine systems could reduce assessed risk.
- Loss of injectivity due to pressure build-up. Assessment ok, but there was some ambiguity about the density (salinity) of the BCS brine that should be clarified.
- Loss of injectivity due to geochemical alteration of the reservoir / Halite precipitation. Post mitigation probability may be higher than current assessment ("Extremely unlikely"). Additional geochemical modelling studies should be conducted to support conclusions.
- Loss of injectivity due to dropping BHP constraints. Assessment ok, but subsurface pressure and pressure gradient should be carefully stated and used. Text in risk register should be revised.

4.3 Containment risk and uncertainty review

The Panel agrees that ample evidence has been provided at this stage of the project to demonstrate that leakage of CO_2 out of the storage complex will be extremely unlikely if the storage site is managed according to indicated plans, contingent upon implementation of a designated risk-based MMV plan and implementation of identified actions to mitigate containment risk. Thus, the Panel has very strong confidence in the top-level containment hypothesis: *Injected reactive fluids will not leak significantly from the containment complex*. The panel recommends, however, that the word "significantly" is carefully defined or removed from the formulation of this hypothesis.

The Panel further agrees that the containment risks are generally accurately assessed, but has the following additional remarks and/or recommendations for modifications:

- Timely demonstration of containment. Description should be reworded to "*Timely prediction of containment for regulatory approval*" (See discussion in paragraph below). The QUEST subsurface team is urged to review this wording and confirm the focus for the risk issue. Post-mitigation probability should be raised from "Extremely unlikely" to Low, but not impossible or higher. The subsurface team is also advised to carefully review assessed post-mitigation impacts.
- Injection induced stress reactivates a fault. Probability should be raised from "Extremely unlikely" to Low, but not impossible.
- Injection induced stress fractures geological seals. Proceed carefully with work-packages identified for thermal effects during CO_2 injection. Consider subdividing risk into the following two elements: "Injection fractures BCS" and "Injection fractures geological seals".
- Migration along a stratigraphic pathway. Additional work packages should be identified to support or defend the assessed reduction in probability post mitigation (from "Extremely unlikely" to "Low, but not impossible"). Potential for brine migration should be considered separately.

- Acidic erosion of geological seals. Further numerical analysis studies should be performed to validate the conclusions. Although reactions between the Lotsberg salts and the near salt saturated BCS formation water will be minimal, this must be documented. Potential reactions between the MCS and a CO_2 charged BCS formation water should be described and documented.
- Migration along legacy wells. Probability might need to be raised from "Extremely unlikely" to Low, but not impossible. More work needs to be done, quantitatively evaluating the mechanisms of up-hole migration of pressure and fluids, to support conclusion.
- Requirement for MMV wells in the BCS. There is an inconsistency between assessment of risks related to injectors and MMV wells that should be more clearly resolved in ongoing work packages.

The risk "Timely demonstration of containment" was introduced to ensure that the cumulative effect of all identified technical containment risks are properly captured and aggregated. This risk does not represent a technical failure mechanism, but is intended to ensure adequate visibility of containment risks to support the need for early and adequate appraisal and to provide a tool to communicate containment risk in general. In the risk register the assessed risk post-mitigation was based on the residual level of risk after regulatory approval of the QUEST project is granted. The Panel is of the opinion that this risk is really about the ability to build sufficiently strong confidence in containment to support a successful application for regulatory approval. This alternative definition of this "umbrella risk" would recognize the potential influence of perceived risks among regulators, stakeholders and the general public, as well as the time needed by ERCB and AUB to absorb the technical documentation provided supporting the regulatory submission.

4.4 Conformance risk and uncertainty review

Four risks are recorded as conformance risks, two of which link to the two monitorability hypotheses, and two which relate to the extent of predictive modeling capabilities. The conformance risk register is the least mature component of the risk register. Indeed, this area was not initially proposed to be covered in the current IPR as this work is still at a very early stage and several activities that aim to manage these risks and support the associated hypothesis have not been initiated.

The Panel was presented a draft of an extensive MMV plan for the QUEST CCS project. This plan shows how the MMV program supports the storage site risk management and provides a comprehensive and systematic overview of the role of monitoring technologies to monitor and detect indicators that trigger implementation of additional safeguards. Both currently selected and rejected monitoring technologies are discussed from a risk-based perspective, i.e., related to their potential to reduce risks ALARP.

Based on this plan and the data and information provided to the Panel, the panel has made the following remarks and/or recommendations for modifications to the conformance risk register:

- Unexpected plume (CO_2) migration. Post mitigation probability should be raised from "Extremely unlikely" to Low, but not impossible or higher. Performance indicators for simulations should be defined, i.e., define "unexpected". Risks for pressure versus CO_2 plume migration should be discussed separately.
- Inability to demonstrate conformance (long term liability/handover). Post mitigation probability may be higher than currently assessed ("Low, but not impossible"). Efforts to quantify long-term

trapping mechanisms should be made to reduce risk. More quantifiable estimates of the ranges of "indicators" identified for each monitoring task should be included within the MMV plan. Specification of performance targets for site closure, and discussing these with regulators up front, should also contribute to reduce risk.

- Unexpected surface heave. Assessment ok, but define "unexpected".

The forth conformance risk "Inability to differentiate contamination from external sources from project emissions" is considered to be correctly assessed. This risk ties to the baseline monitorability hypothesis: *Domains are mapped; current levels/fluxes of CO_2 are established and can be differentiated from project emissions; tolerances are understood.* The Panel concurs that at this stage baselines are not established and tolerances are not established or adequately understood. This is however to be expected at the current stage of project, and the Panel agrees that plans are in place to build confidence in this hypothesis.

The Panel believes that the draft MMV plan may need to be augmented with observation wells in the BCS to provide confidence in the containment monitorability hypothesis: *Likely and high risk (consequence) movements of injected CO_2 within the container and between each domain can be detected by proposed technology.* Currently the option to have monitoring wells in the BCS is considered as a contingency if remote monitoring technologies fail to give sufficient confidence in this hypothesis.

5 DNV REVIEW OF RISK MANAGEMENT FRAMEWORK

The risk management activities for the QUEST project, either carried out to date or planned for the next stage of the project (up to July 2011), are outlined in Appendix F. DNV agrees that these activities form a well founded risk and uncertainty management framework for the storage site and give confidence that planned characterization work will enable a decision on a final injection plan.

The framework for ensuring that all relevant risks within the scope of the project are identified and adequately understood and classified in terms of probability and consequence is discussed below.

5.1 Risk assessment activities

The purpose of this section is to review the risk assessment work carried out by to date in the QUEST project, and, from the external perspective of DNV, comment on the appropriateness of the risk assessment methodologies applied and the completeness and accuracy and transparency of the results.

The risk assessment framework for the QUEST CCS project consists of the following components:

- **Risk identification:** Internal risk database and internal group-based risk identification process.
- **Assessment and management of uncertainty:** TESLA and internal group-based process to provide "scores" to evidence for and evidence against.
- **Recording and assessment of risks and actions to mitigate risk:** EasyRisk Manager and internal group-based process to assess risks (and degree of risk reduction) based on defined probability and consequence classes (See Appendix D). To each risk, actions that have or will be implemented, with target closing date and risk owner are listed. For each risk, the target risk level corresponding to anticipated residual risk after all actions have been implemented is also defined.
- **Semi-quantitative bow-tie analysis:** A bow-tie has been provided to visualize the strategy for managing risks relating to possible loss of containment and potential associated HSE consequences. Based on the bow-tie, a probabilistic model has been derived that assigns a stochastic effectiveness to each safeguard. The stochastic effectiveness parameters are then used as input parameters to derive probabilistic scenarios for the cumulative effect of all safeguards associated with each identified threat and each identified consequence. The approach represents a semi-quantitative model for estimating the likelihood of each risk causing significant impact.
- **MMV plan:** A draft MMV plan has been prepared to demonstrate how the MMV plan will be designed and implemented to effectively manage risks down "As Low As Reasonably Practicable".

A summary of recommendations by DNV regarding the performed risk assessment activities is presented in Table 2.

Table 2: Recommendations by DNV regarding framework for risk assessment.

Observations	**Recommendations**
A significant effort has been made to link the degree of uncertainty to the risk ranking by attaching sub-hypotheses to each risk. However, it is not always intuitive how to relate the assessed degree of uncertainty for these hypotheses to the degree of uncertainty in probability and/or consequence of the associated risk.	To more directly couple the assessed degree of uncertainty with attached risks, it is suggested that hypotheses supporting risk assessments are defined when establishing the initial risk register. This would allow external reviewers to more objectively assess if risks have been assessed conservatively in light of the level of uncertainty.
Alternative safeguards that have been considered as measures to reduce risk, but rejected, have not been recorded.	For each risk in the risk register, alternative safeguards that have been considered but rejected should be recorded.
Performance targets for site closure/liability handover have not been defined. Performance targets have not yet been discussed with regulator at this stage.	Performance targets should be discussed with regulator and proposed performance targets for site closure/liability handover should be defined.
The definition of the top event is currently inconsistent with the placement of some of the preventive active safeguards in the bow-tie.	The definition of the top-event in the bow-tie for the containment risks should be made consistent with the respective placement of safeguards in the bow-tie.
Some safeguards are misplaced on the left hand side of the bow-tie, leading to an incorrect analysis of the probability that the corresponding threats may trigger the top event. The assessment of the performance of preventive safeguards for the threat posed by migration along legacy seems too optimistic. It is also hard to assess the validity of effectiveness and uncertainty values assigned to some of the consequence reducing safeguards (e.g., geological seals) if top event is triggered by migration along wells.	The semi-quantitative bow-tie analysis should be revisited and critically examined. Assumptions behind the assignment of effectiveness and uncertainty scores for safeguard performance should be more clearly stated. It is suggested to split the bow-tie into two subsets, one relating to threats of migration through geological pathways, and one relating to migration along wells.
HSSE risks are presented in a 5-by-5 matrix with color-coding as for the QUEST Risk Assessment Matrix (RAM). The probability classes for the QUEST RAM and the Shell Global HSE Risk Matrix do not match, and a mapping between the probability classes is not given. The probability classes for the QUEST RAM have been applied. The Shell Global HSE Risk matrix has 6 consequence classes, whereas risks are presented in a 5-by-5 matrix. A map from the 6 consequence classes for the Shell Global HSE risk matrix to the 5 consequence classes for the HSSE matrix is not defined. The color coding of the HSSE risk matrix follows the color coding of the QUEST RAM, and does not reflect Shell's internal assessment of ALARP categories as indicated in the Shell Global HSE Risk Matrix.	An effort should be made to ensure consistency between the QUEST Risk Assessment Matrix and the Shell Global HSE Risk Matrix. HSSE risks should be presented in a risk matrix with colors reflecting Shell's internal assessment of the three ALARP categories.

5.1.1 Risk identification

The initial risk identification process was carried out internally without using a specific methodology for risk identification. The Shell global risk database was used as input to identify risks. Additional discussions around potential hazards were triggered by internal TESLA workshops. Finally, several "novelty" workshops have been held to identify any risks that may be associated with "novel" (e.g., application of new technologies or application of existing technologies in circumstances that has not earlier been encountered) elements to be encountered in the next development stage of the project.

The applied process to identify risks associated with the subsurface component of the QUEST CCS project is quite comprehensive, with a systematic plan for revisiting and updating the risk register with potential additional risks. It is also the consensus view of the Panel that all potentially significant *technical risks* have been identified and recorded. The risk register does not include any reference to potential hazards that has been considered but disregarded on the basis of being insignificant. For completeness and transparency it is recommended that a register is kept for recording hazards that have been considered, but considered insignificant. This register should also include a brief explanation for why the associated hazard was judged to be insignificant.

5.1.2 Assessment and management of uncertainty

The QUEST project has applied the TESLA software provided by Quintessa Ltd. to address and manage uncertainties. In TESLA, root hypotheses are formulated, and a tree structure is defined with sub-level hypotheses that support the next higher level hypotheses. The tree structure may have multiple levels of sub-hypotheses, where each sub-hypothesis underpins a hypothesis on the next level.

The QUEST project has applied five "root"-hypotheses for capacity, injectivity, containment, baseline monitorability and containment monitorability. These are[3]:

- **Capacity:** There is sufficient pore space for full life-cycle of the required volumes of CO_2.
- **Injectivity:** Injectivity can be sustained for the full life-cycle.
- **Containment:** Injected reactive fluids will not leak significantly from the containment complex.
- **Baseline monitorability:** Domains are mapped, current levels/fluxes of CO_2 are established and can be differentiated from project emissions; tolerances are understood
- **Containment monitorability:** Likely and high risk (consequence) movements of injected CO_2 within the container and between each domain can be detected by proposed technology.

The considerable work towards quantification of uncertainty performed by the QUEST subsurface team is pioneering for a large scale CCS project, and in particular for projects considering storage in saline aquifers. It is recognized that the suitability of saline aquifers for long-term storage of CO_2 will often be associated with a significant degree of uncertainty. The ability to drive towards a common framework for how to judge the significance of the uncertainty is therefore of critical importance. In particular, there is a need to have discussions around what information is critical to have and what information is "nice to have". It is the opinion of DNV that the work done in the QUEST project represents a step-change in this direction.

[3] The hypotheses are an integral part of the Qunitessa software, it is not currently possible to modify them to individual project needs.

5.1.3 Recording and assessment of risks and actions to mitigate risks

The QUEST project has applied the EasyRisk Manager software licensed from DNV to establish a project risk database or register. The database contains a record of project risks, associated results of risk assessments, actions implemented or planned to reduce or mitigate risk, and the anticipated effect of risk reduction measures, henceforth referred to as safeguards.

For enhanced oversight, the risk register has been split into four separate documents; one for capacity risks; one for injectivity risks; one for risks related to potential loss of containment; and one for risks labeled as conformance risks. Each of these documents includes the TESLA sub-hypotheses that link to the corresponding risks in the respective documents.

It is the opinion of DNV that the risk register includes adequate descriptions of the rationale for the risk ranking to allow the panel to make an independent evaluation of the appropriateness of the risk ranking proposed. The Panel has suggested only minor calibrations to the assessed risk level, indicating that the risk level initially assessed by the subsurface team represents a reasonably objective view of the significance of the respective risks. Furthermore, the risk register lists actions that have been or are planned to be implemented to address uncertainties or to mitigate risk. The risk owner is defined for each risk as well as the person responsible for each identified associated action.

Overall, EasyRisk Manager has been used in a proper and transparent way to demonstrate that an appropriate plan to manage each identified risk is being implemented.

5.1.4 Bow-tie for containment risk and risk quantification

The QUEST subsurface team has defined a unified bow-tie for all containment risks to enhance oversight of the risk management strategy and to drive towards a probabilistic risk quantification model. This was done by assigning an effectiveness score to each safeguard based on qualitative expert judgments. Based on a coarse review of the analysis, DNV[4] made the following observations:

- In a risk assessment bow-tie, safeguards that serve to reduce the probability of the top event occurring should be shown on the left hand side, and safeguards that serve to limit consequences if the top event occurs should be placed on the right hand side. The identified safeguards are generally placed on the appropriate side of the bow-tie, but the placement of some of the preventive active safeguards on the left hand side of the bow-tie is currently inconsistent with the definition of the top event. These safeguards are triggered by monitoring systems that represent indicators that the top-event *has* occurred, and not indicators that it *may* occur. This implies that either the definition of the top event must be modified or that the safeguards corresponding to these monitoring systems should be removed from the left hand side of the bow-tie.
- The analysis of the probability that the threat "T1: Migration along a legacy well" could trigger the top event is inaccurate. Several of the safeguards to prevent that this threat will trigger the top event were incorrectly placed on the left side of the bow-tie, and the effectiveness assigned to some of the remaining safeguards seems very optimistic. For this threat there was also a significant

[4] A review of this risk analysis should preferably have been performed by the Panel. But because it was not communicated to DNV prior to the workshop that the semi-quantitative risk analysis was performed, a review of this analysis was not initially part of the scope. However, for the current IPR to deliver on the objective to do a "critical review of the project's risk assessment work performed," it was considered necessary to check that the bow-tie was correctly defined, and that the results of the risk analysis was consistent with the probabilities in the risk register. DNV therefore decided to do a coarse review of the semi-quantitative risk analysis based on the information in the draft MMV plan. This review was carried out after the workshop without input from the Panel. It should be noted that the risk analysis presented in the draft MMV plan has not yet been through an internal review.

mismatch between the derived probability and the probability range reflecting the Panel's assessment of the likelihood that this threat could trigger the top event.

- The choice to introduce a "unified" bow tie has the implication that any identified consequence reducing safeguard is assessed to be equally effective regardless of which threat triggers the top event. For instance, generic values are assigned to the effectiveness of seals above the containment complex irrespective of whether the top event may be triggered by migration through a well-bore, which could represent a pathway through the seal, or by migration along a geological pathway. The assessment of effectiveness of the consequence reducing safeguards is generally tailored to the case of migration along a geological pathway. It was therefore difficult to see how this analysis applies to cases where the top event is triggered by migration along wells.

Overall, not withstanding the above remarks, DNV considers the probabilistic risk quantification model appropriate for the current application. DNV also considers the internal consensus driven approach to set effectiveness and uncertainty of safeguards to be appropriate in absence of empirical data to support the assessments. However, by being an internal driven process, and by relying on qualitative expert judgments to assess effectiveness and uncertainty, the bow-tie analysis reflects a semi-quantitative approach to risk assessment. A fully quantitative approach would require empirical data about frequency and magnitude of historical features, events or processes, which is currently not appropriate as the relevant data is not yet available due to the limited global CCS history. Care should therefore be exercised when interpreting the results in a quantitative sense.

In terms of completeness, DNV agrees that the bow-tie gives a systematic overview of the general risk management strategy, but an effort should be made to ensure that the respective placement of all safeguards in the bow-tie is consistent with the definition of the top event. Furthermore, to ensure a complete and proper assessment of the performance of the consequence reducing safeguards, DNV would suggest splitting the main bow tie into two subsets, one relating to threats of migration through geological pathways, and one relating to migration along wells.

In terms of accuracy, the assessed performance of some safeguards seems to be too optimistic. In particular the analysis of the likelihood that the threat posed by migration along legacy wells will trigger the top event has been reviewed in some detail, and DNV finds that this analysis seems optimistic. A discussion of the reasoning to support this conclusion is provided in Appendix G.

Finally, in terms of transparency, DNV feels that the analysis could benefit from enhancing the transparency of the probabilistic model by more clearly defining the assumptions behind the assignment of effectiveness and uncertainty scores for safeguard performance.

5.1.5 Risk-based MMV plan

The draft MMV plan for the QUEST CCS project is quite likely the most comprehensive MMV plan for any CCS project in the world today. It clearly outlines how the MMV program supports the risk management of the storage project, it defines the principles and precedents that has influenced the design of the MMV program, and it provides a comprehensive and systematic overview of the role of monitoring technologies to monitor and detect indicators that trigger implementation of additional safeguards. Both selected and rejected monitoring technologies are discussed from a risk-based perspective, i.e., related to their potential to reduce risks ALARP.

DNV is of the opinion that the approach taken to formulate the MMV plan is state-of-the-art and may serve to set a precedent for design of MMV programs for CCS projects world-wide.

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APPENDIX A: TERMS OF REFERENCE

Objectives of the Review

The overall objective of the review was to provide an independent verification of the suitability of the QUEST storage site for a sequestration capacity of 1.2 Mt per annum of CO_2. (Note annual contractual volume will be 1.08 at 90% uptime). The review was funded by Shell Canada and took place in September-November 2010, prior to Shell Canada's submission to the regulator for a storage permit. DNV was engaged to manage the review process. The review was conducted by an independent panel of CCS experts selected by DNV which in the interest of total independence excluded Shell Group and Canadian government participation. The main deliverable was a report for public disclosure.

Background

The storage site characterization at the time of the review was based on the following data set:

- Regional data including wells logs and 2D seismic data
- Two appraisal wells that have been drilled close to the Area of Interest (AOI)
- Two 3D seismic data sets that have been acquired over part of the area of interest
- A third appraisal well in the centre of the AOI to be spudded in July 2010 (only preliminary results of this well was available at the time of the review)
- High resolution aero magnetic survey over the AOI

At the time of the review, Shell Canada had completed an initial stage of site characterisation and a feasibility report which supported the application for pore space tenure made in December 2009. A preliminary injection plan based on this feasibility study and a draft conceptual MMV plan was made available for the review. The final injection / MMV plan will not be complete until mid-2011 incorporating the well data and additional 3D seismic to be acquired in Q4 2010.

Scope

The expert panel was tasked to do a "critical review of the project's risk assessment work performed by the QUEST subsurface team." As part of this task, the following questions related to the suitability of the targeted storage site were addressed:

A. Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity and containment (and conformance[1])?
B. Are plans for future characterization work suitable to enable a decision on a final injection plan?
C. Is there an appropriate risk and uncertainty management framework in place for the storage site?
D. Are the risks and uncertainties related to the storage project adequately understood and classified in terms of probability and consequences?
E. Are the right plans in place in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?
F. Are there any additional hazards or risks within the scope of the project have not been identified?

[1] Conformance was not part of the initial scope, but was added during the review process. The reason for including it was that part of the objective of the review was to do a critical review of the risk assessment work carried out by the QUEST subsurface team, and that the risks associated with the subsurface component of the QUEST project was split into four subcategories: capacity, injectivity, containment and conformance. The risks in each category were associated with a corresponding hypothesis that would support the statement that "the injection site has been adequately characterized at this stage of the project in terms of the corresponding characteristic". It was therefore natural to also consider the level of characterization in terms of conformance. It should be recognized, however, that work on conformance is at an early stage and that many of the activities that are intended to manage conformance issues have not yet been initiated.

Format

The expert panel members were asked to commit a total of 10 days for the IPR. The tasks and activities to be performed by the expert panel during these 10 days comprised of the following:

- 3 days of pre-read: to read material provided by the QUEST subsurface team to provide a general understanding of the work that has been carried out to date to characterize the storage site through tailored appraisal and risk management activities.
- 5 days for attending an IPR workshop: to allow the QUEST subsurface team present results from the most recent site characterization and appraisal activities, to critically review Shell's internal assessment of risks listed in the risk register, to allow the expert panel form an independent assessment of the completeness and accuracy of the assessment given prescribed principles to guide this process, to review the risk management activities carried out to date and those planned for the next stage of the project, and to feedback to the QUEST subsurface team a preliminary individual assessment of the storage project. The QUEST subsurface team included a Houston based reservoir modelling team responsible for doing the static and dynamic modeling of the storage site.
- 2 days for preparing respective individual summary reports: to formulate a subjective response to the above high level questions based on their understanding of the project, to comment on the completeness and accuracy of the risk register, and to communicate any technical issues within their specific areas of expertise that they feel the QUEST team has not adequately addressed, or for which they would challenge the results and/or conclusions derived based on available data.

Instructions for individual expert assessments

1. Provide short biography with emphasis on competence relevant for the IPR.
2. Respond to top-level questions as a high-level summary. 1-2 pages
3. Review risk register and top-level TESLA hypotheses. Justify suggestions to modify risk ranking. Indicate if alternative safeguards should be considered. Indicate if you agree with the ranking (contingent upon implementation of actions), but feel that the conclusions are not supported by data. Finally, indicate the significance of any risk re-ranking on the relevant top-level TESLA hypothesis.
4. Within area of expertise, make any additional comments considered to be appropriate. Keep in mind that the development timeline is until July next year. Number your comments.
5. Substantiate comments in a way that allows readers to comprehend the underlying reasoning. To allow the risk review to be auditable, it is important that external reviewers can read the report and assess the "validity" of our assessments.

Follow Up Review

A follow up review is proposed to take place after the final injection and MMV plans are available and the well-3 data and any additional 3D seismic has been integrated in the reservoir characterisation.

APPENDIX B: DOCUMENTS AND PRESENTATIONS

Pre-read documents

1. Terms of Reference – Draft – Independent Review of the QUEST storage site, 2 pages.
2. EP 2010-3099: Quest CCS Project – Technical Feasibility & Forward Plans to FID, Revision 3, 2010-05-16, 255 pages.
3. Appendix A1 to EP 2010-3099: HAZID Findings, 12 pages.
4. Appendix A2 to EP 2010-3099: Geophysics, 24 pages.
5. Appendix A3 to EP 2010-3099: Petrophysics, 69 pages.
6. Appendix A2 to EP 2010-3099: Sedimentology, 36 pages.
7. Appendix A2 to EP 2010-3099: Geochemistry, 29 pages.
8. Appendix A2 to EP 2010-3099: Static and dynamic modeling, 62 pages.
9. Appendix A2 to EP 2010-3099: Geomechanics, 27 pages.
10. Capacity Risk and Uncertainty Review, Revision 1, 2010-09-17, 15 pages.
11. Injectivity Risk and Uncertainty Review, Revision 1, 2010-09-17, 29 pages.
12. Risk 4159 – Migration along a QUEST well – Compromised completion or wellhead integrity, 3 pages (Missing sheets in Injectivity Risk and Uncertainty Review document).
13. Containment Risk and Uncertainty Review, Revision 1, 2010-09-17, 52 pages.
14. Conformance Risk and Uncertainty Review, Revision 1, 2010-09-17, 26 pages.
15. 07-03-ZW-6409-0001: Well Proposal – Well 3 (Radway 8-19-59-20W4), Revision 3, 2010-06-28, 56 pages.
16. OXAND CETU / 2010 / 17 / A: Final Report – Well integrity study of the QUEST project proposed appraisal well #3 – Phase 1: Design review, long term integrity performance and gaps analysis with practical risk-based recommendations, 2010-08-20, 72 pages.
17. End of Well Report – Scotford Appraisal and Water Disposal Well (SCL-Redwater-11-32-55-21W4M), Revision 4, September 2009, 47 pages.
18. End of Well Report – Redwater Appraisal Well (SCL-Redwater-03-04-57-W4M), Revision 4, September 2009, 45 pages.
19. QUEST Core Analysis Program – Overview to AERI – 11-32-55-21W4M (Scotford) and 3-4-57-20W4M (Redwater) cores, 2010-07-20, 15 pages.
20. QUEST Core Analysis Program – Overview to AERI – Radway Core Analysis Program, 2010-07-20, 4 pages.
21. Wells Status – 3rd party legacy wells, 2010-03-03, 15 pages.
22. Draft proposed terms of reference – Environmental assessment report for the proposed QUEST carbon capture and storage project, 2010-08-06, 39 pages.
23. QUEST IPSM Compressor Design Modeling Results, 29 pages.
24. QUEST Subsurface Appraisal Strategy, Version 1, 2010-05-12, 11 pages.
25. QUEST Integrated Subsurface Modeling, Overview, Status and Forward Plans, 3 pages.
26. QUEST Capture and Storage Project Plan Outline, Storage MMV Section, Version 2, 2010-06-23, 22 pages.
27. Agenda for IPR workshop – external version.

Workshop material and presentations

1. Agenda
2. Description of QUEST team members
3. Description of external panel members
4. Slide packages for the following presentations
   - David Coleman, DNV: IPR of storage part of CCS project
   - Ian Silk, Shell: QUEST CCS Project - Overview
   - Syrie Crouch, Shell: QUEST CCS – Introduction
   - Kathy Penney, Shell: QUEST Carbon Capture and Storage Regulatory Update
   - Mauri Smith, Shell: QUEST CCS – Storage & MMV – Geology and Geophysics
   - Sean McFadden, Shell: QUEST CCS – Risk and Uncertainty Management Process
   - Satinder Malik, Shell: QUEST CCS – QUEST Wells
   - Stephen Bourne, Shell: QUEST CCS – MMV Review
   - Stantec: Shell QUEST CCS Project – Overview of Environmental Assessment
   - Robert Pierpont, Shell: QUEST CCS – Storage and MMV (Oct. 4^{th} and Oct. 5^{th} versions).
   - Syrie Crouch, Shell: QUEST CCS – Site Selection
   - Hein de Groot, Shell: QUEST CCS – How pressure and fracture gradients impact capacity, containment and injectivity
   - Mario Winkler, Shell: QUEST CCS Integrated Modeling Strategy (Generation 3 static and dynamic reservoir modeling)
   - Satinder Malik, Shell: QUEST CCS – Integrated modeling – IPSM
   - Stephen Bourne, Shell: QUEST CCS Project – Feasibility of InSAR for Monitoring CO_2 Storage and Leak Detection
   - Jørg Aarnes, DNV: Slides defining principles and guidance for review of risk assessment work.
5. Spreadsheet for review of risk register
6. Shell Global Risk Assessment Matrix with description of impact categories.
7. List of Active Control Response Options
8. Shell QUEST CCS Project Measurement, Monitoring and Verification Plan – Draft

APPENDIX C: GUIDING PRINCIPLES

The current section details the principles that formed the basis for the IPR.

Principle 1: Risks should be reduced ALARP

For all risk (impact) categories apart from HS(S)E, and partly reputation, the significance of a given impact relates to its economic, commercial or regulatory influence on Shell's operations. Such impacts are primarily of corporate concern for Shell and its partners in the QUEST CCS project, Chevron and Marathon Oil. The expert panel has *not* been asked to make any judgment about the degree of acceptability of anticipated impacts within these categories.

The principle that risks associated with the QUEST project should be reduced ALARP therefore applies only to potential HS(S)E impacts, and partly also to impacts on reputation as reputation impacts may have replications for the CCS industry as a whole.

Figure 1 provides a schematic of the ALARP principle. The principle does not relieve a risk owner from the need to evaluate acceptance criteria for risk significance. Indeed, as Figure 1 shows, risks in the top red segment of the triangle are judged to be unacceptable. However, the ALARP principle recognizes that there is a "grey-zone" between the unacceptable cut-off and the threshold for entering the green region where risks are commonly agreed to be acceptable.

The ALARP principle itself does not provide specific guidance on what the thresholds between the ALARP region and the unacceptable and negligible or broadly acceptable region should be. To evaluate if QUEST's indicative evaluation of risk significance for HSE/reputation risks (as reflected by the colors applied to the HSE risk matrix) is appropriate, the expert panel members were asked to invoke the principle that "risks posed by an activity should not outweigh the expected benefits". Applying this principle implies that potential negative local impacts should not outweigh the expected global benefit in terms of reduced CO_2 emissions in the fight against global warming and climate change.

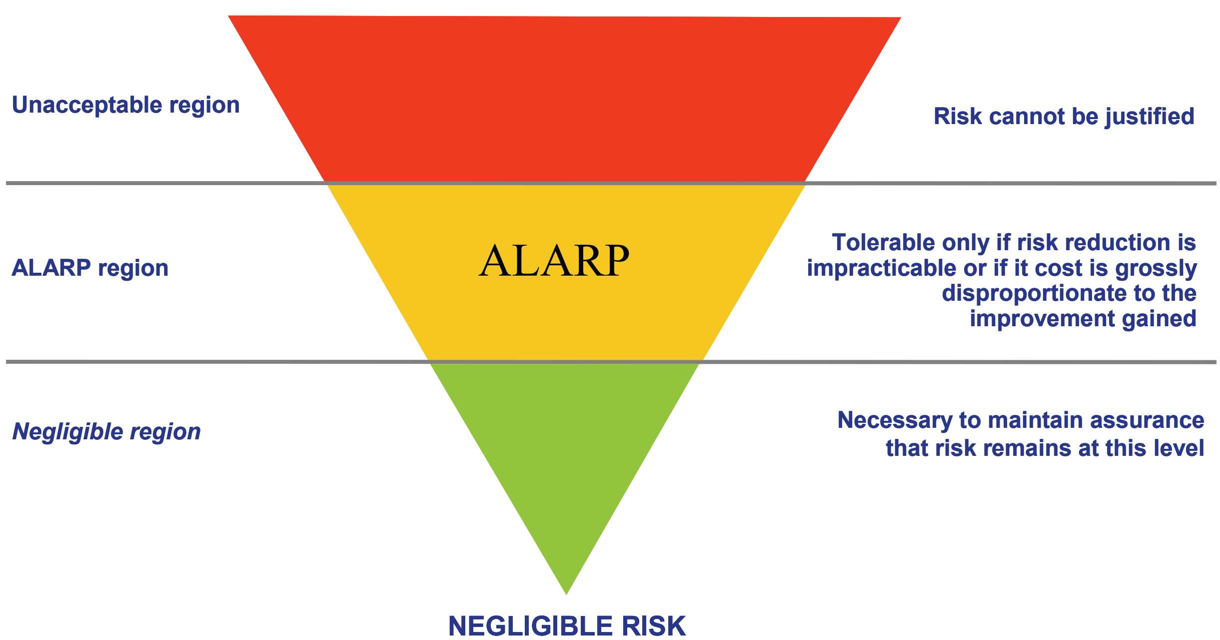


Figure 1: Schematic of ALARP principle.

Principle 2: Performance targets should be defined

The concept "performance target" is defined in the CO2QUALSTORE guideline as "*target level of risk/uncertainty reduction achieved through implementation of a defined safeguard, or range of safeguards.*" Thus, in addition to a notion of the desired terminal risk level, it implies specification of the risk mitigation measures that have been or are planned to be implemented to achieve the terminal risk level.

In the risk register the QUEST subsurface team has recorded, for each risk, the anticipated risk level that would be achieved through implementation of the attached actions to reduce probability, consequence or uncertainty. Hence, QUEST has complied with the recommendation in the CO2QUALSTORE guideline to define (operational) performance targets.

The CO2QUALSTORE guideline also makes the following additional recommendations:

- Actions that have been considered which could contribute to reduce risk, but disregarded due to technical or commercial reasons, should be recorded. This would enhance the transparency in the design of the risk management program and allow regulators and external stakeholders to assess if they agree with the decisions to reject certain safeguards with reference to the ALARP principle.
- To provide both project developer and regulator with more clarity on what project specific conditions will apply to enable liability handover, it is suggested to define performance targets for site closure. These are defined in the same way as operational performance targets, but additional conditions may apply. In particular, it is anticipated that an enhanced level of confidence in storage performance (containment and conformance) will be required relative to the requirements that will apply to enable initial project approval. Specified performance targets for site closure should be revisited and updated throughout the project. However, any deviations from previously defined targets should be properly substantiated. Specifying project specific performance targets for site closure may be regarded as a measure to reduce the risk of delay in the liability handover.
- Proposed performance targets should be discussed with the relevant regulator to enhance transparency of the risk management process.

Principle 3: Risks should assessed conservatively in light of uncertainty

The final principle that the expert panel has been instructed to take on-board is the principle that risks should be assessed conservatively in light of uncertainty, albeit without unduly exaggerating risk. This implies that the probability of a particular feature, event or process with potential for negative impacts should be assessed at the pessimistic end of the probability scale, but without taking the "end-points" of the probability distribution. Similarly, credible, but relatively unlikely consequences should be considered among the potential consequences that form the basis for assigning the significance of impacts.

This principle should not only apply to the assessment of current levels of risk, but also to future levels of risk contingent upon implementation of defined safeguards. However, when considering the effect of multiple safeguards that are applied to mitigate a certain risk, it would be in conflict with the principle to not unduly exaggerate risk to consider the performance of each and every safeguard conservatively. It is the cumulative effect of all defined safeguards for each risk that should be assessed conservatively in light of the cumulative uncertainty attached to the performance of the stack of multiple safeguards.

APPENDIX D: PROBABILITY AND CONSEQUENCE CLASSES

Figure 2 shows the probability classes and the consequence classes for five of the six defined impact categories for the QUEST CCS project. Consequence classes for HSE impacts are defined below.

Last Update: April 22, 2010

Risk Category						IMPACT ↑	PROBABILITY → 1 VLO	2 LO	3 MED	4 HI	5 VHI	Score Assessment		IMPACT ↑
Cost/Benefit in CDN $[1]	Schedule delay to FID[2]	Schedule delay to SO[3]	System Capacity[4]	HSE[5]	Reputation		0-5% Occurs in almost no Projects (Extremely Unlikely)	5-20% Occurs in some Projects (Low but Not Impossible)	20-50% Occurs in Projects (Fairly Likely)	50-80% Occurs in most Projects (More Likely than Not)	80-100% Expected to Occur in Every Project (Almost Certain)	Score	Assessment	
> 50 mln	> 6 mos	> 6 mos	>25% downtime	Refer to HSE RAM	International impact		5	10	15	20	25	5	VHI	
25-50 mln	3 - 6 mos	3 - 6 mos	20% - 25% downtime		National impact		4	8	12	16	20	4	HI	
10-25 mln	1 - 3 mos	1 - 3 mos	15% - 20% downtime		Considerable (Regional) impact		3	6	9	12	15	3	MED	
5-10 mln	0.5 - 1 mos	0.5 - 1 mos	10% - 15% downtime		Limited impact (public concern/ local media)		2	4	6	8	10	2	LO	
< 5 mln	< 0.5 mos	< 0.5 mos	< 10% downtime		Slight impact (some public awareness)		1	2	3	4	5	1	VLO	

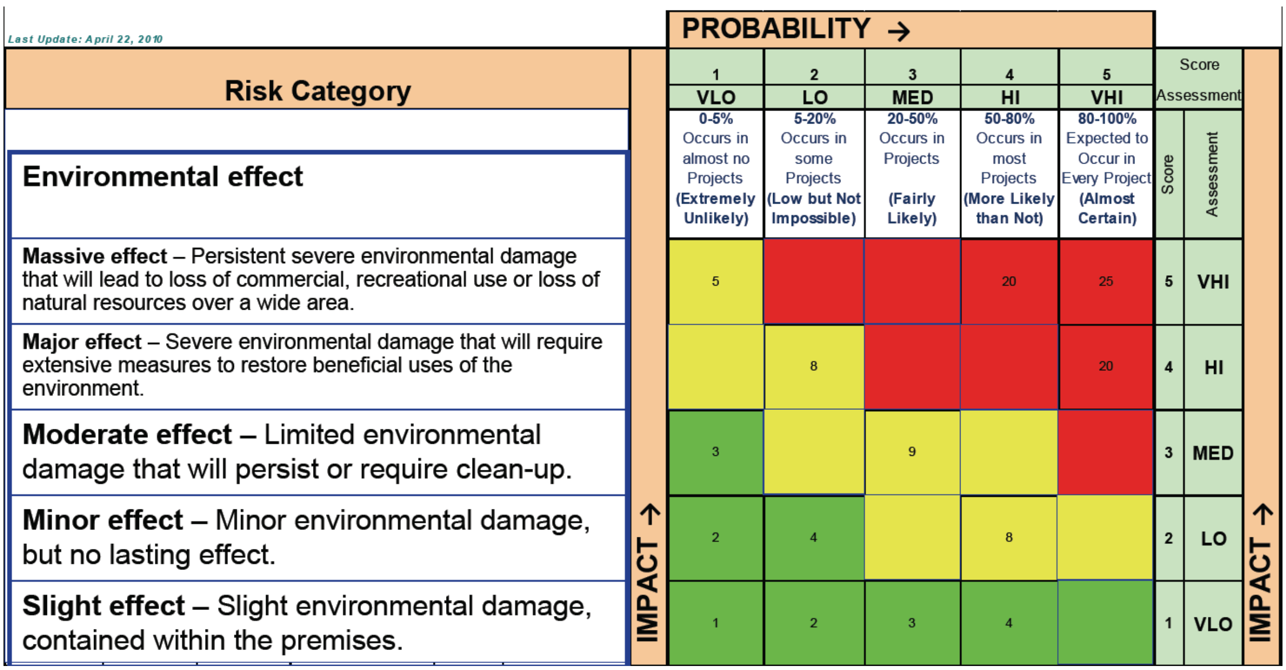
Figure 2: Probability classes, impact categories, and consequence classes for the QUEST project. Here cost/benefit refers to cumulative impact on cost during period with governmental funding (first 10 years of operation); Schedule to Financial Investment Decision (FID) is schedule between now and ~Q1 2012; Schedule to Sustained Operations (SO) is schedule from FID to meeting contractual disposal requirement; and System Capacity refers to capacity of combined capture, pipeline and sequestration system during period with governmental funding (first 10 years of operation). Consequence classes for HSE impacts are defined below.

Although the QUEST subsurface team claims the Shell Global HSE Risk Matrix is used to assess and classify probability and consequence of HSE risks, there was some ambiguity in how to interpret the results of the risk assessments in this category. The reason for this is that the Shell Global HSE Risk Matrix is a 6-by-5 matrix, and the HSE risks were presented in a 5-by-5 HSSE risk matrix. Furthermore, the definitions of the probability classes for the Shell Global HSE Risk Matrix differ from the probability classes applied for the other impact categories.

To resolve this ambiguity, it was agreed that the probability categories from the QUEST Risk Assessment Matrix (RAM) should be applied to assess HSE risks. It was further agreed that the severity of potential HSSE consequences should be interpreted as the bottom five consequence classes in the Shell Global HSE Risk Matrix, thus disregarding the row corresponding to no impact. Finally, the color coding in the Shell Global HSE Risk Matrix should be taken to indicate Shell's interpretation of the ALARP categories. However, to this end it is necessary to "translate" the probability classes for the Shell Global HSE Risk Matrix to the probability classes for the QUEST RAM. There is no obvious way to do this, but DNV has made an effort by translating the probability classes as follows:

- A: Never heard of in the industry. Translates to VLO: Extremely unlikely, occurs in almost no projects. (Since the CCS industry is still in its infancy, it seems appropriate to interpret industry in a wider sense, including EOR, acid gas disposal and natural gas storage operations).
- B: Heard of in the industry. Would probably also translate to VLO: Extremely unlikely, occurs in almost no projects.
- C: Has happened in the organization or more than once a year in the industry. This would probably translate to LO: Low, but not impossible, occurs in some projects.
- D: Has happened at the location or more than once a year in the organization. Considering the duration of CCS projects, this might translate to HI: More likely than not, occurs in most projects.
- E: Has happened more than once a year in the location. This would correspond to VHI: Almost certain, expected to occur in every project.

Applying this translation, and coloring the medium probability column with the same colors as the high probability column (since there is no match for medium in the probability classes for the Shell Global HSE Risk Matrix) we obtain the risk matrix shown in Figure 3.



Last Update: April 22, 2010

Risk Category — Environmental effect	PROBABILITY → 1 VLO 0-5% Occurs in almost no Projects (Extremely Unlikely)	2 LO 5-20% Occurs in some Projects (Low but Not Impossible)	3 MED 20-50% Occurs in Projects (Fairly Likely)	4 HI 50-80% Occurs in most Projects (More Likely than Not)	5 VHI 80-100% Expected to Occur in Every Project (Almost Certain)	Score	Assessment
Massive effect – Persistent severe environmental damage that will lead to loss of commercial, recreational use or loss of natural resources over a wide area.	5			20	25	5	VHI
Major effect – Severe environmental damage that will require extensive measures to restore beneficial uses of the environment.		8			20	4	HI
Moderate effect – Limited environmental damage that will persist or require clean-up.	3		9			3	MED
Minor effect – Minor environmental damage, but no lasting effect.	2	4		8		2	LO
Slight effect – Slight environmental damage, contained within the premises.	1	2	3	4		1	VLO

IMPACT →

Figure 3: HSSE risk matrix for the QUEST project with coloring indicative of Shell's assessment of ALARP categories. Brief descriptions of the consequence classes for environmental impacts are shown. More detailed descriptions of the consequence classes for environmental and reputation impacts are provided below.

The expert panel has been asked to evaluate if the coloring given in Figure 3 is representative of their individual assessment of ALARP, i.e., if the red boxes represents risk that can not be justified, the yellow boxes represents risk that are tolerable only if risks have been reduced ALARP, and if the green boxes represent risks that are negligible or broadly acceptable. Furthermore, they have been asked to assess if all of the HSE and reputation risks that have been assessed to be in the ALARP region (post-mitigation) (there are no HSE or reputation risks that have been assessed to be in the red region with the coloring in Figure 3) have been reduced ALARP. To facilitate this, the detailed descriptions of the consequence classes for environmental and reputation impacts have been provided (Safety risks from well operations are outside the scope of the IPR).

Description and examples of consequence classes for environmental impacts (CCS specific examples in parenthesis):

- **Slight effect:** Slight environmental damage, contained within the premises. Examples: Small spill in process area that rapidly evaporates. (Short duration of CO_2 venting or small scale leak along well bore not contaminating groundwater).
- **Minor effect:** Minor environmental damage, but no lasting effect. Examples: On-site groundwater contamination, complaints from up to 10 individuals. (Short duration small scale leak along wellbore that seeps into groundwater, minor but noticeable induced seismicity).
- **Moderate effect:** Limited environmental damage that will persist or require clean-up. Examples: Observed off-site effects or damage (e.g., fish kill or damaged vegetation). Off-site groundwater contamination. Complaints from community or organizations or >10 individuals. (Leakage into groundwater with implied degradation of groundwater quality, longer term small scale leaks, minor observed localized structural damage attributable to surface heave or induced seismicity).
- **Major effect:** Severe environmental damage that will require extensive measures to restore beneficial uses of the environment. Examples: Off-site groundwater contamination over an extensive area. Many complaints from community organizations and local authorities. (Large scale leakage into groundwater that requires extensive remediation measures to be implemented. Restoration period after leakage event is mitigated < 3 years. Major observed localized structural damage with risk implications attributable to surface heave or induced seismicity.)
- **Massive effect:** Persistent severe environmental damage that will lead to loss of commercial, recreational use or loss of natural resources over a wide area. Examples: Crude-oil spillage resulting in pollution of a large part of a river estuary and extensive clean up and remediation measures. (Major leakage event with inaccessible effective remediation measures, restoration period > 3 years. Significant release of H2S or traces of heavy metals to groundwater).

Description and examples of consequence classes for impacts on reputation:

- **Slight impact:** Local public awareness but no discernible concern. No media coverage.
- **Minor impact:** Local public concern. Local media coverage.
- **Moderate impact:** Significant impact in region or country. Regional public concern. Local stakeholders, e.g., community, NGO, industry and government are aware. Extensive attention in local media. Some regional or national media coverage.
- **Major impact:** Likely to escalate and effect Group reputation. National public concern. Impact on local and national stakeholder relations. National government and NGO involvement with potential for international NGO action. Extensive attention in national media. Some international coverage. Potential for regulatory action leading to restricted operations or impact on operating licenses.
- **Massive impact:** Severe impact on Group reputation. International public concern. High level of concern among governments and action by international NGOs. International media attention. Significant potential for effect on national/international policies with impact on access to new areas, grants of licenses and/or tax legislation.

APPENDIX E: EXPERT PANEL ASSESSMENTS

Farid Ahmadloo, IPAC-CO2/Saskatchewan Research Council

Farid Ahmadloo is a research engineer working on EOR field development at Saskatchewan Research Council (SRC) in Regina. Prior to joining SRC, he worked as petroleum engineer in Iran and UK on a wide range of projects involving phase behavior modeling, reservoir modeling of various EOR processes, reserve estimation, formation evaluation, and gas hydrates in different companies and research centers. He is a Ph.D. candidate in Petroleum Systems Engineering at the University of Regina where he is conducting research on capillarity effect on mass transfer phenomena in the VAPEX process. Farid holds a B.Sc. in petroleum engineering from Petroleum University of Technology (Iran) and Master's degrees in reservoir and petroleum engineering from Sharif University of Technology (Iran) and Heriot-Watt University (UK). He is a member of SPE and APEGS.

Top-level questions

Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity, containment, and conformance?

Capacity: Conducted modeling based on available data in a broad range of possible scenarios (i.e., reservoir connectivity and quality) in Gen-2 and Gen-3 models (i.e., low, mid, and high) show that the BCS storage complex has the required capacity for sequestration of 1.2 Mt CO_2 per annum for minimum 10 years.

Injectivity: Presented formation evaluation data, IPSM, simulation studies of BCS storage complex, and uncertainty management framework show that the injectivity can be achieved in the lifecycle of the CCS project.

Containment: Presented data on quality of BCS, geological seals (i.e., Middle Cambrian Shale, Lower Lotsberg Salt, and Upper Lotsberg Salt), wells, and conducted flow modeling provide strong evidence on containment of injected CO_2 in the storage complex.

Conformance: Proposed MMV program is designed to monitor the storage performance and ensure the containment during four distinct phases over the lifecycle of the Quest CCS project. However, there is some uncertainty about the applicability of the proposed MMV plan for monitoring storage mechanisms and getting the necessary information for tuning the flow models.

Are plans for future characterization work suitable to enable a decision on a final injection plan?

The proposed plans for future characterization work (e.g., Gen-4 simulation model, seismic data, and geomechanical studies) are suitable to improve the quality of the models and confidence in quality of predictions for final injection plan.

Is there an appropriate risk and uncertainty management framework in place for the storage site? Are the risks and uncertainties adequately understood and classified in terms of probability and consequences?

In my opinion, the generated risk and uncertainty management framework is a comprehensive and practical framework. In presented risk and uncertainty management framework for the storage site, a good understanding of the risks and uncertainties and their consequences has been presented. However, there are some disagreements with proposed probability and consequences of some of the risks.

Are the right plans in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?

The future plans for reaching acceptable level of risks and uncertainties in terms of capacity, injectivity and containment will be effective. However, at this stage there is no MMV plan available. There are also uncertainties about possibility of using proposed monitoring technology options in presented MMV risk mitigation review.

Are there any additional risks within the scope of the project have not been identified?

The presented risk and uncertainty management framework includes the major hazards and risks within the scope of the project.

Additional comments

The conducted study in site selection and characterization of storage complex by Quest team is a remarkable integrated study. The provided comments and recommendations in this section are based on presented information by Quest team on proposed risk and uncertainty framework. These recommendations are:

- CO_2 Injectivity Predictions: Considering the uncertainty in relative permeability curves used in Gen-3 models, it is recommended to conduct relative permeability measurements (CO_2-Brine system) in the expected pressures and temperatures in the lifecycle of the CCS project. These measurements can improve the quality of the predictions and address concerns that may be raised in review process during regulatory application.
- Migration along Legacy Wells: Presented information on legacy show considerable uncertainties on wellbore integrity and quality abandonment in these wells. Considering the potential for leakage of brine out of the storage complex through these wells, it recommended to conduct series of modeling studies using available information from these wells and simulation studies to investigate the possibility of migration of brine along these wells under different scenarios.
- Non-Isothermal Injection: At this stage, there is no study on the effect of non-isothermal injection of CO_2 on formation and injectivity. It is recommended to conduct a simulation study to investigate the non-isothermal effect of CO_2 injection into the formation and its potential impacts on formation and CO_2 injectivity.
- MMV plan: Proposed candidate monitoring technologies in MMV plan will not provide the necessary information for verification of simulation models to determine the storage mechanism that can be a part of requirements during the regulatory application review process. It is recommended to investigate other potential techniques (e.g., MMV wells in the BCS) for monitoring the storage mechanisms during the lifecycle of the project.

Rick Chalaturnyk, University of Alberta

Dr. Rick Chalaturnyk has established the Reservoir Geomechanics Research Group (RG2) which consists of over 20 graduate students and research engineers working on reservoir geomechanics for unconventional resource recovery (oil sands, bitumen carbonates shale gas, coalbed methane) and geological storage of CO_2 related research. Dr. Chalaturnyk serves on the organizing committees of International Energy Agency GHG R&D Networks in Risk Assessment, Wellbore Integrity and Monitoring, serves as a theme leader and researcher in the IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project, is a principal investigator in the Canadian Centre in Clean Coal/Carbon and Mineral Processing Technology, is a theme leader for carbon storage research in the newly established Helmholtz Alberta Initiative, is a principal investigator in newly formed International Performance Assessment Centre for CCS (IPAC-CO_2), is a member of the Science and Engineering Research Committee and Investigator in the Aquistore CO_2 storage demonstration projects and was one of four principal investigators on Penn West Energy Trust's Pembina Cardium CO_2-EOR Pilot Project. Dr. Chalaturnyk was also a co-author of CANiSTORE (2004), a report developed from Canadian roadmapping consultations on capture and geological storage of CO_2. Dr. Chalaturnyk has served as a member of an international peer review team for the Australian Government's review of Chevron's Gorgon CO_2 Project, and was also a member of the IEA GHG Peer Review team of the CO2CRC's Otway Project Measurement, Monitoring and Verification Program. Dr. Chalaturnyk is also Executive Vice President of Opsens Solutions Inc., a company providing world class reservoir surveillance solutions based on fiber optic and conventional instrumentation to the oil and gas industry.

Top-level questions

<u>Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity, containment and conformance?</u>

<u>Capacity</u>:

Shell conclusion on capacity (from p. v in Feasibility Report, EP 2010-3099):

1.2.2. Capacity
Sufficient capacity for storage of CO2 captured from Scotford is present in the BCS. The BCS, a regional aquifer with an average porosity of 15% and an average gross formation thickness of 35 m provides sufficient pore space to store the anticipated CO_2 volume of approximately 30 million tones (Quest CCS Project base case, 1.1 Mt, 25 year injection time). Sufficient connected pore volume is very likely present, taking into account that both, a dense grid of 2D seismic lines, as well as a small offset 3D seismic survey, shows no indication of disconnected reservoir compartments.

(from p. 9 and 28 of the same report)
Using the volumetric method for CO_2 resource estimation described in the US Department of Energy 2008 Carbon Sequestration Atlas (II) of the United States and Canada, a static calculation of a Township unit area potential for saline aquifer storage of CO_2 in the BCS ranges from 9 to 28 Mt per Township. The storage capacity of the BCS in the Quest AOI is between 1.5 to 5 billion tonnes of CO_2. This is sufficient capacity for the proposed Quest CCS project requirement of 1.2 million tonnes of CO_2 per year over the expected 25-year lifetime of the Scotford upgrader.

CO_2 storage capacity is an estimate of the amount of CO_2 that can be stored in a reservoir. For the most part, the factors controlling injectivity are the same as those controlling capacity; the primary difference is the fact that capacity is more strongly influenced by the larger-scale attributes of the reservoir, and the fluid displacement/interaction processes that will occur over a somewhat longer time-frame. Factors affecting CO_2 storage capacity include the density of the CO_2 at subsurface reservoir conditions, the amount of interconnected pore volume of the reservoir rock and the nature of the formation fluids. Due to the flow behavior of CO_2 in the subsurface, not all potentially available pore volume of the reservoir will become occupied during injection and migration, with flow preferentially occurring either upward due to buoyancy forces or laterally below low permeability zones (*i.e.*, spreading out in thin layers beneath intraformational seals or the regional top seal rather than filling the entire pore volume) (Gibson-Poole, 2008).

The potential CO_2 storage capacity is therefore assessed in terms of available interconnected pore space, accounting for factors such as injection rate, rate of CO_2 migration, the dip of the reservoir, the heterogeneity of the reservoir and the potential for fill-to-spill structural closures encountered along the migration path. In addition, long-term prospects for storage, including residual trapping, dissolution into the formation water, or mineral trapping (formation of new minerals) can also be considered (especially for estimating potential storage volume within deep saline formations). Evaluation of the CO_2 storage capacity in a deep saline aquifer is complex due to the various trapping mechanisms involved that act at different rates - saline aquifer CO_2 storage capacity evolves through time. The storage capacity that is relevant is that capacity that can be accessed and achieved during the injection stage of a CO_2 storage project and can be broadly defined as the maximum volume of CO_2 that can be injected in a water-bearing formation without resulting in a spill, leak or other undesirable effects during and/or after the injection period. This comprises:

- the amount of CO_2 that will be eventually immobilized by filling of any and all structural and stratigraphic traps; and
- any additional amount of CO_2 that will be stored by residual gas saturation, dissolution and mineral precipitation along the CO_2 migration path from the injection point(s) to the final trapping place.

Such issues are best addressed by building geological models and running numerical flow simulations to test the importance of the various factors inherent to each specific site. The numerical flow simulations can give a more accurate assessment of how much of the available pore volume is actually used (sweep efficiency) *in each particular type of trapping* (italics added)(Gibson-Poole, 2008).

If we take the above description of capacity, which is generally adopted by the Task Force for Review and Identification of Standards for CO_2 Storage Capacity Estimation for the Technical Group of the Carbon Sequestration Leadership Forum (which includes a discussion of the USDOE 2008 Atlas approach) and the proposed approaches adopted by Shell (outlined in the slide package of Hein de Groot – How pressure and fracture gradients impact capacity, containment and injectivity), then I am extremely confident that Shell at this stage of the project (QUEST) has adequately characterized capacity in the broad sense of "capacity that can be accessed and achieved during the injection stage of [the] storage project". Geological studies confirm the thickness and extent of the BCS reservoir.

Regarding the injection stage of the project, Shell has employed numerical flow simulations appropriately to define the various storage complex characteristics on capacity, in the sense of the ultimate controls on injectivity. As pointed out above, capacity is very closely linked to injectivity, and this has been studied and assessed very well by Shell. For instance, the Gen-3 modelling of reservoir quality and reservoir connectivity combined with dynamic reservoir property sensitivities provided a convincing argument on the range of uncertainties for injectivity and consequently, on the capacity estimates.

There does, however, appear to be a mismatch between the static and material balance capacity estimates provided by Hein de Groot where unconstrained Quest AOI capacity is reported as between 66 Mt and 358 Mt of CO_2 (with the variability noted in slide 4) while the Feasibility Report (as noted above) "the storage capacity of the BCS in the Quest AOI is between 1.5 to 5 billion tons of CO_2". I suspect I have missed an explanation somewhere in the Feasibility Report or during the presentation of Dr. de Groot but Shell is urged to ensure the reported capacities are consistent.

And while confirmation of capacity within the context of injectivity is an important element of the project design, partitioning of the capacity estimates with respect to solubility trapping, residual gas trapping and hydrodynamic trapping (mineral trapping is accepted to be negligent within the Quest project) is recommended as Shell moves forward with the technical work packages over the next year.

Injectivity:

I would submit that at this stage of the project, injectivity has received the most attention and the technical arguments surrounding injectivity and its impact on well numbers are sound. The additional work packages that have been identified by the Shell Quest team will be very effective at refining technical predictions of injectivity.

Containment:

Recognition of the impact of the pressure plume and the subsequent displacement of saline reservoir fluids provides evidence of Shell's focus on all the risk elements related to containment. Convincing arguments have been presented by the Quest team for containment of the CO_2 plume. The drilling of three appraisal wells to assess local variances in geology, the mapping of multiple vertical seals within the storage complex and the application of technologies such as HRAM, have added to a strong understanding of the geological setting of the injection formation and the bounding seals (the storage complex) and provides ample evidence that the possibility for CO_2 leakage out of the storage complex is extremely unlikely.

Conformance:

An exhaustive and technically rich MMV plan has been developed to provide evidence for conformance (and containment) of the CO_2 and brine pressure plumes. The initial arguments around conformance relate to the trust placed in the monitoring technologies and the implementation of an MMV plan that accounts for all eventualities in the evolution of the CO_2 plume and the displaced brine plume. Ultimately, it will likely be a requirement to demonstrate "how" the CO_2 is stored within the BCS and that the CO_2 is going to stay where it is predicted to stay. These may place additional demands on the MMV plan beyond what is currently anticipated. Over the next 3-9 months as the MMV plan is finalized, it is recommended that additional consideration be given to implementing technologies that will assist Shell in refining their estimates of the CO_2 storage mechanisms over the 25 year project life and more importantly, over the closure and post-closure stages leading up to liability transfer to the province of Alberta.

Are plans for future characterization work suitable to enable a decision on a final injection plan?

Yes, as it pertains to well count and injectivity estimates for the BCS. It is exactly this issue to which the Quest team appears to have spent a considerable time assessing prior to the November ERCB regulatory submission. Injectivity and its impact on well count are significant business factors to be constrained and Shell has done a great deal of work in this regard. The remaining uncertainties that have arisen from this work are articulated as work packages to be undertaken over the next 9-10 months.

As the injection plans are finalized, it is recommended that Shell continue to look beyond the 10 and 25 year periods of assessment to ensure that questions regarding potential future injection scenarios will be possible. Within the AOI, Shell has already stated that the pore volume storage capacity estimates can be in the range of 66 Mt – 358 Mt of CO_2 and questions concerning the potential for injecting volumes beyond the project design requirements of approximately 27 Mt may be relevant for optimizing pore space use. It is expected this can be assessed with Gen-4 modelling of 1000 yr plume migration for the final (five?) well injection scenario.

<u>Is there an appropriate risk and uncertainty management framework in place for the storage site?</u>

Shell has advanced a risk and uncertainty management framework that in my opinion is state-of-the-art for CO_2 storage projects. It combines both evidence-based decision making (TESLA) and resource industry accepted risk assessment matrix approaches (i.e., HAZID, RAM) to assess project risks such as capacity, reputation, schedule delays and health, safety, environment (HSE) risks. Effective mapping of these risks using DNV's EasyRisk Manager risk reporting software appears to have been completed to a very high degree of completeness and multiple passes through the risk registers have been completed to update storage related risks. Regarding uncertainty management, Shell has defined the contributions of additional appraisal activities (such as the drilling of the 3rd appraisal well) in terms of "de-risking" contributions.

It may be somewhat early to provide a judgment of whether the "risk and uncertainty management framework" adopted by Shell is the "***appropriate***" one for the storage site. Appropriateness will follow from the successful management of the risks during the storage project and the demonstration that indeed all the risks have been identified and minimized to ALARP. For instance, the Risk Assessment Matrix that was utilized for the Quest risk assessment developed impact categories based on internal Shell experience. It is expected that within the global CCS community, including regulators, difference may exist on what constitutes a low impact or a high impact. These judgments on risk impact (and probability) will ultimately be part of the assessment of "appropriateness" as the project proceeds towards closure and post-closure following the design 25 year injection period. Based on my experience with several other projects, however, it should be clearly stated that the approach followed by Shell for the Quest project is exemplary.

<u>Are the risks and uncertainties adequately understood and classified in terms of probability and consequences?</u>

To address this question, a detailed review of the large table of summarized risks and top-level hypotheses was undertaken by the review panel. Procedurally, this was a valuable exercise and was completed after several days of presentations and discussions with the Quest team. The challenge that did exist with this review was the requirement to review Shell's assessment of probability and impact "post mitigation", given the time allotted for the full panel review. Shell's assessment of the "before action" and "after action" (or post mitigation) probability and impact was done qualitatively using expert judgment by members of Shell's Quest Venture team and internal discipline CO_2 experts. So based on the caveat that understanding the detailed rationale for expert judgments on changes to probability and impact risk assessments "post mitigation" within the timeframe for the panel review was challenging, the following provides my opinions (in italics) regarding the treatment of probability and impact for the risk factors identified for the Quest project:

Capacity

Risk 4166 and 4160: *Probability and impact are within the range of reasonable uncertainty but caution regarding the degree of understanding of "residual dissolution" is urged due to the uncertainty surrounding preliminary fluid-rock interaction experiments related to salt precipitation from drying out of the near well region.*

Top Level Hypothesis - Sufficient pore space for full life cycle (25 years) of required volumes of CO_2: *Agreed, but as discussed in the initial section of my comments, capacity for CO_2 sequestration is about more than just the volume injected during the operational phase and the additional work programs should carefully address the role of each major trapping mechanism in order to better refine the capacity estimates for the BCS within the entire AOI.*

Injectivity

Risk 4135, 4172, 4131, and 4525: *Probability and impact appear to be within the range of reasonable uncertainty but to provide consistency with the HSSE impact assessments for other injectivity risks; it is recommended that all HSSE impacts be recorded as <u>minor effect</u>.*

Risk 4150 – CO_2 injectivity estimated from water injection test: *Without both laboratory experiments on CO_2 – brine relative permeability measurements (and their associated endpoint saturations) and a field experiment of CO_2 injection, the assessed probability of 0-5% (extremely unlikely) is judged to be optimistic. It is recommended that the post mitigation probability should be raised to 5-20% (low, but not impossible). And the impact from over-estimating injectivity would likely be larger for the cost/benefit (due to the need for well stimulation) and Schedule FID to SO (due to the uncertainty this would bring in the project when a majority design element was over-estimated). It should be noted that Shell has identified an associated action item for this risk (A 3065) which is to decide on the need for a CO_2 test on the 3rd appraisal well.*

Risk 4136 – Loss of injectivity from dropping BHP constraints: *This particular risk element links to Risk 4154 (discussed subsequently in the Containment section). For Risk 4136, which is related to injectivity, the post mitigation probability and impact estimates appear to be reasonable.*

Top Level Hypothesis – Injectivity can be sustained for the full project life-cycle: *Agreed but some confusion over the period of the "life-cycle" arose during the discussions. Contractual obligations for a period of 10 years and the 25 year period considered for the TESLA hypotheses caused some confusion regarding the period being considered for the assessment of sustained injection.*

Containment

Risk 4157, 4177, 4168, 4167, 4520, 4132, 4133, 4159, 4522, 4523 and 4524: *Probability and impact appear to be within the range of reasonable uncertainty. For risk 4168, while probability and impact assessments are acceptable, it is recommended that additional work packages be identified that will support or defend the risk reduction assessments post mitigation. Currently no explicit work packages are identified for this risk.*

Risk 4339 – Timely demonstration of containment: *As discussed during the panel sessions, the wording of this risk was confusing and ultimately, it was more or less reworded as "**timely prediction of containment for regulatory approval**". Shell is urged to review this wording and confirm the focus for the risk issue. For timely prediction of containment, I would suggest that the ability to judge the acceptability of Shell's technical arguments by both energy and environmental regulators is not certain and given the investment levels by the Alberta Government and the due diligence that will be undertaken by them that there would be a "Low, but not impossible" probability that this risk may occur. And the importance of defendable predictions of containment for regulatory approval would also point to impact judgments that may be larger than those documented by Shell. As noted by Kathy Penney in her Regulatory Update presentation, there will be increasing potential for NGO issues with security of storage being among many of the key arguments that Shell will need to defend. This may lead to post mitigation impacts that are beyond the values listed by Shell for Risk 4339 and a careful review of these is recommended.*

Risk 4154 – Injection induced stress fractures geological seals: *For this reviewer, this is likely the one technical issue where I think Shell needs to proceed carefully with the additional work packages that have been identified for thermal effects during CO_2 injection. This risk is intimately linked to Risk 4136 and relates to unintended fracturing within both the BCS and the geological seals.*

Firstly, an inconsistency in the fracturing conditions within the BCS was identified in the text. In the "before action" section of Risk 4154, the text appears to show that "although initiation of a fracture in the BCS is fairly likely, its much less likely that these will be able to propagate through the LMS, up into the MCS and beyond into the Lotsberg salts" whereas in the assumed mitigations section for Risk 4136, it is assumed that the BHP constraint of 28 MPa provides a sufficient margin (it is approximately 4 MPa below the interpreted fracture propagation pressure of the LMS) to be robust against the risk of fracture propagation out of the BCS. Clearly these risk descriptions allude to a degree of uncertainty around the role of fracturing within the BCS that should be reflected in the post mitigation probability assessments. I would submit that Risk 4154 should be subdivided into two elements: injection fractures BCS and injection fractures geological seals. This would allow Shell to refine and direct work packages to focus on fracture conditions within and outside the injection horizon (BCS). For the cooling conditions expected (and reported) for the Quest project, I would suggest that fracture conditions within BCS will be reached for pressures of 28 MPa because even modest assumptions of thermal properties for the BCS can result in predicted stress reductions that exceed 4 MPa. Figure 4 *below provides the results of simulations conducted for the IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project to study the impact of thermal cooling on the in situ stress sate. As seen in these figures, substantial stress reductions are not impossible but of course, depend on several factors such as formation stiffness, thermal expansion coefficients, etc.*

This reviewer acknowledges that Shell is very aware of the issues regarding thermal cooling and its impact on formation stresses - mitigations assumed for Risk 4136 clearly state that "Geomechanics will further define the expected impact (including uncertainty range) of low temperature CO_2 injection on formation stress and fracture gradients".

Risk 4149 – Requirement of MMV wells in BCS threatens containment: *As noted above, the risk issues related to Quest wells (which are drilled and completed using modern approaches) have been judged by Shell to have an extremely unlikely probability of contributing to containment risk but yet for this risk (Risk 4149), where MMV wells are constructed with the same modern approaches, the argument of poor cementing is invoked as a rationale to argue against the implementation of MMV wells within the BCS. This inconsistency should be more clearly resolved by Shell in their ongoing work packages.*

Top Level Hypothesis – Injected reactive fluids will not leak SIGNIFICANTLY from the containment complex: *Agreed but some resolution over the definition of "SIGNIFICANTLY" is required. From discussions during the panel review sessions, it was suggested that the limits of "significantly" would be defined by external consultants chosen to conduct the EIA for the Quest project. These limits would be defined for particular CO_2 flux rates and their impact on environmental and human assets identified within the EIA. This will be a difficult exercise as the consequences of CO_2 migration (leakage) into the biosphere, hydrosphere and atmosphere is currently an area of active research with a substantial degree of uncertainty on the epidemiological impacts, the impacts to groundwater, etc. It is recommended that Shell proceed with caution regarding how a "SIGNIFICANT" leak is defined.*

Conformance

Risk 4163, 4342, 4503 and 4164: *Probability and impact assessments appear to be within the range of reasonable uncertainty. For Risk 4342, the intimate link to the MMV plan that will be developed over the next 6-9 months is critical to managing this risk. As Gen-4 modelling proceeds in concert with the refinement of the MMV plan, it is recommended that more quantifiable estimates of the ranges of the "indicators" identified for each monitoring task included within the MMV plan (as described in Table 7 in the MMV Plan Report). It is understood that history matching and model updating will be an on-going process during injection in order to evolve the predictive confidence in preparation of post-closure and liability transfer. Predicting the degree of departure from the expected behavior of the storage complex is an important element in this history matching process and provides a defensible rationale for the implementation of additional MMV technologies if there is a departure from the expected behavior.*

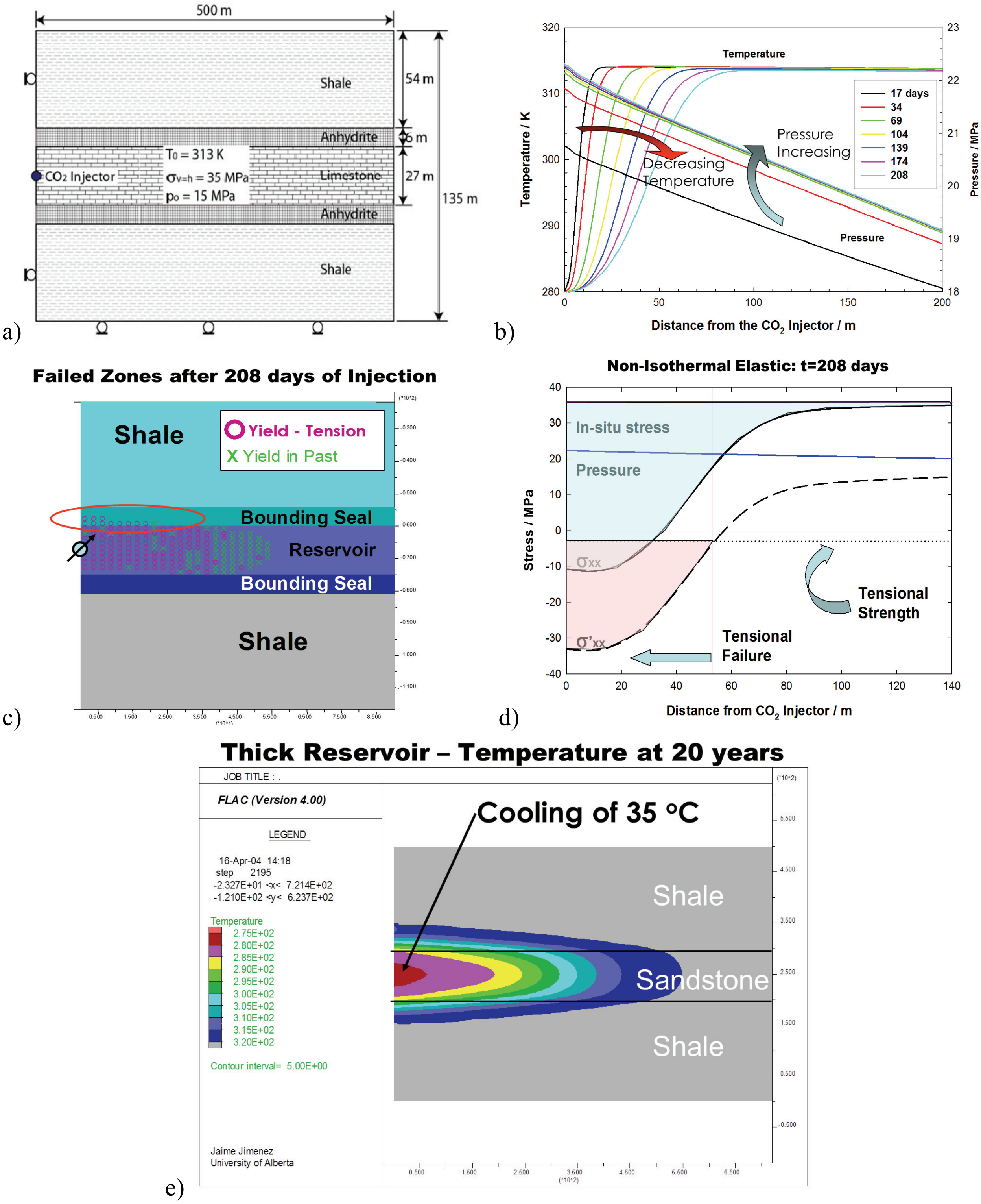


Figure 4: Simulation results from IEA GHG Weyburn –Midale CO_2 Storage and Monitoring Project highlighting potential impact of thermal cooling on reservoir behavior. a) Geometry of problem chosen for study b) Temperature distribution away from wellbore c) Propagation of failed zone upward into bounding seal layers – 208 days of injection d) propagation of tensile failure zone 50 m away from CO_2 injection well – 208 days of injection and e) propagation of cooling front up into bounding seal layers

Top Level Hypothesis 1 – Baseline Monitorability: *In general, I agree with this overall hypothesis with the exception that at this point in the project, I would submit that the tolerances for CO_2 fluxes is not understood, especially within the biosphere, hydrosphere and atmosphere. Shell has identified work packages to achieve these and as it relates to EIA activities, is urged to focus close attention on the outcomes of these studies.*

Top Level Hypothesis 2 – Containment Monitorability: *As stated by Shell, MMV plan provided for the review was a conceptual plan only and that the feasibility assessment of the monitoring technologies is currently ongoing. Consequently, it may be premature at this point in the project to conclude that movements of the CO_2 between domains (geosphere, biosphere, hydrosphere and atmosphere) can be detected by the proposed technology.*

<u>Are the right plans in place in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?</u>

The work packages identified for each of the major risks is closely linked to de-risking activities and the reduction of uncertainty in many of the technical elements of the project. Discussions around the need for activities on CO_2 relative permeability, for instance, have already been identified. I strongly recommend that the issue of thermal cooling within the reservoir over the 25 year injection period be studied closely to ensure that fracturing risk within the BCS and into any overlying zones is minimized to ALARP levels.

<u>Are there any additional risks within the scope of the project that have not been identified?</u>

While not specifically related to risk, a project related issue that appeared during the panel review was the focus on operational issues related to the development of a CO_2 injection project and the regulatory submissions to allow the project to proceed. This is identified as a project related issue because the subsurface component of the Quest project is seen as a CO_2 sequestration project that is intended to provide scientific evidence for the safe storage of CO_2 in a saline aquifer and not just a project to inject some CO_2. To date, the focus has been on the practical aspects of project development, quite rightly given the financial investments that will be necessary for the project to come to fruition. But in the end, the subsurface component will be about safe effective storage and the scope of the remaining work packages will need to increasingly focus on the "sequestration" elements of the project and not just the 25 yr injection period.

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Don Lawton, University of Calgary

Dr. Don Lawton is a Professor of Geophysics and Chair in Exploration Geophysics in the Department of Geoscience at the University of Calgary. His areas of expertise include acquisition, processing and interpretation of multicomponent seismic data, seismic modelling and seismic imaging. In terms of CO_2 storage projects, he has competencies in interpretation of geophysical data for site selection and characterization, and in seismic monitoring technologies. He has been involved in carbon capture and storage (CCS) research projects in Alberta, including the Pembina-Cardium CO_2 Monitoring Pilot, the Wabamun Area CO_2 Sequestration Project (WASP), and the Heartland Area Redwater Project (HARP). He is an Associate Director of the Consortium for Research in Elastic Wave Exploration Seismology (CREWES) and was recently appointed Theme Lead in *Secure Carbon Storage* for Carbon Management Canada, a $25M National Centre of excellence. He is also an invited member of the expert panel on monitoring for the Carbon Capture Project (CCP).

Top-level questions

<u>Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity, containment and conformance?</u>

Note – conformance was added during the review week, but this is absent from the Executive Summary draft. In my opinion, the Shell team has done an outstanding job in the technical work completed at the time of the IPR review, as well as work that is proposed to be completed through to July, 2011. Each of the components is considered separately.

<u>Capacity</u>:

The pore-space capacity of the Basal Cambrian Sand was assessed initially through the reprocessing and interpretation of legacy 2D seismic data over the general QUEST area of interest (AOI), and a small 3D legacy seismic volume as well as well data from legacy wells near the perimeter of the AOI. Subsequently, a high-resolution airborne magnetic survey over the AOI and analysis of available gravity data enabled adequate interpolation between 2D seismic lines and the general identification of 'bald highs' in the Precambrian basement against which the BCS lapped out. Understanding the depositional environment of the BCS was refined through the Scotford and Redwater wells in addition to new 3D seismic data that were collected within the AOI. These datasets were used to predict reservoir qualities in the new Radway 8-19 well. Initial results from this well met expectations, but further tests will be carried out over the next 6 months. I am in agreement with that the results presented suggest that sufficient pore space capacity exists in the BCS for 25 years of CO_2 injection.

<u>Injectivity</u>:

A design scenario was presented that uses a constraint of 28MPa bottom-hole pressure in order to establish a pressure buffer below the expected fracture gradient determined from the appraisal wells. In the discussion, there was a recommendation that the rel-perm measurements should be made (this is not my area of expertise). Loss of injectivity due to various near-well effects (geochemistry, pressure) was considered but impact was extremely unlikely or low, but not impossible. Thermal effects from the injection of cool CO_2 are not yet fully ascertained. At the time of the IPR Workshop, injectivity overall was less well understood than capacity, but the documentation put forward was detailed, although discussed for a 10-year time frame generally rather than the full 25 year project. An imminent water injectivity test in the Radway well should likely reduce remaining uncertainties.

<u>Containment</u>:

A well-presented case was put forward that vertical flow out of the storage complex is extremely unlikely due to the regional extent and physical properties of the seals (MCS and Lower and Upper Lotsberg salt). The case for containment is very strong. Faults have been mapped at the basement level, but seismic data show that these do not propagate through the seals, at least at the resolution available from the seismic data (estimated at 15 m). Ample evidence was presented to support integrity of the seals. Reactivation of faults due to injection and possible injection-induced fractures were issues that were raised by the IRP for further consideration. This would tie into a recommendation for a more detailed study of regional and local seismicity.

<u>Conformance</u>:

This is identified on the risk matrix as baseline monitorability and containment monitorability. These are the least mature components of the top-level assessment as the measurement, monitoring and verification (MMV) plan is still being formulated. The suite of technologies suggested and assessed for the QUEST site are comprehensive and the implementation strategy is well-founded. However, the description is very high-level and the efficacy of the techniques to be employed will depend significantly on how the monitoring surveys are designed. It is recommended, for example, that the 3D vertical seismic profile surveys use multicomponent geophones and that pure modes and well as converted waves be used to image the CO_2 plume.

<u>Are plans for future characterization work suitable to enable a decision on a final injection plan?</u>

In my opinion, the future characterization work will enable an informed decision to be made for a final injection plan. The second phase of the 3D seismic data acquisition and full amplitude-preserving processing of the entire 3D seismic program will provide a very high quality volume encompassing the proposed CO_2 injection wells. Water injectivity tests and full analysis of the Radway well data will further refine this interpretation. A close tie between the processed seismic data and synthetic seismograms generated from the Radway well sonic logs will increase confidence in the petrophysical model of the injection site, or reveal artifacts, such as multiple reflections, that may be contaminating the seismic volume.

<u>Is there an appropriate risk and uncertainty management framework in place for the storage site?</u>

The approach to risk and uncertainty management is very comprehensive, but designed generally from the point of view of an oil and gas operating company rather than a CCS project operator. There was insufficient time available at the Workshop to fully understand some of the uncertainties ascribed in the TESLA framework.

<u>Are the risks and uncertainties adequately understood and classified in terms of probability and consequences?</u>

Generally yes, but in a few instances it is considered that assessed probability may be too low, as indicated in the risk spreadsheet in Section 3.

<u>Are the right plans in place in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?</u>

Yes for capacity, injectivity and containment, with the suggestions outlined in Section 3. For conformance, the MMV plan is still evolving, particularly the environmental impact plan. In my opinion, the use of time-lapse seismic data to demonstrate conformance has higher uncertainty than shown at the Workshop. Laboratory measurements of P and S wave velocities on core samples at reservoir temperatures and pressures as a function of CO_2 saturation would help predict the efficacy of 4D seismic to detect the CO_2 plume within the BCS, although the difference in frequency band between field and laboratory measurements is a legitimate concern.

Are there any additional risks within the scope of the project that have not been identified?

I consider that all of the technical risks associated with this project have been identified, but from the perspective of an oil and gas operating company. However, from the point of view of a CCS project, I believe that the identification and mitigation of *perceived risk* should be revisited, primarily related to public acceptance of CCS as a safe technology. For example, public concerns about the effects of induced seismicity during injection of CO_2 may lead to project delays and measurements of permeability of CO_2 through the rock samples of the sealing formations may seem unnecessary from a technical viewpoint, but are important for public assurance.

Additional comments

Overall, the technical work program undertaken by the Shell team is outstanding. The regional characterization of the BCS through well data, seismic and airborne magnetic surveys is excellent and the local scale characterization based on the Radway well and the new 3D seismic data is without precedent.

Although the MMV program is still being developed, the linkage between risk identification and the MMV plan, with multiple levels of protection, is a novel approach. The only caution here is to balance the MMV program between being proactive versus reactive. A proactive approach is beneficial for public acceptance and regulatory conformance issues, but needs to be balanced against costs compared with a reactive strategy. The efficacy and cost of the MMV programs will depend on the design and survey intensity, which is not yet discussed in any of the documentation.

Some additional comments specific to the risk register are:

- 4177, 4154 – injection induced faults/fractures. These would be detectable in microseismic arrays in an observation well near faults or fractures, but may fail if the fractures are distal to the observation well. As noted earlier, some mitigation could be provided by continuous measurements of seismicity throughout the baseline and operational aspects of the project, whereas microseismic monitoring would likely take place during only the injection phase (timelines not yet established in the MMV plan).
- 4520 – migration along a legacy well. Well-head CO_2 detection may be difficult since most legacy well heads have been removed, but wells could still be located with ground magnetometer surveys if coordinates are known with sufficient precisions. Flux chambers could be established over the legacy wells once the exact locations are known.
- 4132 – migration of CO_2 or brine along a QUEST well. Brine would be detected only through pressure or sampling. However CO_2 should be detectable through the 4D VSP and/or surface seismic methods using both amplitude and traveltime attributes. The MMV document discusses only amplitude changes but differencing methods will also show changes in reflection traveltime through zones with relatively low (< 40%) levels of CO_2 saturation. This would be particularly true for migration into zones at depths less than ~800 m, where the CO_2 will be in gas phase, and readily detectable in seismic data. However, migration out of the storage complex into these shallow zones is highly unlikely.
- 4524 – third-party induced migration. Table 3 of the proposed MMV plan discusses the use of the 2D and 3D seismic data for detecting CO_2 in the protected groundwater zone. However the likely design of seismic surveys would be focused on imaging the BCS storage complex and will be

inappropriate for imaging the hydrosphere. Specific surveys would need to be designed for hydrosphere programs. These would have to be targeted where leakage was suspected as the costs for regional surveys of this type would be prohibitive.

- 4163 – unexpected plume migration. Risks for pressure versus CO_2 plume migration should be discussed separately. In the MMV plan, high emphasis is place in INSAR for monitoring the lateral extent of the pressure plume, and identifying short-wavelength surface heave that might be indicative of vertical migration of CO_2 out of the storage complex. Whilst INSAR has been demonstrated to be an effective monitoring tool at the In Salah CO_2 storage project, the impact of seasonal variations within Canada on INSAR precision have not yet been fully assessed. Also, the proposed MMV plan uses ground deformation in a qualitative sense, rather than attempting to match observed ground deformation with that predicted from geomechanical models. Baseline INSAR analysis prior to injection should enable precision levels to be better understood.
- 4324 – inability to demonstrate conformance. There is no plan to undertake a pilot injection project, but rather the project will move toward full-scale injection. I support this strategy as numerical seismic modelling suggests that significant volumes of CO_2 will need to be injected for the plume to be detectable using 4D seismic surveys. It is proposed to map the extent of the plume initially using 3D VSP surveys. Again, this will depend on the survey design as VSP surveys are not ideal for imaging purposes due to the limited migration aperture. However, attribute studies, such as amplitude vs offset (AVO) should be fully exploited to match petrophysical data extracted with time-lapse logging data from the injection wells.

High-level hypothesis – "likely and high risk (consequence) movements of the CO_2 within the container and between each domain can be detected by the proposed technology". There is considerable uncertainty in this statement, particularly for movement of CO_2 within the storage complex. The MMV plan could be augmented by cross-well surveys (seismic, ERT or EM) if an observation well is drilled through the BCS. Although cross-well surveys provide information only in the local plane that contains the injection and observation wells, such surveys may provide local information about the vertical and lateral distribution of CO_2 (i.e. saturation profiles) that could be used to calibrate the interpretation of 3D VSP and surface seismic surveys; i.e. to match seismic response to a particular thickness/saturation model. The BCS facies model could then be used to propagate a possible realization of the saturation model elsewhere in the BCS. This would provide confidence in the ability of the seismic data to map the full extent of the CO_2 plume.

Rajesh Pawar

Dr. Rajesh Pawar has been working in the area of geological CO_2 sequestration for past 10 years. He has led a number of multi-disciplinary research projects focused on various aspects of long-term CO_2 storage in geologic formations. These projects range from fundamental aspects of CO_2 interaction with geologic media to field experiments to characterization of long-term risks associated with large-scale CO_2 storage. Dr. Pawar received his Ph.D. in Chemical Engineering from the University of Utah. His primary interests are in the area of multi-phase fluid flow in porous media including fluid flow simulations and development of numerical simulation capabilities.

Top-level questions

Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity, containment and conformity?

The proposed large-scale Quest CCS operation is first of its kind industrial saline aquifer storage project in North America. Typically, saline aquifers are not as extensively characterized as oil and gas containing formations. This leads to a unique dilemma as far as understanding and predicting CO_2 injection and resulting multi-phase, multi-fluid flow in saline reservoirs due to CCS operations. The Quest CCS site faces similar challenges due to the quantity and quality of pre-existing data and in turn it is challenging to assess the level of adequacy associated with the characterization effort. Based on the information provided as part of the review process, I believe that at the current stage of characterization:

- The proposed site seems to have adequate capacity for storing the amount of CO_2 during the duration of the project
- Unlike capacity there appears to be relatively higher uncertainty in injectivity calculations. Current injectivity calculations account for CO_2-brine relative permeabilities using analog measurements and limited in scope to account for near wellbore non-isothermal effects. It appears that addressing these limitations is part of Shell's near-term plans. In addition, Shell is addressing the effect of uncertainty in injectivity by having excess injection capacity through additional wells.
- The proposed storage complex contains multiple seals including the MCS and Lower and Upper Lotsberg salts. Based on available data it appears that the combined seals together will provide an effective barrier against CO_2 and brine migration beyond the Upper Lotsberg salt unit. Further characterization may be needed to determine the spatial extent of individual seals, if required.
- The monitoring plan presented during the review was a proposal and not a final plan. The proposed plan is designed for limiting risks associated with failure by focusing on limiting the impacts in case failure occurs. But in its current stage the monitoring plan has limited applicability for providing the data necessary for defining plume extent as well as determining distribution of CO_2 in various phases (free, dissolved, etc.). These issues may be critical in meeting the conformance, but will ultimately be determined by the regulatory requirements (which appear to be undefined at this stage).

Are plans for future characterization work suitable to enable a decision on a final injection plan?

Based on presentations and accompanying discussions during review, I believe that Shell is planning to address a number of issues which have higher uncertainties through future characterization work. If successful, the results of these additional activities will help enable the decision making process on a final injection plan.

Is there an appropriate risk and uncertainty management framework in place for the storage site and are the risks and uncertainties adequately understood and classified in terms of probability and consequences?

Due to the time available for the review and the type of information shared, at this stage only a qualitative judgment can be made on the overall risk analysis and management approach. Based on the data & results presented during the review process it appears that Shell has made a genuine attempt towards understanding and characterizing the risks and uncertainties at the Quest CCS site. The process has led to identification of potential hazards, probabilities of failures, potential impacts and uncertainties associated with various FEPs. Though, this analysis has been performed through an "in-house" expert elicitation process in a largely "qualitative" manner. Based on the data provided, it is difficult to adjudge the quantitative adequacy of probabilities and consequences of risks. The critical part of the risk management framework is the proposed MMV plan. The MMV proposal is "conceptually" geared towards minimizing risks and mitigating consequences. Further work may be needed to quantitatively address effectiveness and applicability of proposed technologies through careful work including integration with detailed numerical modeling.

Are the right plans in place in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?

The central part of this question is the proposed MMV plan. On a "conceptual" level the proposed plan appears to merit assurance of lowering of risks and uncertainties to an acceptable level (it needs to be pointed out that the definition of "acceptable level" is entirely dependent on the underlying regulatory framework, which at this stage remains largely uncertain). But this largely depends on effectiveness of proposed technologies in identifying failures in a timely manner. Very little evidence on thorough analyses of effectiveness of these technologies (taking into account resolution, sensitivity, etc.) was provided. In the proposed plan, significant emphasis is given to above surface monitoring technologies (INSAR, 3D surface seismic) for tracking the pressure and saturation changes resulting from CO_2 injection. But, a careful quantitative analysis which takes into account the geologic characteristics at the site to characterize the effectiveness of these (as well as other proposed technologies) is warranted before the next project phase.

Are there any additional risks within the scope of the project that have not been identified?

I believe the project has done a good job of identifying the hazards and risks.

Additional comments

I believe that Shell has done a good job to characterize the proposed Quest storage site. Unfortunately, due to the limited time allocated for IPR as well as level of information provided, it is not possible to make any quantitative assessment of the risk and uncertainty analysis. Based on the information provided, it appears that the storage complex (as defined by Shell) has the containment necessary for safe CO_2 storage. Below are a few suggestions and comments.

- CO_2-brine relative permeability characterization: Shell has attempted to model the CO_2-brine relative permeability behavior with experimental data generated using a brine and oil as surrogate for CO_2. I will encourage conducting experiments with CO_2-brine system spanning the P & T region that will reflect potential conditions in the reservoir during large-scale injection. This will be useful in determining how the interfacial behavior varies between super-critical CO_2 and analog oil and its impact on the relative permeability. It is very likely that an explanation as to sufficiency of the current approach to accurately characterize the multi-phase, multi-fluid flow may be asked during the regulatory application review process.

- Grid effects during numerical simulations: I will suggest a careful review of effect of numerical grid resolution on calculation results, especially, on CO_2 plume migration. The results presented during review appeared to have some ambiguity with respect to effect of grid refinement.
- Non-isothermal calculations: The numerical models were performed assuming that CO_2 comes to an instantaneous thermal equilibrium with the reservoir. The current calculations do account for the difference in mobility due to temperature through wellbore kh. But this approach does not account for the effect of temperature variation over a region close to the wellbore that extends well beyond the wellbore vicinity. I will suggest performing non-isothermal simulations that can account for this and see how the results impact injectivity calculations.
- Legacy wellbore leakage modelling: Some of the calculation results indicated that for certain low range scenarios the deltaP in the region near legacy wells could potentially reach levels that may be sufficient to exceed the hydrostatic head. In order to understand whether this could be potentially a risk for brine migration through legacy well, it will be beneficial to perform careful analysis taking into account all of the information available on the configuration used to abandon the wells. If such information is not available for a specific well, I will suggest using the data available on most prevalent abandonment practices used at the time. This data can then be used to develop numerical models for legacy wells and perform fluid flow simulations using what-if scenarios for various potential failures to ultimately characterize the brine migration potential as well as flow rates to upper formations through these wells. These simulations can be performed using a range of deltaP developed from detailed reservoir simulations.
- Shallow aquifer geochemical impact modelling: In order to characterize the impact of potential CO_2 and brine migration on shallow aquifer geochemistry it will be beneficial to set up a numerical model for shallow aquifer that incorporates results of mineralogical characterization as well as laboratory experiments on CO_2-water-rock interactions. This model could be used to determine the level of CO_2-brine flow rate that could lead to significant impact on shallow aquifer geochemistry. This information could also be beneficial for designing the MMV program.
- Conformance: The current MMV plan provides no data that can be used for verifying the plume extent as well as CO_2 state in the reservoir (free phase, dissolved in brine, etc.). As this is a "long-term CO_2 storage" project, it may be entirely possible that the project will be asked to provide information for these. This information will be useful for verifying the reservoir models and increase confidence in their predictive capabilities. In addition, at the end of the project the operator may be asked to demonstrate that the plume is stabilized and risks due to plume migration is minimal. The current plan does not necessarily provide information that can be used for such purpose. I will strongly encourage addressing these needs prior to designing and deploying the final MMV plan.

Frontier project: Finally, no matter which way Shell and its partners look at the project, the broader stakeholders as well as the CCS community is looking to Quest (and other early starts) as opportunities that help fill the knowledge gaps related to effectiveness and long-term safety of this technology. Success of these projects is paramount for increasing confidence in this technology. I will strongly encourage the JV to design and execute the project in a manner that provides every possible opportunity to gather data that will be beneficial for wide-scale deployment of CCS technology.

Ernie Perkins, Alberta Innovates

Ernie Perkins is a technical specialist/senior scientist in the geochemistry of CCS in the Carbon and Energy Management Department of Alberta Innovates – Technology Futures. He received his Ph.D. from the University of British Columbia. He is an internationally recognized expert in geochemical modelling, geochemical sampling and interpretation of subsurface reactions, and has been involved in CCS activities since the early 1990's. He has been a lead geochemist for the CO2CRC Otway program in Australia, Penn West CO_2 monitoring Program in Alberta, and the Weyburn CO_2 monitoring program in Saskatchewan. Currently, he is the Project Leader for geochemical projects in the HARP and PRISM programs. He is active as an advisor and a senior scientist for other CO_2 storage activities, including Spectra in north eastern British Columbia. He is also active as a project leader/specialist in the use of geochemical monitoring for the interpretation (and prediction) of changes in formation mineralogy and fluid composition in Enhanced Oil Recovery, especially thermal projects.

Top-level questions

<u>Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity, containment and conformance?</u>

Background: The location of the proposed Quest CCS operation is based on well based information from a limited number of wells which penetrate the BCS, on surface seismic geophysical interpretation and on an understanding of the evolution of the Alberta Basin. The seismic data includes older surveys and a survey undertaken by Shell last winter over more than over one half of the proposed area. They plan to complete the survey during the next winter. There are about 5 historical wells in the vicinity of the proposed location. Shell has currently drilled three wells, one next to the Scotford refinery, one on the edge of the proposed area and one near the centre of the proposed area. These have been logged with reservoir properties measured. Based on their proposed development plans, additional injection wells in the proposed area will be drilled and reservoir properties will be measured. Although the primary well based data is limited, the measured data has been found to be consistent and more will be obtained.

Within this context, the issues of capacity, injectivity, containment and conformance will be discussed.

<u>Capacity</u>:

The storage capacity of the BCS is based a geological model defined via geophysical measurements, well based logging and core samples, and a regional geological model. Based on this data, the reservoir properties of the latest well, Radway 80-19, were predicted adequately lend confidence to the geological model and the associated properties. As new wells are drilled and logged, it is expected that the storage capacity will be refined if the data warrants.

I am confident that the current estimate of storage capacity of the BCS is sufficient for the planned injection volumes.

<u>Injectivity</u>:

At this time, reservoir injectivity has been evaluated through numerical modelling. A water injection test is planned for the Radway well and depending on the results, a CO_2 injection test may be considered afterwards. The current development plan is to have 3 injection wells, but up to 10 wells are being planned for, thus allowing for any uncertainty in reservoir injectivity. The plan is to have at least one well available in excess of anticipated needs, thus allowing a decreased injection rate if all wells are used and allowing total CO_2 injection rate to be maintained if a well needs to be taken off line.

At this stage, I am confident that reservoir injectivity is sufficient and that any departure will be addressed by either the additional well or by increasing the total well count. The planned injection test(s) will help establish the necessary number of wells.

However, I feel that additional work be undertaken in three areas:

a. I am not confident in the methodology used for the CO_2 – water rel-perm measurements. In these measurements, CO_2 was replaced by a mineral oil. It is not clear that this is appropriate and I recommend that CO_2 – water rel-perm measurements be made and the data re-evaluated.
b. During internal presentations, numerical modelling results using various ranges of reservoir and fluid properties were presented. This is appropriate and establishes the process sensitivity. During this project, the numerical modellers chose not to use some of the more extreme combinations of values as they believed them to be unrealistic and they were time constrained. In an oil and gas setting, I agree with this approach and the conclusions. I do not agree with this in a CCS environment as I believe that it is the responsibility of the proponent to show that the extreme data combinations are not appropriate or significant. Thus I recommend that additional numerical simulations be undertaken, primarily to establish that all bounding cases have been considered.
c. The potential geochemical reactions which could occur in the reservoir due to interactions of injected CO_2, formation water and formation minerals were calculated. However the main focus of the report was in salt precipitation in the near well and the other processes were not reported. It appears that only two scenarios (one homogeneous reservoir, the other with layered permeability) were calculated. Based on personal experience, I agree with the conclusions. However, I do not believe that sufficient geochemical modelling has been undertaken to establish this and more should be undertaken. This is discussed in more detail below.

I should emphasize that the additional proposed work is expected to support the existing conclusions and not to modify them.

Containment:

The main concern with respect to containment is that there are adequate seals bounding the storage horizon and that there are no leakage "paths" through these seals. The geological model has shown that there are multiple large regional seals and that they are expected to be effective over the "area of influence". Faults have been mapped but the geophysical data suggests that no major faults cross the seals. The potential storage area has been chosen such that there are no wells penetrating the BCS in the immediate vicinity – all are more than 15 km removed from the proposed injection wells. Thus there are no issues regarding cement integrity, casing corrosion or well abandonment. Based on the information provided by Shell, the injection wells have been appropriately designed and there should be no concerns.

The seals should be stable with respect to mixtures of formation fluid and the injected CO_2, which is one of the elements identified in the risk assessment. Conclusions were presented for this risk but no geochemical support for these conclusions was given. In the justification, there was an inconsistency between several of the statements. Based on personal modelling experience, the seal stability should not be an issue, however it must be demonstrated through modelling. This is discussed in more detail below.

Not withstanding the issue the issue with respect to the geochemical stability of the seals, I believe that at this stage of the project, containment has been adequately established. I expect that it will be re-visited as the project matures.

Conformance:

In this context, conformance is identified as the ability to monitor fluid migration (both CO_2 plume and brine) and the pressure changes within the BCS and potentially in the overlying aquifers and at surface. It depends on an appropriate MMV (Measurement, Monitoring and Verification) plan and an effective MMV field implementation.

The MMV plan has not yet been developed. However, a MMV conceptional framework has been developed based on the risk matrix and potential monitoring technologies identified. The process used is quite powerful and comprehensive. The value of a measurements which will indicate an anomaly has not yet been established as it depends on the technique (yet to be established) and the baseline conditions. Baseline seismic, hydrology and ground chemistry measurements are underway. Some baseline reservoir properties have been made.

In conclusion, the development of the MMV plan and the establishment of various baseline measurements are well underway. It is appropriate for this stage of the project and I have confidence that it is proceeding appropriately.

The risk assessments place a high risk on the placement of monitoring wells in the BCS. Additional wells are not needed for direct measurements in the BCS as the current plan is to have at least one additional injection well above what is needed. Various well bore based tools (RST, MDT, etc) can then be used to obtain fluid and other types of samples, measure CO_2 saturation, etc. By rotating these measurements through each of the planned injection wells, a spatial assessment can be made. At the end of the injection period, then all of the injection wells can be used as monitoring wells. Although not ideally sited, they can be used to evaluate the storage mechanisms and help evaluate containment.

<u>Are plans for future characterisation work suitable to enable a decision on a final injection plan?</u>

I believe that the current activities and planned future activities are suitable to decide on the operational plan.

<u>Is there an appropriate risk and uncertainty management framework in place for the storage site?</u>

The risk management framework is designed on the perceived potential and real risks in the project. It is directly linked to the MMV framework, then to the MMV plan and it's implementation, and ultimate linked to any necessary remediation actions. It is flexible and comprehensive. The only significant issue is that it is based on an oil and gas industrial perspective which may not be broad enough in a CCS environment. Much of the uncertainty for CCS projects is ultimately driven by public perspective and potential government legislation and regulation. I don't believe that these can be adequately captured in the risk and uncertainty framework. However, our exposure to this portion of the project was limited and I do recognize that plans are in place and that it is being managed.

<u>Are the risks and uncertainties adequately understood and classified in terms of probability and consequences?</u>

The risks and uncertainties are adequately understood and classified. There were a number of instances where the probability was either inconsistent or too low. These have been modified and are reported within this document.

<u>Are the right plans in place in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?</u>

I believe that the right plans and processes are in places to move forward.

<u>Are there any additional risks within the scope of the project that have not been identified?</u>

I believe that all of the appropriate risks have been identified. However, the issues of public acceptance, the timely passing of government legislation and timely implementation of appropriate regulations are beyond Shell's direct control. Thus, from a project view, they are high risks items.

Additional comments

The activities are based on the traditional strengths of a large oil and gas company - geological assessment and related activities, facility (including wells) design and reservoir engineering - are all well in hand with excellent interim results. The "non traditional" activities necessitated by CCS – primarily monitoring related activities, are not as far advanced. Their status is appropriate to this stage of program development.

Because of my personal background, I have examined the geochemical issues in more detail. There are three major areas where geochemical issues are significant.

The first geochemical area is within the overlying aquifers, specifically the fluid compositions. This activity is underway with ground water sampling. It was not clear from the presentations, but there should be extensive use of the existing fluid compositional data bases. Regional trends must be evaluated and integrated with the Shell activities.

The second geochemical area concerns the potential geochemical reactions which could occur in the reservoir due to interactions of injected CO_2, formation water and formation minerals. There is an appendix that details the calculations. The report focus was on salt precipitation in the near well. Issues that were not addressed (although much of this would have been calculated by the simulation package) were the spatial and temporal variation in the mineralogy of the BCS and the spatial and temporal variation of the BCS fluid composition (which gives the potential composition of any brine leakage). The specific details of the simulations were not presented. Various minerals were not included (these were not identified, nor a reason given) – I am sure that this was reasonable but it needs to be explained. Only one mineralogical composition was used, there should have been a sensitivity analysis for both it and the formation fluid composition. Grain size and reactive surface area was not discussed. It was not clear if the sampled formation fluid was corrected to formation conditions by the inclusion of lost gas. These last points should not affect the results in any significant manner, but they must be done to confirm this. The sensitivity analysis does not need to be undertaken using the Tough series of geochemical computer codes, there are more effective numerical tools for this purpose.

The third geochemical area relates to the geochemical stability of the seals, which is present in the risk register. A number of statements were made with respect to the potential reactions but they were not validated by numerical analysis or accompanying documentation. It is clear that two of the primary seals are salt and that the BCS formation water is near salt saturation, thus reactions will be minimal. But this must be documented. The other seal contains quartz, carbonate, feldspars and clays and thus has the potential to react. No reports were available to describe the potential reactions between this seal and a CO_2 charged BCS formation water. Statements were made that the void space would decrease and block any leakage – I am not convinced that this is the case, particularly as a function of time. The fastest, hence the initial, mineralogical reaction would be carbonate mineral dissolution, thus increasing the void space. The silicate reactions are slower and depending on the final state, may or may not decrease void space. As seal integrity due to acidic BCS fluids is in the risk register, numerical modelling and the accompanying documentation must be made available.

Benjamin Jay Rostron, University of Alberta

Ben Rostron is Professor in Geology at University of Alberta. He was involved with the initial scientific formulation of the IEA-GHG Weyburn-Midale CO_2 monitoring and storage project and served on the project as the "Hydrogeology Coordinator" throughout Phase 1 of the project (2001 – 2004). His research group served as one of 80+ "Research Providers" in Phase 1, characterizing the deep (>250 m) hydrogeology and hydrochemistry of the 100 km block around Weyburn oil field. He is also currently a research "Theme Leader" for the "Final Phase" of the project (2005 – 2011).

Professor Rostron was also involved with the initial scientific formulation of the Aquistore project, a relatively-new saline aquifer CO_2 sequestration project in Canada with a goal to inject and monitor 600 tons/day of CO_2 from a refinery/upgrader near Regina, Saskatchewan. Professor Rostron currently serves as a member of the Aquistore Science and Engineering Research Committee.

Top-level questions

<u>Has the injection site been adequately characterized at this stage of the project in terms of capacity, injectivity, containment and conformity?</u>

In terms of <u>capacity</u>, my answer would be an <u>un-qualified yes</u>. In terms of pore space, the site selection process has identified an exceptional injection horizon (Basal Cambrian Sandstone, BCS), and the injection horizon has been well-characterized to date. There is ample pore space available to contain the planned injection amount within the injection horizon, with the added bonus of additional pore space available within the containment complex. The BCS has one of the highest porosities and lateral continuity of any lithologic unit in the Western Canadian Sedimentary Basin.

"There is sufficient pore space for the full life cycle (25 years) of the required volumes of CO_2."

In terms of <u>injectivity</u>, my answer would be <u>in general, yes</u>, but with a couple of items that might be potential problems. The BCS is an excellent unit to inject into because of its generally high permeability, high net-to-gross reservoir properties, relatively homogeneous regional permeability characteristics, and relatively favorable (and predictable) large lateral extent and simple structural characteristics (i.e., flat and generally undeformed/unfaulted). There is also a strong technical plan and operational experience within Shell to mitigate any possible injectivity issues.

Two items of possible concern are discussed in more detail under their respective sections in the risk register, but at a high level they are the unknown effects of relative-permeability and the potential impact of halite precipitation in the near wellbore region. First, the relative-permeability characteristics of the BCS to super-critical CO_2 have not been measured. This is a critical parameter and despite the theoretical and analog work that has been done, this parameter needs to be measured to understand the permeability of the formation to super-critical CO_2 as a function of saturation. Second, information presented by Shell indicated the potential for halite precipitation near the wellbore during injection of CO_2 (with the supercritical CO_2 "drying out" the rock, causing halite to precipitate from the ambient brine). Experimental and theoretical results presented by Shell were equivocal, thus it is uncertain whether this will occur or not in the subsurface. Given the large uncertainty, and its potential impact, it is worthwhile to investigate this process further. I agree with Shell's position that after planned mitigative measures, these two effects won't jeopardize the project in terms of injectivity.

"Injectivity can be sustained for the full project life cycle"

In terms of <u>containment</u>, my answer would be <u>in general, yes</u>, but with a number of items that might be cause for concern. The "containment complex" as defined by Shell is likely one of the best locations in the Western Canadian Sedimentary Basin to store/contain CO_2 in the subsurface. There are a number of reasons for this, ranging from: the number of (i.e., multiple) sealing layers; extremely favorable (low) hydraulic properties of the sealing units; lateral continuity and thickness of the sealing units; distance from (10's km) few known significant vertical faults; favorable stress conditions in the injection horizon; and low number of legacy wellbores penetrating the sealing units; favorable subsurface hydrodynamic flow directions and rates (i.e., cm/yr flow rates, directed parallel to aquifer boundaries laterally up-dip); and substantial isolation between the containment complex and the overlying potable aquifers in terms of vertical distance, intervening secondary seals, and basin hydrodynamics. Furthermore, Shell has extensive experience successfully drilling and completing injection wells that are not going to provide leakage pathways for CO_2 to the surface.

There are a number of items of concern with respect to containment, and each of them are discussed in detail under their respective sections in the risk register. In general, the concerns fall into two groups: an overall concern related to timeline, and concerns related to "proving to the public" that what is expected will in fact be true. In my opinion, the largest risk to the entire project is identified as Risk 4339 "Timely demonstration of containment". I think this is the largest risk because it likely is out of Shell's control… whether or not containment will be "demonstrated" will almost certainly depend on an external body of unknown composition, with unknown timelines, using as yet unknown regulations. Given the relatively tight timelines of this project, I have a real concern about that the regulators will be able to keep up their end of the schedule.

The second areas of concern deal with a number of instances where Shell thinks they understand a system and can predict its behavior, but they don't have actual data to support their position. Examples of these include: Risk 4520 (Migration along legacy wells), where Shell feels that in the event of any leakage up a legacy borehole, that the formation pressure is insufficient to drive brine to the potable aquifers. However, there is no actual demonstration of how this might work, by a numerical simulation, for example. Regulators and the public are going to want to see how this process does (or doesn't work). Similarly, Risks 4154 (Injection induced stress fractures geological seals) and 4177 (Injection stress reactivates fault) both depend on detailed measurements of stress states, hydraulic and elastic properties, and temperature fields, etc. Some of these have been measured, other measurements are planned, but the ERP was not shown a model of how they all fit together and interact. I am certain that the regulator and the public will want to see further details of the operations of this site before granting their approval.

In the end, I agree with Shell's position that the risks related to containment can be overcome.

"Injected reactive fluids will not leak significantly from the containment complex"

In terms of <u>conformance</u>, my answer would be <u>a reluctant no.</u> I don't think that Shell will be able to predict the movement of the injected CO_2, nor the displacement of brine, nor the extent of the pressure plume to the satisfaction of the regulators nor the public at the present time. From an operational and "risk" point of view I don't think it will matter to the project that the exact conformance of the various plumes be predictable: it is extremely unlikely that the CO_2 plume will migrate out of the storage complex vertically, and out of the Area of Interest (AOI) laterally. Furthermore the pressure distortion caused by injection will most likely not be large enough to cause brine to migrate up into the overlying potable aquifers. However, the vertical migration of CO_2, brine, and the effects of elevated pressures have not been quantitatively studied as far as I can see. Numerical modelling conducted thus far has not been extended vertically to include any layers above the storage complex: this, by definition, precludes any vertical migration out of the storage complex, and furthermore has a direct impact on the extent of the horizontal pressure distortion (i.e., if the pressure were allowed to dissipate vertically, the horizontal plume extent might be smaller). In addition, the ERP was shown only one slide? (e.g., pg 59, Integrated Modelling Strategy presentation) illustrating the predicted 1000 year CO_2 plume extent. I think that the public and the regulators will require much more extensive demonstration of results in this area.

My concerns in this area fall under three risk elements: 4163 (Unexpected plume migration); 4503 (Inability to differentiate contamination from external sources from project emissions); ultimately leading to 4342 (Inability to demonstrate conformance). Each of my concerns are detailed in the sections below, but in summary, I have concerns over the lack of modelling conducted outside of the storage complex (4163); the importance of baseline water-chemical sampling cannot be under-stated (4503); and Shell needs to do additional work to demonstrate conformance (4342), for example: conduct Compound Specific Isotope Analysis (CSIA) gas baseline sampling, and to quantify the various forms of CO_2 trapped in the storage complex.

I concur that Shell's proposal for MMV will provide sufficient operational details to outline the extent of the CO_2 plume and that it is unlikely that excess pressure and/or brine will be driven up into the potable aquifers above. However, I'm not certain that the regulators, nor the public, will be satisfied with the current level of work done to demonstrate this.

<u>Are plans for future characterization work suitable to enable a decision on a final injection plan?</u>

<u>In general, yes</u>, with some caveats. As mentioned above, additional work needs to be done:

- measuring the relative permeability characteristics of the BCS with respect to supercritical CO_2;
- measuring the elastic and hydraulic properties (porosity, permeability, compressibility, etc) of the sealing layers within and (at least) immediately above the storage complex;
- measuring the stress state within, and above, the storage complex;
- complete the baseline chemical characterization of the formation fluids (water, gas) in as many units in the stratigraphic succession as possible;
- complete the hydrogeological characterization of the BCS aquifer, paying particular attention to mapping the lateral hydraulic gradients, including the effects of density-dependent flow on lateral flow rates, and flow directions, and explicitly calculating the current formation-fluid flow rates.

<u>Is there an appropriate risk and uncertainty management framework in place for the storage site and are the risks and uncertainties adequately understood and classified in terms of probability and consequences?</u>

This question contains several clauses that need to be examined individually:

a) Is there an appropriate risk and uncertainty management framework in place for the storage site?

<u>Unequivocally, yes</u>.

The ERP was presented with impressive amounts of information documenting Shell's well-developed Risk Management framework for the Quest project. It appears that the entire project is based on, and revolves around, the risk and uncertainty management framework. Shell is one of the world leaders in this type of management of projects, and the risk framework forms a solid basis for the entire Quest project.

b) Are the risks and uncertainties adequately understood?

This question is a little more difficult to answer, mostly because of a lack of suitable definition of "adequately". The ERP spent considerable time reviewing the "Risk Summary" containing 27 specific risks from the risk register. In general, my opinion is that <u>for the most part</u>, the risks and uncertainties are adequately understood, but there remain some important areas for which further work is needed. My detailed comments on the 27 risks make up Part 2 of this summary, below.

c) (Are the risks and uncertainties) classified in terms of probability and consequences?

As with question b) above, this question is difficult to answer, partly because different experts might assign different values of probability to certain event triggers, and partly because of the "timing" question discussed previously. For example, when the ERP questioned Shell about a particular probability and then consequence in the register, almost always the response was given in terms of "after mitigation". In other words, plans are in place to reduce the probability and/or consequence. However, the ERP was not given sufficient time to review the details of many of those plans therefore it is difficult to assess whether the probability and consequences are properly classified. As above, I think that for the most part, the probability and consequences are adequately classified, but there remain some important areas for which further work is needed. My detailed comments on the 27 risks make up Part 2 of this summary, below.

Thus, my response to Question 2 would be: in general yes, but with further work needed in some areas.

Are the right plans in place in the next phase to ensure risks and uncertainties of CO_2 storage reach acceptable levels?

Based on the information shown to the ERP, I think so, but it depends if the feedback from the ERP is incorporated into the project planning. For example, the ERP was shown a "concept" of a risk-based MMV plan, but told that this wasn't a "plan" as yet because it hadn't gone through Shell's internal review process. Furthermore, there are "operational" level plans that might take a higher priority over planned characterization activities, etc (for example, the inability of a core program to retrieve a core, collect a MDT sample, etc). Sometimes, it physically won't be possible to carry out the plans as specified. I'm convinced that Shell has an excellent plan in place to make the Quest project one of the world's flagship CCS projects.

Are there any additional risks within the scope of the project that have not been identified?

For the most part, I don't think there are any additional hazards or risks that haven't been identified within the scope of the project. A couple of caveats:

- this assumes that Shell incorporates some (or all) of the suggestions provided below in the sections discussing the risk register and regional hydrogeology;
- this assumes that Shell "takes to heart" the feedback from the ERP regarding operating this project as a "storage" project versus an "oil and gas" project. In short, the public and regulators are going to want to see different things in a storage project (1000 year predictions, for example) versus an oil reservoir. The public will want evidence that the "low permeability" aquitards (or salt aquicludes) indeed do have some measured low permeability, etc.

Detailed Assessment of Major Risks

Capacity Risk 4166 (Lower than expected capacity as reservoir properties and connected volume are worse than expected) – I agree with Shell's assessment.

Capacity Risk 4160 (Contribution of LMS to primary storage capacity could be less than anticipated) – I agree with Shell's assessment.

Injectivity Risk 4135 (Low injectivity due to poorer than expected near well bore properties (kh and skin) – I agree with Shell's assessment.

Injectivity Risk 4150 (CO_2 injectivity over-estimated from water injectivity test (rel-perm and non-Darcy skin)). Shell's probability estimate is too low, I think it should be 5-20% chance, or even higher. Shell's impact should be elevated to minor impact. Comments: Shell has not measured the relative-permeability to CO_2 on the BCS. Instead, they are relying on "calculated" R-P curves for their injectivity calculations, and relying on drilling additional injection wells if the relative permeability causes sufficient loss in permeability (injectivity). When the ERP talked via conference-call to Shell's in-house relative-permeability expert (name?), he finally agreed that this was something that should be done. I think that the difficulty and cost of conducting a CO_2 relative permeability test more than offsets the risk of drilling additional well(s). On the other hand, I do not think that it is necessary for Shell to conduct a field CO_2 injection test on a well.

Injectivity Risk 4172 (Loss of injectivity due to pressure build-up) – I agree with Shell's assessment. However, there was a consistent question related to the boundary-conditions used in the modeling, in particular the density of the brine in the BCS. Specifically, what is the density of the brine in the BCS? In some places, it is stated as: "approximately 280 kppm NaCl equivalent" (pg v, EP-2010-3099) or "Hyper Saline Brine (269 kppm NaCl salinity)" (e.g., Geology and IPSM presentations) while elsewhere it is listed as 269,000 mg/L (e.g., Pressure and Fracture Gradient presentation, p. 18). At this level of Total Dissolved Solids (TDS) the distinction may seem academic but in fact there can be a significant difference in density depending on which are the correct units of the water analysis. Clearly this needs to be clarified and propagated back through out the other aspects of the project. For certain the geochemical models must be using the correctly measured water chemistry values. Similarly, the aquifer boundary conditions need to be understood – in this case, not so much the physical boundaries but the nature of the ambient flow field (more on this in Section 3 below).

Injectivity Risk 4155 (Loss of injectivity due to geochemical alteration of reservoir and/or Halite precipitation) – Shell's probability estimate is too low, I think it should be at least a 5-20% chance, or even higher. There is a large uncertainty related to this estimate. Shell's impact should be elevated to minor impact. Comments: there were differences of opinion presented to the ERP with regard to the potential of halite precipitation in the near wellbore region. Scientific publications have promoted the idea that NaCl will precipitate out of the local brine near the wellbore thus reducing permeability in that area. Shell's lab experiment data seemed to be equivocal, with little impacts noted on in-house experiments. There was some question regarding the laboratory equipment used, hence adding to the doubts about this process. Shell's response was that if NaCl were to precipitate in the near wellbore, reducing permeability, they would "operate" their way out of the problem (with freshwater flushing, or wellbore stimulation, etc) ultimately drilling additional wells if there was a loss of injectivity. It would seem prudent to solve this problem before getting to the stage of drilling additional wells (and their enormous cost).

Injectivity Risk 4131 (Loss of injectivity due to operational upsets) – I agree with Shell's assessment, except that the HSSE impact should likely be elevated to a minor effect.

Injectivity Risk 4525 (Loss of injectivity due to injection well interventions (required by MMV)) – I agree with Shell's assessment, except that the HSSE impact should likely be elevated to a minor effect.

Injectivity Risk 4136 (Loss of injectivity due to dropping BHP constraints) – I agree with Shell's assessment. My only comment is that the subsurface pressure and pressure gradient needs to be carefully stated and used. The text in the risk register (pg. 27) for this risk needs to be cleaned up. Is the vertical pressure gradient in the BCS 9.8 kPa/m or 11.7 kPa/m or something else? A 9.8 kPa/m vertical pressure gradient is not "hydrostatic" in a formation containing brine with a nominal pressure gradient of 11.7 kPa/m. This also relates to comments made for Risk 4172 above.

Containment Risk 4339 (Timely demonstration of containment) - Shell's probability estimate is too low, I think it should be 5-20% chance, or even higher. The impact might even be higher than what is listed. Comments: As it stands, I think this is the biggest risk to the whole project because it depends on outside parties: regulators and government politics. There was discussion at the review that this risk should be re-titled "timely prediction of containment" or the probability of getting to post-mitigation reduction of risk, etc. The bottom line is that it is very difficult to predict what the requirements will be to demonstrate containment. Therefore, I feel that without knowing what the requirements will be, it must be a higher probability than "extremely unlikely 0-5%" that the project will be able to meet the requirements. The impacts must be greater than a 1-3 month delay... what will happen, for example, if there is substantial debate, opposition, and/or revision required to the new government regulations. Those factors are entirely out of Shell's control.

Containment Risk 4157 (Migration along a fault pathway) - I agree with Shell's assessment, except that the impact should likely be reduced to a minor effect. There is a large uncertainty about minor faults in the AOI, but that should be reduced with the baseline seismic surveys. Once the baseline hydrochemical characterization is completed, I strongly suspect the formation waters will provide evidence against the presence of major cross-aquifer/aquitard faults (similar to the types of arguments made at the IEA-GHG Weyburn-Midale Storage and Monitoring project). In essence, there are likely distinct water chemistries in the aquifers above the storage complex. If there were major conductive faults present, they would have provided pathways for fluid homogenization during the geological evolution of the basin.

Containment Risk 4177 (Injection induced stress re-activates fault) - Shell's probability estimate is too low, I think it should be 5-20% chance, but the potential impact level is about right. Looking over the group of three risks related to injection causing problems (4157, 4177, and 4154), I feel that 4177 is the highest risk of the group, and should be higher than 4157 (at 0-5%). I don't think that there are major faults present, but small pathways activated by injection are more likely than the major fault pathways in 4157. Likely after the baseline surveys are completed, this shouldn't be much of a problem.

Containment Risk 4154 (Injection induced stress fractures geological seals) – As above, Shell's probability estimate seems too low, I think it should be 5-20% chance, but the potential impact level is about right. Looking over the group of three risks related to injection causing problems (4157, 4177, and 4154), I feel that 4154 is the middle risk of the group, and should be higher than 4157 (at 0-5%). Detailed measurement of the subsurface temperature field, stress state, and material properties is required to keep this risk as low as possible.

Containment Risk 4168 (Migration along a stratigraphic pathway) - I agree with Shell's assessment, I don't think there is much chance for loss of containment due to migration along some stratigraphic pathway, given the geology and hydrogeology of the site. In fact, containment will likely be enhanced by the ambient brine flow-field that probably contains a significant (as yet un-recognized) down-dip flow component. This is discussed further in Section 3 below.

Containment Risk 4167 (Acidic fluids erode geological seals) - I agree with Shell's assessment, however at least one member of the ERP disagreed with this, and I would defer to his expert judgment. It might be in Shell's best interest to examine available data regarding potash mining injection into the Deadwood Formation several 100 km's east of the AOI in Saskatchewan. The potash mines have a fairly long history of dealing with inflows into their mining horizon – which happens to be in the middle of an approximately 200m thick "impermeable" halite layer. In fact, the Patience Lake potash mine just east of Saskatoon was lost due to a catastrophic mine inflow, and later converted to a surface solution mine.

Containment Risk 4520 (Migration along legacy wells) – I'm unsure about this one. The probability might be about right, but I'm not sure that Shell is in a position to be able to convince the regulators and/or the public of this. I think that more work needs to be done quantitatively evaluating the mechanism of up-hole migration of pressure and fluids: where will a brine plume go if it was pushed upward from the BCS into the Cooking Lake or Leduc aquifers? I doubt it will make it to the potable aquifers above, but there may be some unpleasant interactions with the overlying aquifers (HARP is nearby!).

Containment Risk 4132 (Migration along a QUEST well – compromised casing integrity) – I agree with Shell's assessment.

Containment Risk 4133 (Migration along a QUEST well – compromised cement integrity) – I agree with Shell's assessment. A question regarding potential risky issues installing fibre optic cables as part of the MMV plan was raised, but I think that other projects around the world have demonstrated that this can be done.

Containment Risk 4159 (Migration along a QUEST well – compromised completion integrity) – I agree with Shell's assessment.

Containment Risk 4522 (Migration along a QUEST well – compromised abandonment integrity) – I agree with Shell's assessment.

Containment Risk 4523 (Migration along a QUEST well as a result of a well intervention) – I agree with Shell's assessment.

Containment Risk 4149 (Requirement for MMV wells in the BCS) – I agree with Shell's assessment, AFTER mitigation measures. There is always the potential of unknown regulations lurking in the future.

Containment Risk 4524 (Third part induced migration) – I agree with Shell's assessment.

Conformance Risk 4163 (Unexpected plume migration) - Shell's probability estimate is too low. I think the chance should be at least 5-20%, and more likely a 20-50% chance of un-expected plume migration. I base this on the fact that very few, if any, CO_2 projects worldwide have worked out exactly as modeled. Shell is basing all of their predictions on "standard" reservoir simulation workflows, and these workflows are not sufficient to predict the behavior of CO_2, brine, and pressure plumes throughout the geosphere. For example, Shell has no numerical model allowing for, hence able to investigate, migration above the storage complex. Furthermore, regulators are going to want to have a "predicted" plume so they will be able to know what is "unexpected plume migration". I don't think they will agree to let Shell proceed with an injection program that doesn't really know where the CO_2 is going – (i.e., it won't be OK to say it is fine as long as it isn't up to the potable water aquifers). The impacts of unexpected plume migration could be severe... in the case that the plume "gets away" it could jeopardize the long-term operation of the project.

Conformance Risk 4342 (Inability to demonstrate conformance in terms of long term liability) – I suspect that Shell's probability estimate might be too low, and more likely as high as 20-50%. I don't think the ERP was shown plans in place to explicitly calculate the "form" of the CO_2 trapping (e.g., solution, mineral trapping, etc.) within the storage complex. I think this is extremely difficult to predict accurately, even harder to demonstrate, yet the public and the regulators are going to want to see this. In my opinion, this is the biggest risk to the project because calculating the subsurface saturation of CO_2 has proven extremely challenging at most (all?) of the world's CCS projects to date. Sure, we think we can image the extents of a CO_2 plume... and they might match a distribution obtained from a numerical simulation, but I don't think the public is going to "buy" that those are the actual saturation levels. Quantified estimates of CO_2 distribution are difficult to obtain. I don't think that the technology is mature enough to make these determinations yet, and that is a large risk to the final closure of a CCS project.

Conformance Risk 4503 (Inability to differentiate contamination from external sources from project emissions) – I think Shell's assessment is probably correct, after they have taken planned mitigative actions. The probability ranking of this risk is about right compared to Risks 4163, 4342, and 4164 (after increasing the numbers as indicated above). The importance of obtaining a comprehensive baseline for things like water chemistry cannot be underestimated. Every opportunity that presents itself to obtain samples for chemical analysis needs to be taken advantage of... one simply cannot have enough baseline data.

Conformance Risk 4164 (Unexpected surface heave) – I think Shell's assessment is probably correct numerically, but they had better define what they mean by "unexpected". The ERP was shown calculations of expected surface heaves, and they were likely small enough not to cause any actual damage at the surface, but perception is likely more important in this case. People are extremely wary of industrial operators who seem to not be concerned about "lifting the ground up" only a few mm here and there.

Detailed Technical Questions/Comments

My area of expertise is in Petroleum (Regional) Hydrogeology: understanding the large-scale movement of deep fluids (oil, gas, water) in the subsurface. As part of the Quest project, Shell made two presentations specifically related to the hydrogeology of the AOI. A number of technical questions arose out of those presentations and a "one-on-one" meeting was arranged between myself and Rob Pierpont on the Thursday afternoon. Besides a number of questions, I would like to provide some additional comments for consideration by Shell for their future work.

Hydrogeology questions/comments:

Q1) Overall, there were a number of plots of Measured Pressure (horizontal axis) versus Elevation (vertical axis), for example, on pages, 5, 8, 9, etc. These plots are formally known as Pressure-elevation (P-Z) plots, and have a long history of use in the field of "hydrodynamics" in petroleum exploration (e.g., originated by M.K. Hubbert, 1953; popularized in the textbooks by Dahlberg, 1994). One of the major uses of these plots is to look for "breaks" and hence "fluid compartments", but those types of interpretations must be done with caution and due attention to the hydrogeological conditions of the flow systems at the site. Another use of these plots, is to project the measured data back to the "zero pressure" axis to calculate the hydraulic head at the points of measurement. Both of these procedures seem to have been done for the Quest data. What is not so widely known is that these pressure data can be plotted against depth (vertical axis) as well, resulting in what is known as a Pressure-Depth (P-D) plot (e.g, Toth, 1978). The utility, among other things, of a P-D plot, is that for a fluid of a known density, and hence nominal vertical pressure gradient, a comparison can be made between the measured vertical pressure gradient, and the nominal gradient. If the measured gradient is higher than nominal, that indicates a component of vertically upward directed flow. In contrast, if the measured gradient is lower than the nominal, then that indicates a component of downward flow. If the measured gradient is equal to the nominal gradient, then that can either indicate "static" conditions (that need to be verified by an alternate method of investigation) or lateral (boundary parallel) flows. The question I would ask is the following: Has P-D analysis been undertaken on the Quest data? (I don't think so). This would help build a stronger case for confined lateral flow in the BCS.

Q2) It is not clear to me what the purpose of showing the pressure data from townships 62-94 on page 5 and 8 is? These are far to the north of the AOI, and I'm not entirely sure how the 150m and 500m outcrop elevations determined from these plots relate to anything? There are many published papers on the hydrogeology of the West Canadian Sedimentary Basin (WCSB) that show clearly that the deep flow systems (especially in the centre of the basin) have little relation to overlying surface elevations. What is the relationship between the Quest AOI and other mapped flow patterns in the WCSB. One suggestion is to examine the regional hydrogeology work completed on the HARP project – they areas are closely related, and if HARP conducted their investigation on a "regional" area, that type of work might be transferable directly to Quest.

Q3) Regional synthesis cross-section, page 15. Does this section pass through the AOI? What is the relation between this diagram and the actual flow directions in the various aquifers? Has any work been done to create this cross-section using data from the Quest project? This type of diagram will be an important tool for the regulatory submission to demonstrate to the public the disconnect between the BCS and the potable water aquifers at the surface. Same comment as Q2 regarding HARP. They may have done this already.

Q4) Basal Aquifer Flow, page 16. It was not overly clear to me how these calculations were made. Presumably, this map was constructed using Horner-extrapolated Drill-Stem-Test pressures, converted to Equivalent Freshwater Hydraulic Head? (In this case, production-influenced-drawdown effects can be neglected because of the lack of hydrocarbon production in the aquifer). How does this map compare to the hydraulic head distribution map published by Bachu et al (1986)? Second, how were the hydraulic gradients calculated? (the map shows differences in hydraulic head, while the sample calculations are in terms of pressure). Third, how were the effects of density-driven flow determined? Were the driving force ratios (DFR?) calculated? Where the DFR's greater than 0.5 indicating significant density-related flows?

Q5) Winnipegosis Water Level Map, page 17. Same questions as Q4.

Q6) Cooking Lake Water Level Map, page 19. Same questions as Q4. The hydraulic head values in this map don't make any sense, and Rob Pierpont indicated that this map needed to be revised due to an error in calculating the data values.

Q7) What about mapped flow directions in the rest of the overlying aquifers (Upper Devonian, Mannville, Viking, etc.)? These will have a direct input into the migration pathways for CO_2 from the BCS to the surface.

Q8) More work needs to be done using published maps on the shallow groundwaters in Alberta. I showed Rob Pierpont the Alberta Research Council's shallow groundwater map series of Alberta. That type of data needs to be incorporated into the shallow groundwater investigation and baseline water-chemistry monitoring program. There may be additional (newer) data available from the PFRA, Alberta Geological Survey, and Regional Municipalities.

Q9) There seems to be a interesting statement in the Containment Risk Register document page 18, that says "DST data (supported by the sonic data) indicates that the Winnipegosis has pressures 3-5 MPa above the BCS". Is that data reflected in Page 10 of the hydrogeology P-Z plots? How about on Page 14? I'm not exactly sure of the pressure profile at the Quest AOI?? Knowing this would certainly help the case for confinement in the BCS.

Q10) Finally, I would strongly urge Shell to consider undertaking a three-dimensional "flow path" groundwater modelling project – to predict the pathways of CO_2 from the BCS to the surface. This could be done on an area similar to the "Generation-3 static model outline", or perhaps on the smaller "Generation-3 dynamic pressure scale boundary" using either a standard groundwater-heat-mass transport code or one of the newer percolation-migration approaches that have been demonstrated for Sleipner, In-Salah, and Weyburn.

APPENDIX F: RISK MANAGEMENT FRAMEWORK

This section maps the appraisal activities to be completed by July 2011 against the recommended workflows in the CO2QUALSTORE guideline. Note that the activities and deliverables proposed in the CO2QUALSTORE guideline do not need to be performed in the order they appear, and do not have a regulatory or mandatory status. They do, however, represent an emerging consensus among industry on the range of activities that should be performed to select and qualify a potential storage site.

Table 1 and Table 2 indicate that the site selection and qualification activities performed or planned are broadly aligned with those proposed in the CO2QUALSTORE guideline.

Table 1: Early stage appraisal activities in workflow for Screen stage in CO2QUALSTORE guideline

Activities	Deliverables	QUEST
Define screening basis		
Initiate the phase and develop criteria for nominating one or more sites for further assessment	List of criteria that a site should meet to be eligible for further site assessment	Quest location screened against 18 site selection & characterization criteria (Dr Bachu et al) 7 site selection criteria defined
Develop screening plan		
Describe screening actions required for fulfilling the criteria defined in screening basis step	Screening plan	Full Project Proposal for the Quest CCS Project (March 31 2009)
Review available data and identify potential sites		
Review available data and identify potential sites	List of potential storage sites	3 areas reviewed as potential sites
Estimate capacity and level of uncertainty		
Prepare capacity estimates and estimates of uncertainty of input and output parameters.	Capacity estimates with quantified uncertainties for potential storage sites	Each "area" assessed to have sufficient capacity, volumetric capacity estimation applied. Gen 2 Modelling outputs
Identification and assessment of risks and uncertainties		
Develop initial register of risks and uncertainties	Initial risk register	Formal risk register available First pass TESLA input.
Select site(s) for further assessment		
Decide which sites, if any, should be assessed further.	Screening report and final selection of site(s) nominated for further assessment	Site selection report: Alternative A selected for further assessment. (Dec. 2009) Main differentiators were superior containment characteristics and less obstacles in securing pore-space access
M2: Shortlist storage sites		
Main question: Is there an adequate level certainty that further site assessment will provide confidence that at least one of the nominated storage sites is suitable for long term geologic storage of the intended volumes of CO_2? ***Decision:*** Commit budget and resources for the assessment stage.		Yes, RFP and pore space application submitted. (Dec. 14th 2009) Appraisal strategy approved Dec. 18th 2009

Table 2: Site characterization activities for Assess and Select stage in CO2QUALSTORE guideline

Activities	Deliverables	QUEST
Exploration permit		
Apply for exploration permit and initiate dialogue with regulator about data requirements	Exploration permit	Pore Space application submitted Dec. 14th 2009 follow-up Jan. 28th 2010 Several engagements with Regulator around pore space request. (May & July 2010)
Define selection basis		
Initiate the phase and develop criteria for initiating the storage permit application process	List of criteria that a site should meet in order to be assessed eligible for a storage permit	Quest location screened against 18 site selection & characterization criteria (Dr Bachu et al) 7 site selection criteria defined
Develop selection plan		
Develop a technical plan for site selection	Technical selection plan	Feasibility Report (May 2010)
Develop a communication plan with respect to regulatory authorities	Communication plan	Kathy Penney - Regular meetings with ERCB, Alberta Energy & Alberta Environment
Acquire data, test, analyze		
Acquire field data, carry out field tests, analyze data and test results	Field survey report	Appraisal Strategy – HRAM, phase 1a 3D seismic and 3rd well complete, WI test, Phase 1b seismic ongoing & CO_2 injection test outstanding
Identify and rank uncertainties and risks		
Perform a critical review of the early stage risk assessment from site screening	Expanded risk database	EasyRisk & TESLA – risk and uncertainty assessment drove appraisal strategy
Identify safeguards and perform barrier analysis	List of safeguards and barrier analysis	MMV and Wells Bow-Tie analysis
Provided sufficient numerical data or statistics exist, perform a more detailed analysis, e.g. a quantitative or semi-quantitative assessment of the most significant risks	Risk analysis report	MMV – containment risk analysis 4 risk and uncertainty reviews (Containment, Conformance, Capacity & Injectivity)
Rank risks and uncertainties	Updated risk database	Risks ranked in EasyRisk Database
Preliminary monitoring plan. Initiate baseline monitoring program		
Identify monitoring targets based on identified risks and uncertainties	List of suggested measurement techniques	MMV Draft Plan to be submitted Nov. 30 2010

Identify suitable measurement techniques for monitoring of identified targets	Identify suitable measurement techniques for monitoring of identified targets	MMV Draft Plan
Differentiate between base case monitoring and contingency monitoring triggered by early warning signals	Preliminary base case and contingency monitoring programs	MMV Draft Plan
Plan and execute baseline monitoring program	Compilation of results from baseline monitoring activities	Project EA baseline program and opportunistic MMV baseline only at the moment. Full baseline activities carried in 2013
Evaluate state of knowledge – sufficient for engineering concept design?		
Evaluate if the existing body of knowledge for a potential storage site will provide sufficient basis for proceeding with engineering concept design	Plan for additional data acquisition, testing and analysis, if required A decision to proceed to engineering concept design	D65 regulatory submission is our "conceptual storage development plan"
M3: Select site & engineering concept		
Main question: Which combination of storage site and engineering concept represents the most cost-effective solution for CO_2 injection and storage? Environmental and safety factors should also be considered. ***Decision:*** Commit budget and resources for preparation of the CO_2 storage permit application.		Budget and resources already committed. CO_2 storage application to be submitted Nov. 30 2010 (D65) Budget and resources available to FID.

APPENDIX G: DETAILS ON METHODOLOGIES FOR RISK AND UNCERTAINTY ANALYSIS

This section provides additional details about the risk and uncertainty analysis carried out by the QUEST subsurface team in order to ensure a transparent basis for the conclusions in the main report.

TESLA

The QUEST subsurface team has applied the TESLA software provided by Quintessa Ltd. to address and manage uncertainties. In TESLA, root hypotheses are formulated, and a tree structure is defined with sub-level hypotheses that support the next higher level hypotheses. The tree structure may have multiple levels of sub-hypotheses, where each sub-hypothesis underpins a hypothesis on the next level.

For all hypotheses at the bottom level, one collects information about the evidence supporting the hypothesis (labeled evidence FOR), and information that may be interpreted as evidence contradicting the hypothesis (labeled evidence AGAINST). Next, one attempts to identify the degree of uncertainty. This is typically done by identifying specific uncertainties that are such that if the relevant information was available it would either count as evidence FOR or evidence AGAINST.

Once the relevant information is collected, a team would typically attempt to judge the significance of the information in each category by assigning a score between 0 and 1 to each category. The scores should be such that they add up to 1 and such that the evidence FOR is properly scaled against the evidence AGAINST and uncertainty. Thus, if a score of more than 0.5 is assigned to the evidence FOR a certain hypothesis, this should indicate that regardless of the uncertainty, the hypothesis is likely to be true. A higher score would then indicate a stronger confidence in the hypothesis. The result of the score is visualized using an "Italian flag bar," with the length of the green, white and red segments proportional to the score for evidence FOR, uncertainty, and evidence AGAINST, respectively.

Evidence is only entered for bottom level hypotheses. The reasoning for this is that a hypothesis should be broken down to a level where it is meaningful to assess the evidence FOR and AGAINST. Once the information and uncertainties are entered for all bottom level hypotheses that link to a given root-hypothesis, then the "Italian flags" for the bottom level hypotheses are aggregated to produce an "Italian flag" for the root-hypothesis. This is done by assigning a weight to each sub-hypothesis according to its significance for the next level hypothesis and using a mathematical formula that essentially takes a weighted average of the scores of the sub-hypotheses.

The QUEST project has applied five "root"-hypotheses for capacity, injectivity, containment, baseline monitorability and containment monitorability. These are:

- **Capacity:** There is sufficient pore space for full life-cycle of the required volumes of CO_2.
- **Injectivity:** Injectivity can be sustained for the full life-cycle.
- **Containment:** Injected reactive fluids will not leak significantly from the containment complex.
- **Baseline monitorability:** Domains are mapped, current levels/fluxes of CO_2 are established and can be differentiated from project emissions; tolerances are understood
- **Containment monitorability:** Likely and high risk (consequence) movements of injected CO_2 within the container and between each domain can be detected by proposed technology.

Bow-tie for management of containment risk and risk quantification

A bow-tie is defined for containment risks associated with the QUEST project. A schematic of a bow-tie is shown in Figure 5. Safeguards that serve to reduce the probability of the top event occurring are shown on the left hand side, and safeguards that serve to limit consequences if the top event occurs are placed on the right hand side. The number of independent safeguards that are being put in place gives a qualitative indication of the level of redundancy in the system. The inter-dependency of safeguards should therefore be considered to avoid potential domino effects where the failure of one safeguard may trigger the failure of others.

All risks in the containment risk register (apart from timely demonstration of containment) are defined as threats in the bow-tie. Potential consequences are compiled into the following six groups; CO_2 enters Winnipegosis; Hydrocarbon resource affected; Fresh groundwater contamination; Soil contamination; CO_2 reaches atmosphere; and CO_2 blowout in a QUEST well.

The top event in the QUEST bow-tie is "Migration of CO_2 or BCS brine above the Upper Lotsberg Salt". This definition is, however, inconsistent with the respective placement of some of the safeguards in the bow-tie. These safeguards are triggered by monitoring systems that represent indicators that the top-event *has* occurred, and not indicators that it *may* occur. Table 3 contains a list of all safeguards that DNV considers to be incorrectly placed on the left side of the QUEST bow-tie.

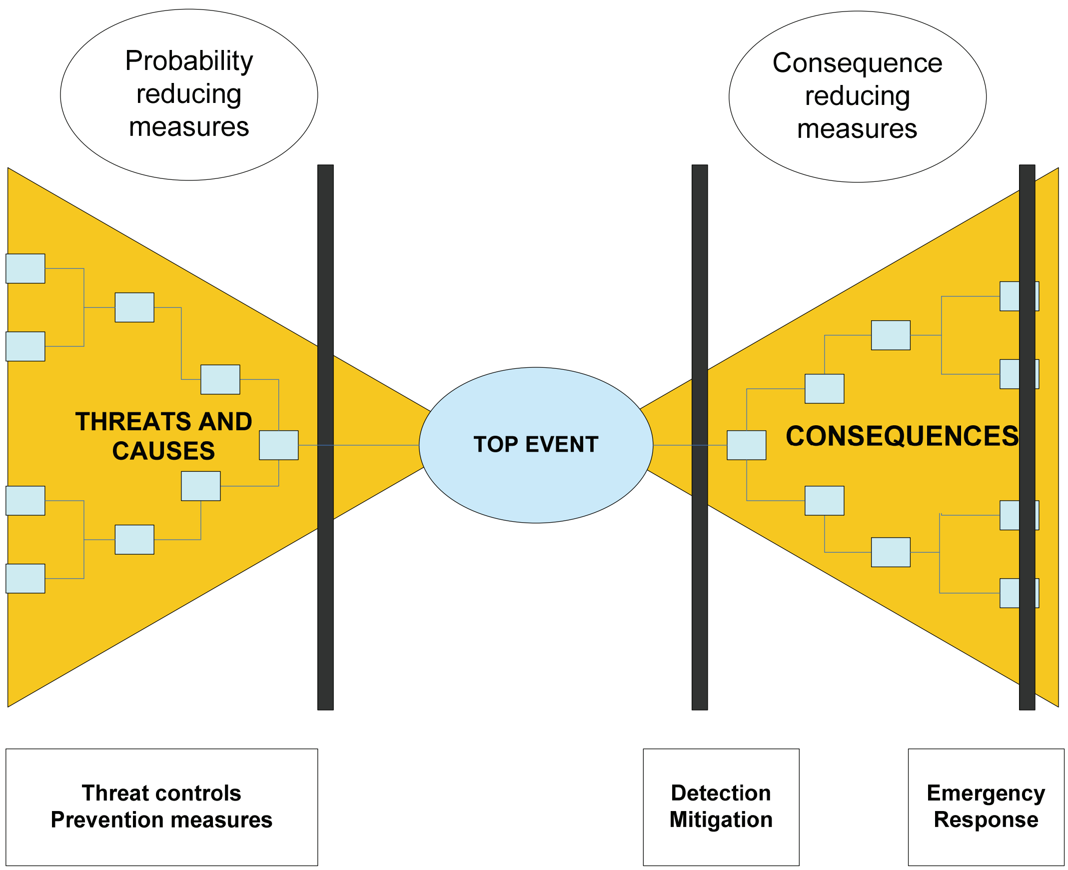

Figure 5: Schematic of bow-tie risk management approach. A sequence of threats and causes may result in a feature, event or process with negative impact. To prevent the threats from occurring, both probability and consequence reducing safeguards should be considered. Safeguards that are implemented to reduce negative consequences after a feature, event or process has occurred may be regarded as emergency response measures.

Table 3: Preventive active safeguards in QUEST bow-tie for which the monitoring trigger represents indication that top-event *has* occurred, and not indication that it *may* occur

Threat	**Safeguard**	**Monitoring trigger**	**Reasoning for why placement in bow-tie is inconsistent with definition of top event**
T1: Migration along legacy well	B1.4	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
	B1.6	Satellite or airborne hyperspectral image analysis	Only detects evidence of CO_2 or BCS brine migration to surface
	B1.7	Well-head CO_2 detectors	Only detects evidence of CO_2 migration to surface. Also, only potential for brine migration. Most legacy well-heads are removed.
	B1.8	Line-of-sight gas flux monitoring	Only detects evidence of CO_2 migration to surface. Also, only potential for brine migration.
T2: Migration along MMV well	B2.7	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
	B2.8	Cement Bond Log	Depends on depth of observation well, only relevant as preventive measure if observation well penetrates Upper Lotsberg Salt.
	B2.9	Fibre-optic distributed temperature sensing	Depends on depth of observation well, only relevant as preventive measure if observation well penetrates Upper Lotsberg Salt.
T4: Migration along a matrix pathway	B4.7 & B4.9	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
T5: Migration along a fault pathway	B5.6 & B5.7	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
T6: Induced stress reactivates fault	B6.7 & B6.10	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
T7: Induced stress opens fractures	B7.6 & B7.9	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
T8: Acidic fluids erode geological seals	B8.4	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis
T9: Migration due to 3rd party activities	B9.2	Down-hole pressure-temp. gauges in Winnipegosis	Only detects evidence of CO_2 or BCS brine migration into the Winnipegosis

Probabilistic model for risk quantification

The QUEST subsurface team has used the bow-tie to drive towards a probabilistic risk quantification model. This has been done by assigning a value between 0 and 1 to each safeguard as a measure of its effectiveness. The value 1 would indicate that the safeguard is 100% effective, whereas 0 would indicate that it has no effect. A value of 0.5 would indicate that there is a 50% chance that the safeguard will be effective. In addition, a measure of uncertainty has been attached to the effectiveness measure. This measure is interpreted as follows: If a safeguard is assessed to be 50% effective with an uncertainty measure of 0.3, this implies that the effectiveness will be in the range 0.35-0.65.

To derive effectiveness and uncertainty measures for each safeguard, the QUEST project has applied an internal consensus based TESLA approach. Thus, evidence is compiled that either supports or contradicts the hypothesis that the associated safeguard will be effective. Once all relevant evidence has been compiled and assessed, corresponding values are assigned to the evidence FOR, uncertainty and evidence AGAINST. The uncertainty measure is then taken to be the value assigned to uncertainty (length of white bar segment in Italian flag). The effectiveness measure is taken to be the value assigned to evidence FOR plus half of the uncertainty value.

Finally, to quantify the probability P(Z) that one of the threats X will trigger the top event Y AND cause significant impact due to consequence Z, the following probabilistic model is applied:

$$P(\text{threat X triggers Y}) = P_0(X) \times \prod_i (1\text{-}E(\text{safeguard } i \text{ reducing prob. of X triggering Y}))$$

$$\text{Total probability of top event} = P = \sum_X P(\text{threat X triggers Y})$$

$$P(Z) = P \times P_0(Z) \times \prod_i (1\text{-}E(\text{safeguard } i \text{ reducing the prob. of Y triggering Z}))$$

Here E(*) refers to the probabilistic effectiveness drawn from a uniform probability distribution in the interval [effectiveness +/- uncertainty/2], $P_0(X)$ is the initial probability that X triggers Y with no probability reducing safeguards in place, and $P_0(Z)$ is the initial probability that Y will cause significant impact due to consequence Z with no consequence reducing safeguards in place. Note that this probabilistic model assumes that the threats and safeguards are mutually independent.

The principle to account for uncertainty conservatively is applied when interpreting the outcome of multiple sample outputs from the probabilistic model. Thus if, say, 100 sample outputs have been computed and the effectiveness scores are unbiased, then selecting the 5^{th} highest probability computed should provide a 95% confidence that the selected probability is not optimistic.

The choice to introduce a unified bow-tie for all containment risks has the implication that the consequence reducing safeguards are assessed to be equally effective regardless of which threat triggered the top event. For instance, generic values are assigned to the effectiveness of geological seals above the containment complex irrespective of whether the top event is triggered by migration through a well-bore or by migration along a geological pathway.

Because it was not communicated to DNV that a semi-quantitative risk analysis had been performed, a review of this analysis was not planned as part of the IPR workshop. However, observations regarding inconsistencies in the way the bow-tie is defined and mismatches between the expert panel assessments and probabilities derived using the probabilistic model spurred a need to do a coarse review of the risk analysis. This review was carried out by DNV after the IPR workshop. Inconsistencies in the way the bow-tie is defined are reported in Table 3 above. To get an understanding of the origin of the mismatch between the assessed probability for risk occurrence by the expert panel and the corresponding probabilities derived by the probabilistic model, DNV reviewed in some detail the analysis of the likelihood that threat "T1: Migration along a legacy well" can trigger the top event and cause significant impact. The observations reported below are provided to support conclusions made in the main report.

Analysis of likelihood that threat "T1: Migration along a legacy well" triggers the top event.

The QUEST subsurface team has estimated that the probability of T1 triggering the top event is on the order of 10^{-4}. This estimate is broken down as follows.

Probability of T1 triggering the top event with no safeguards = 0.1. The QUEST subsurface team has indicated that the reasoning behind this number is that if the 3-10 injectors are placed at "random" within the AOI, then the likely distance to the nearest legacy well is about 10 km. The estimate of 0.1 probability is derived by applying an initiation rate which stems from a UK HSE study on failure rates of underground gas storage wells (for wells located within the gas accumulation zone). With an offset distance of 10 km, the likelihood that a legacy well would be exposed to the CO_2 plume is considered small, so the main potential failure mechanisms is the potential for brine migration. Thus, the 0.1 probability estimate reflects that the QUEST subsurface team has assessed the likelihood of pressure being sufficient to drive sufficient brine up a legacy well with an offset distance of 10 km to be 0.1.

DNV feels that the reasoning applied here, with random location of injection wells, and resulting minimum offset distance to nearest legacy well of 10 km to be a bit speculative. We would therefore recommend instead that this estimate is included in the estimate of the effectiveness of safeguard "B1.1: Injectors located away from legacy wells". The assessed effectiveness of this safeguard is 0.93, implying that the probability of T1 triggering the top event with only this safeguard is estimated to be as low as 0.007. This seems low considering that the expert panel has recommended that the probability of this happening, contingent upon implementation of an adaptive MMV plan, may need to be upgraded to from "Extremely unlikely (0-5%)" to "Low, but not impossible (5-20%)". Furthermore, this estimate is not adequately justified. Taking the expert panel's assessment into account, DNV would claim that it would be appropriate to raise this estimate significantly, possibly by as much as an order of magnitude.

The assessed effectiveness interval for the next safeguard "B1.2: Cement plug" is [0.3,0.6]. To evaluate the effectiveness of this safeguard one needs to evaluate the additional assurance it provides that migration (of brine) along a legacy well will not occur above the Upper Lotsberg Salt. To this end one needs to consider the potential situation that pressure in the BCS is sufficiently elevated to initiate upward migration of brine along legacy well, and evaluate the effectiveness of cement plugs to stop this flow. Clearly, for a cement plug to contribute to reduce the probability of the top event from occurring, it has to be placed at a greater depth than the top of the Upper Lotsberg Salt. Two of the legacy wells in the AOI do not have any cement plugs at this depth. Thus for these wells the effectiveness of the "cement plug" safeguard is 0. However, the QUEST subsurface team justifies their reasoning behind the estimated effectiveness range by treating the group of legacy wells statistically as one threat. The claim is that for the two wells without deep enough plugs, safeguard B1.2 has an effectiveness of 0, whereas the other 5 wells within the AOI the respective effectiveness is assessed to be 1. The average effectiveness of the cement plug is thus 0.72(?).

DNV is of the opinion that it is improper to assess the performance of the "cement plug safeguard" as a barrier against threat T1 statistically. If pressure is sufficiently elevated to drive brine through a legacy well above the Upper Lotsberg Salt if there is no cement plug to stop the flow, and the migration occurs in only two of the seven wells, this would still cause loss of containment. It is therefore recommended that the effectiveness of the safeguard B1.2 is set to 0. The deep cement plug in the remaining legacy wells could still be considered a consequence reducing measure as the rate of leakage would be limited by the number of wells in which leakage occurs.

DNV has no comments about the assessed effectiveness of safeguard "B1.3: WPGS – Hydraulic pressure", which is set to 0.08.

Down-hole pressure-temperature gauges in observation wells in the Winnipegosis will only be able to detect evidence that migration of CO_2 or BCS brine into the Winnipegosis has occurred. This implies that the top event has occurred, and does not represent an indication that it may occur. The safeguard B1.4 should therefore be moved to the right hand side of the bow-tie. Thus, this safeguard does not contribute to reduce the probability that T1 triggers the top event.

For the safeguard B1.5 associated with the InSAR monitoring trigger, the effectiveness for threat T1 was assessed to be in the range 0.6 to 0.8. This range reflects a strong confidence that InSAR will be able to monitor the surface footprint of the pressure plume, and that the surface footprint can be effectively used to history match the pressure plume predictions in a sufficiently detailed way to detect/predict pressure elevations at legacy well locations. DNV believes, however, that there is attached more significant uncertainty to the effectiveness of InSAR as a monitoring trigger for this safeguard than the QUEST subsurface team has indicated in the assessment. In particular, DNV feels that an average effectiveness of 0.7 for this safeguard is very optimistic.

The safeguards B1.6, B1.7 and B1.8 are triggered by monitoring systems that represent indicators that evidence of CO_2 or brine migration to surface. Hence, this clearly implies that the event has occurred. These safeguards should therefore be removed from the left hand side of the bow-tie. In fact, since it is highly unlikely that any of the legacy wells will be exposed to CO_2, the safeguards "B1.7: Well-head CO_2 detectors" and "B1.8: Line-of-sight gas-flux monitoring" are irrelevant for this risk. The effectiveness of these safeguards should therefore be set to 0, also when considered as corrective safeguards.

Thus, in summary, we feel that the combined the probability of T1 triggering the top event with only safeguard B1.1 is too optimistic and may need to be raised by as much as an order of magnitude. The effectiveness of B1.2 should be 0. The assessed effectiveness of B1.3 (0.08) is ok. The safeguards B1.4, B1.6, B1.7 and B1.8 should be removed from the left hand side of the bow-tie, so their respective effectiveness as measures to reduce the probability of T1 triggering the top event should be 0. Finally, DNV does not have confidence in the assessed effectiveness of InSAR as a technology to help predict elevated pressure levels at legacy well locations in order to prevent brine migration along legacy wells above the Upper Lotsberg Salt. This leads us to the conclusion that probability that the threat T1 triggers the top-event may be more than two orders of magnitude higher than the assessment of the QUEST subsurface team, and hence that the analysis for this particular threat is systematically biased.

Analysis of likelihood for significant impacts if the top event is triggered by T1

The sequence of safeguards for mitigation of significant impact due to the consequences listed on the right hand side of the bow-tie does not reflect which threat initiated the top event. Assigning a value to the effectiveness of a safeguard irrespective of whether the top event was triggered by migration through a well-bore or along a geological pathway may be difficult. DNV feels that this obscures this part of the analysis, i.e., it lacks the recommended transparency.

For instance, the effectiveness of the Prarie Evaporite Seal is assessed to be in the range 0.6-0.8 with no justification of the relevance of these values to indicate the performance of the Prarie Evaporite Seal as a barrier for migration along wells. DNV suggests that a separate analysis of the performance of consequence reducing safeguards for potential migration along wells should be performed. To this end, DNV suggests splitting the main bow-tie into two subsets. The same consequences can be listed, but the assessed effectiveness of the associated safeguards should reflect whether or not the initiating threat represents migration along a wellbore or migration along a matrix, fault or fracture pathway.