An Integrated Risk Management Framework for Carbon Capture and Storage In the Canadian Context

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Thesis Abstract

Climate change is a risk issue of global proportions. Human health and environmental impacts are anticipated from hazards associated with changes in temperature and precipitation regimes, and climate extremes. Increased natural hazards include storms and flooding, extreme heat, drought, and wildfires. Reduced food and water quality and quantity, reduced air quality, new geographic range of infectious diseases, and increased exposure to ultra-violet radiation are also predicted. In order to make a measurable contribution to reducing carbon dioxide emissions at point source fossil fuel and industrial process sites that contribute to climate change, estimates suggest that up to 3,000 dedicated large scale carbon capture and geological sequestration (CCS) projects will be necessary by 2050. Integrated projects include carbon dioxide capture; compression into a supercritical stream; transport, most often by pipeline; deep injection at wellheads; and sequestration in suitable saline aquifer geological formations, usually 800 metres or more below the earth's surface.

In implementing CCS as part of an overall climate change mitigation strategy, it is important to note that population health and environmental risks are associated with each of these value chain components of integrated projects. Based on an assessment of existing regulatory and non-regulatory guidance for risk assessment/risk management (RA/RM), an analysis of the application, assessment, and approval process for four large scale Canadian projects, and findings from a structured expert elicitation focused on hazard and risk issues in injection and storage and risk management of low probability high impact events, this research developed an Integrated Risk Management Framework (IRMF) for CCS in the Canadian context. The IRMF is a step-wise systematic process for RA/RM during the life of a project, including engagement with wide ranging government and non-government partners that would contribute to a determination of acceptable risk and risk control options. The execution of the IRMF is an intervention that could reduce local hazards and associated risks in terms of likelihood and consequence, as well as identify and document risk management that could underpin broad acceptance of CCS as a climate change mitigation technology. This would thereby also have an important part in protecting global population health and wellbeing in the long term. Indeed, diverse stakeholders could be unforgiving if hazard assessment and risk management in CCS is considered insufficient, leading to ‘pushback’ that could affect future implementation scenarios. On the other hand, RA/RM done right could favourably impact public perception of CCS, in turn instilling confidence, public acceptance, and ongoing support for the benefit of populations worldwide. This thesis is composed of an introduction to the research problem, including a population health conceptual framework for the IRMF, followed by five manuscripts, and concluding with a discussion about other barriers to CCS project development, and a risk management policy scenario for both the present time and during the 2017-2030 implementation period.

Acknowledgements

This journey began with my enrollment in the University of Ottawa's Graduate Diploma in Population Health Risk Assessment and Management. Dr. Daniel Krewski led off the first session of the first course, asking for examples of risk. I raised my hand, as wont to do, and said that joining the program seemed to be a risk to me – in starting something new at my age and stage. Without missing a beat, Dr. Krewski suggested the risk was very low – what poor outcomes in probability or consequence could there be? Indeed.

This has been an enjoyable experience at the University of Ottawa. Dr. Caroline Andrew was my supervisor during the first two years of the PhD program. At a turning point, she and Dr. Louise Bouchard, Program Director, were so supportive of my move to complete this thesis research project with Dr. Krewski.

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Acronyms

AER	Alberta Energy Regulator (formerly ERCB - Energy Resources Conservation Board)
CBM	Coal bed methane
CCS	Carbon capture and storage (sequestration in saline aquifers)
CCUS	Carbon capture utilisation and storage
CO_2equiv	Carbon dioxide equivalent
EOR	Enhanced oil recovery
EPA	(US) Environmental Protection Agency
GCCSI	Global Carbon Capture Storage Institute
GHG	Greenhouse gas
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas Program
INDC	Intended Nationally Determined Contribution (under UNFCCC)
IPCC	Intergovernmental Panel on Climate Change
IRMF	Integrated Risk Management Framework
LPHI	Low probability high impact (event)
NETL	US National Energy Technology Laboratory
OECD	Organisation for Economic Cooperation and Development
RA	Risk assessment
RM	Risk management
MMV	Measurement, monitoring, and verification
UNFCCC	United Nations Framework Convention on Climate Change

$GtCO_2$	Gigatonnes CO_2 (emissions, equivalent to 1,000 Mt)
$MtGO_2$	Megatonnes CO_2 (emissions, equivalent to 1,000,000 metric tons)

Chapter 1 Introduction

1 Statement of the problem and research purpose

1.1 Climate change

Climate change has been identified as the greatest potential global health threat of the 21st century (Costello et al., 2009). From a population health perspective, diverse direct and indirect impacts on human health and wellbeing are expected from concomitant social, economic, and environmental effects. Globally, the magnitude and severity of negative impacts from increased surface air temperatures, ocean warming, a loss of ice sheets and glaciers, and sea level rise, will be greater than positive impacts, and are expected to be increasingly so (IPCC, 2014c).

Injury, disease, and death, including psychosocial and mental health impacts, are associated with direct and indirect effects of wide ranging and difficult conditions, including: increasing natural hazards such as storms and flooding, extreme heat, drought, and wildfires; reduced food, water and air quality; reduced food and water quantity; new scope of infectious diseases transmitted by insects, ticks and rodents; and increased ultraviolet radiation (Berry et al., 2014, IPCC, 2014b, McMichael et al., 2006). Furthermore, other affected determinants of health include impacts on natural resources, industry, and infrastructure, as well as effects on biodiversity (Warren and Lemmen, 2014). The IPCC (2014c) discussed lost work capacity and reduced productivity for vulnerable populations, increased displacement and poverty, and other issues of human security. Limited positive effects of climate change were discussed by Health Canada (2008) and the IPCC (2014c) with low to medium confidence levels, entailing “modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes, geographical shifts in food production, and reduced capacity of vectors to transmit some diseases" (p. 20).

Global issues related to climate change include disparities both regionally and generationally between those most contributing to human-induced causes of climate change and those most affected. Risks are not anticipated to be evenly distributed and were found to be "generally greater for disadvantaged people" around the world (IPCC, 2014a, pp. SPM-10). Moreover, the Commission on the Social Determinants of Health (2008) recommended that mitigation and adaptation strategies for climate change should not unnecessarily and unfairly negatively impact populations, and health equity should be considered in their development and implementation. Climate change therefore includes a dimension of social justice.

While climate change is being caused by anthropogenic greenhouse gas (GHG) emissions, the focus of this research and described next, wide ranging co-benefits of moving to a low-carbon economy are acknowledged. These include improved air quality and reduced fossil industry-based impacts on water quality, water quantity, and land resources -- environmental determinants of health upon which all living organisms depend. Social benefits of addressing climate change could therefore include reduced burden of disease, as well as poverty reduction, enhanced community resilience, and reduced inequity (Watts et al., 2015). Indeed, on a positive note, tackling climate change has also been described as potentially the greatest opportunity for improving global health (Watts et al., 2015).

1.2 Greenhouse gas emissions

Climate change is being caused by anthropogenic greenhouse gas (GHG) emissions. Total emissions were the highest in human history from 2000 to 2010, reaching 49 (±4.5) $GtCO_2$equiv [equivalent]/ yr in 2010 (IPCC, 2014b). Without abatement, global emissions are trending towards or may exceed 62 $GtCO_2$/year through 2050.

Carbon dioxide (CO_2) from fossil fuel and industrial processes has been identified as a significant driver for climate change (IPCC, 2014b), estimated to account for 73% of net anthropogenic radiative forcing of the climate system in 2011 relative to 1750 (IPCC, 2013). GHG emissions attributed to these sources have increased from approximately 28 $GtCO_2$/yr in 2005 (IEA, 2009) to 32 $GtCO_2$/yr in 2010 (IPCC, 2014b). Other contributions come from forestry and other land use (CO_2-FOLU), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases covered under the Kyoto Protocol (F-Gases).

In terms of atmospheric concentration, CO_2 had reached 391 ppm in 2011, a rise of about 40% from pre-industrial levels (IPCC, 2013); 400 ppm was surpassed in 2016 and the IPCC (2014b) suggested that measured CO_2eq from all forcers could exceed 450 ppm by 2030, possibly reaching between 750-1300 ppm CO_2eq by 2100. This concentration has been estimated to result in 6^oC increase (6DS scenario) in global average surface temperature in the long term, post 2100 (IEA, 2013a), a long term projection that is associated with dire predictions for population health and environmental impacts worldwide. Indeed, while the severity of impacts is anticipated to increase with higher GHG atmospheric concentrations, a reduced warming scenario through reduced GHG emissions would decrease potential effects (IEA, 2013a, IPCC, 2014c).

Leading up to the 21st Session of the Conference of the Parties to the United Framework Convention on Climate Change (UNFCCC) held in Paris in December, 2015, member states submitted intended nationally determined contributions (INDC) to reduce GHG emission levels that contribute to climate change. The Paris Agreement, with 180 signatory nations, then pronounced (United Nations Framework Convention on Climate Change, 2015, p. 21):

> (a) "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
>
> (b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
>
> (c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development."

Current INDCs lead to a projected level of 55 $GtCO_2$/year in 2030 (United Nations Framework Convention on Climate Change, 2016): it is expected that fossil fuel production and use will remain a significant part of our energy mix through 2050. This is suggested to be a period of transition to other energy sources and improved fossil energy efficiency in industrial processes. The discussions in Paris also noted "with concern that the estimated aggregate greenhouse gas emission levels in 2025 and 2030 resulting from the intended nationally determined contributions do not fall within least-cost 2˚C scenarios" (United Nations Framework Convention on Climate Change, 2015, p. 3).

1.3 Research purpose

As part of the solution for climate change, carbon capture and geological storage (CCS) technology has been identified within the portfolio of mitigation options to reduce point source CO_2 emissions from fossil fuel and selected industrial process atmospheric emissions. Promising sites include coal and natural gas electricity generation facilities, and cement, steel, fertilizer, and oil upgrader industrial sites (International Energy Agency [IEA], 2009, IEA, 2010b, IEA, 2013a, IPCC, 2005, IPCC, 2014b). Pilot and demonstration projects have been implemented worldwide over the past twenty years (GCCSI, 2014b, Massachusetts Institute for Technology, 2016),

Large scale integrated CCS sequestration projects (LSIPs[1]), "considered to be at sufficiently large scale to be representative of commercial-scale process streams" (GCCSI, 2014a, p. 30), include several value chain component activities: CO_2 capture and compression to a supercritical state; transport using pipelines; deep underground injection at wellheads; and storage in saline pore space of geological formations more than 800 metres below the earth's surface. It has been estimated that up to 3,000 dedicated LSIPs are required globally by 2050 if CCS is to contribute a projected 13% total CO_2 emission reductions (GCCSI, 2016a, IEA, 2015a). The implementation of CCS, however, is in its infancy.

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[1] LSIPs are defined as projects involving the capture, transport, and storage of CO_2 at a scale of at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO_2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014b).

Given the magnitude of the potential expansion and contribution of this technology, the overarching objective of this research project was to develop an *Integrated Risk Management Framework (IRMF) for Carbon Capture and Storage in the Canadian Context,* a framework that addresses both practical and current population health risk issues. Indeed, human health and environmental hazards and associated risks have been identified within the entire CCS value chain, described fully in Section 1.3. The systematic and comprehensive IRMF provides a blueprint for safe and effective implementation of the CCS technology for dedicated emissions reduction purposes in saline aquifer sequestration project types. A step-wise process of risk assessment and risk management is depicted, including a continuum of options for wide-ranging partner engagement such that input provides clarity as to what is important, what is acceptable, and what risk control options are to be applied.

Applying an IRMF to CCS would create opportunities for meaningful discussion on both the safety and contribution of CCS to mitigate climate change, thus also having a role to play in public acceptance. Its application could thereby help minimize the potential for local harm, while also helping to ensure that this technology contributes to mitigating climate change with concomitant positive effects for global population health over the long term.

2 CCS process and progress

CCS is a technological process that includes CO_2 capture and compression to a supercritical state, transport (usually by pipeline), injection at deeply drilled wellheads, and sub-surface storage (with four project types) (Figure 1.1). These value-chain activities are described as follows.

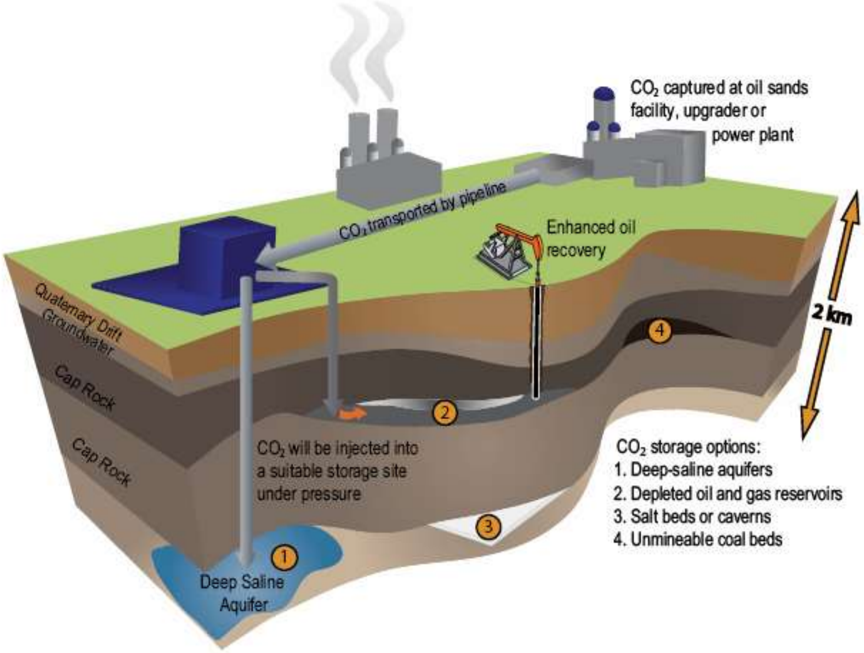


Figure 1.1: Schematic diagram of CCS value chain (capture, transport, injection, storage) including four geological storage options (with permission of the Government of Alberta)

2.1 Capture, transport, and injection

The three main technologies being used or proposed for CO_2 capture at power generation and industrial facilities are pre-combustion, post-combustion, and oxy-fuel capture processes. The capture chain activity includes compression to a supercritical state, with a CO_2 concentration approaching 99% pure. The Special Issue of the *International Journal of Greenhouse Gas Control* (Gale et al., 2015), commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change *Special Report on Carbon Dioxide Capture and Storage* (IPCC, 2005), includes several review articles focused on carbon capture technology (Abanades et al., 2015, Jansen et al., 2015, Liang et al., 2015, Stanger et al., 2015). Boot-Handford et al. (2014) also reviewed capture technologies and Senior et al. (2013) reviewed emissions and risks associated with oxyfuel combustion in particular. At the time of writing, ten power plant operating projects use pre-combustion capture; one project is using post-combustion capture; and none are using oxy-fuel technology (Massachusetts Institute for Technology, 2016). Four projects are using industrial separation.

The foremost transport method for the CO_2 stream is high pressure pipelines that run between the capture facility and close to injection well sites. Pump facilities are located at intervals and during operations, the CO_2 stream moves through smaller diameter piping from the transport pipeline to injection wells. Deep wellbore injection of the CO_2 stream occurs at drilled wellheads, approximately 800-2000m into geologic formations.

2.2 Storage project types

CO_2 capture for utilization and storage (CCUS) has a history in depleted oil and gas reservoirs for enhanced oil or gas recovery operations (CCS-EOR). CO_2 was identified as a superior agent for miscible flooding and further fossil fuel resource development post conventional well operations. Indeed, the oil industry did not initially view CCS-EOR as an approach to climate change mitigation (Markusson et al., 2012b).

Today, the contribution of CCS-EOR has been described as demonstrating proof of concept that CO_2 remains permanently stored underground over a period of time. Since inception, a large fraction of the CO_2 has been shown to remain underground (IPCC, 2005). CO_2 is injected at wellheads and while some returns to the surface with the oil, the gas is separated and re-injected. CCS-EOR proponents support the mitigation technology because project costs are offset by the oil and gas revenue stream. CCS-EOR accounts for 76% of LSIPs and 81% of the capture rate.

On the other hand, it has been suggested that CCS-EOR projects "merit cautious treatment as an indicator of progress in CCS deployment" (IEA, 2013b, p. 59). With the CO_2 stream a cost of production to be avoided, Dixon et al. (2015) found that CO_2 storage through EOR has been successful, although projects in the US, Canada, and Middle East have been operating under existing hydrocarbon legal and regulatory frameworks not designed for long term CO_2 sequestration objectives. In discussing considerations reviewed by Bachu et al. (2013), Dixon et al. (2015) suggested that "while there seems to be a mutually beneficial arrangement, the future requirements of CO_2 storage – namely those for storage site qualification, well construction, closure, and monitoring and verification – go beyond traditional practices of CO_2-EOR operators and impose additional costs on their business" (Dixon et al., 2015, p. 443).

A second CCUS approach is enhanced coal bed methane resource recovery operations (CCS-CBM), an application that also includes potential revenue generation. Field pilots have injected CO_2 into partially depleted coal seams where it is adsorbed by coal, with displaced methane coming to surface to be captured and consumed as fuel. CCS-CBM is the least common project type (Massachusetts Institute for Technology, 2016); no LSIPs are being executed or are operational. Salt beds or caverns are also indicated in Figure 1, but these structures have more limited capacity; although they could be used for temporary storage, as a buffer, or to hold CO_2 streams for use in other commercial applications (Wildenborg and Lokhorst, 2005).

A CCS process not indicated in Figure 1.1 is biomass energy (bioenergy) conversion with carbon capture and storage (BECCS). This has been demonstrated on a small scale and offers potential large scale net CO_2 removal from the atmosphere because biomass growth first removes carbon during the growing cycle, followed by capture of emissions that are permanently stored underground (Gough and Upham, 2011, IEA, 2013a, Kemper, 2015). This could be an important technology if global CO_2 emissions are to meet the 2DS objective (IEA, 2013b), particularly for synfuels and hydrogen processing industries (IEA, 2009, IEAGHG, 2011). However, in addition to technical and logistical/infrastructure issues in capture and transport, debate for BECCS implementation includes the sustainability of biomass production scenarios (eg bio-ethanol or bio-diesel), public acceptability regarding competition of landuse for food and forestry, life cycle energy assessment of biomass production and carbon storage, costs, incentives, and carbon pricing (Gough and Upham, 2011, IEA, 2013a, IEAGHG, 2011). Kemper (2015) provides a review of BECCS in the period since the *IPCC Special Report on Carbon Capture and Storage* (IPCC, 2005), concluding that this approach is inextricably linked and requires a systems discussion within the food-water-energy-climate nexus.

The favoured destination for permanent CO_2 storage is sequestration in the pore space of saline aquifer geologic formations (CCS-GS, hereafter CCS). As the subject of this thesis, these projects permit an absolute reduction in CO_2 emissions, identified as necessary if atmospheric CO_2equiv concentrations are to stay within the Paris Agreement 2DS scenario (IEA, 2015a). Suitable formations have a number of geophysical and geochemical trapping mechanisms (Figure 1.2), discussed further in Chapters 4 and 5.

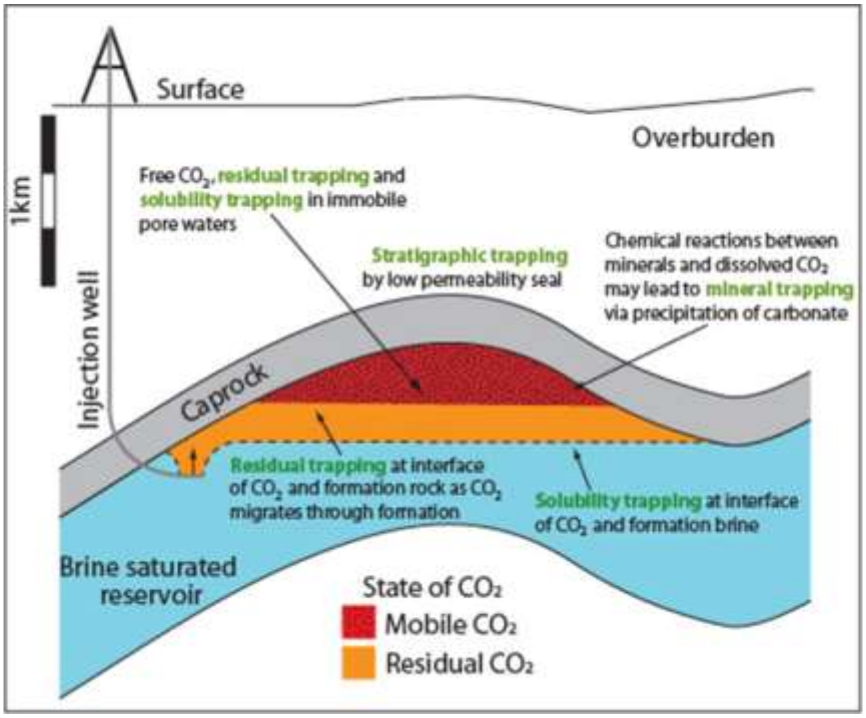


Figure 1.2: CO_2 trapping mechanisms (with permission of Dr. Mark Naylor, School of GeoSciences, University of Edinburgh)

Saline aquifers have the greatest capacity for CO_2 storage and are widely distributed worldwide. Although the global theoretical capacity for saline sequestration is estimated at 35,300 $GtCO_2$, the “effective” capacity could be 13,500 $GtCO_2$, with a “practical” capacity of 3,900 $GtCO_2$ (Dooley, 2013, cited in Committee on Geoengineering Climate (2015)). Other capacity estimates are provided in Table 1.1. Bachu (2015) recently reviewed factors and methodologies related to storage capacity and storage efficiency in saline aquifers, issues that are discussed more fully in Chapter 4.

Table 1.1: CO_2 storage potential in saline aquifer formations (volume)

Country	Storage resource estimates ($GtCO_2$)		
	Low	Medium	High
USA (North American Carbon Atlas Partnership, 2012, US Department of Energy, 2015)	1,610 (2012) 2,379 (2015)	8,328	20,155 (2012) 21,633 (2015)
Canada (North American Carbon Atlas Partnership, 2012)	28	110	296
Mexico (North American Carbon Atlas Partnership, 2012)	100		
Norway (Norwegian Petroleum Directorate, 2013)		4.4	
IEA projection (IEA, 2013c)		Cumulative 123 by 2050	

In the Canadian context, using a set of fifteen intrinsic and extrinsic criteria, Bachu (2003) illustrated an assessment and ranking of twelve sedimentary basins in terms of suitability for CCS (Figure 1.3). Since then, the *North American Carbon Capture and Storage Atlas* provided a coordinated overview of storage potential for Canada, Mexico, and the United States (North American Carbon Atlas Partnership, 2012). Its primary purpose was to show the location of large stationary CO_2 emission sources and the geographic range of various storage formations, including cross border reservoirs for CCUS and CCS. The potential capacity in the US is greater than Canada (Table 1.1) in part because more work has been done to assess land based formations compared with Canadian sedimentary basins that exist under the marine environment.

Figure 1.3: Distribution of sedimentary basins in Canada (Bachu (2003), with permission of Springer).

2.3 International CCS development to date

Worldwide development of CCUS and CCS LSIPs is characterized as follows (GCCSI, 2014b, Massachusetts Institute for Technology, 2016).

- Fourteen operational projects, with capacity for approximately 28.4 $MtCO_2$/yr.
- Seven LSIPs being executed, with approximate additional capacity of 11.6 $MtCO_2$/yr.
- Twelve other projects in earlier stages of development.
- 76% of projects and 81% of the capture rate are CCS-EOR project types.
- Three CCS saline sequestration projects are completed; two are being executed; and one is suspended.

As noted previously, there is a need to implement CCS on a rapidly increasing scale if this technology is to contribute the projected cumulative 13% CO_2 emissions reduction that has been proposed through 2050 (GCCSI, 2014a, IEA, 2013a). The total CO_2 capture and storage rate, excluding EOR, must increase from the tens of megatonnes per year in 2013 (approximately 7.3 $MtCO_2$/yr) to 8,000 megatonnes per year in 2050 (GCCSI, 2014a, GCCSI, 2014b, IEA, 2013a). Nykvist (2013) identified four main challenges, each requiring a tenfold increase in: the size of operations, from pilot plants to commercial demonstration projects; the number of constructed large-scale demonstration plants; annual funding needed for the next 40 years; and the price of CO_2 emissions. Figure 1.4 illustrates a potential global trajectory through 2035.

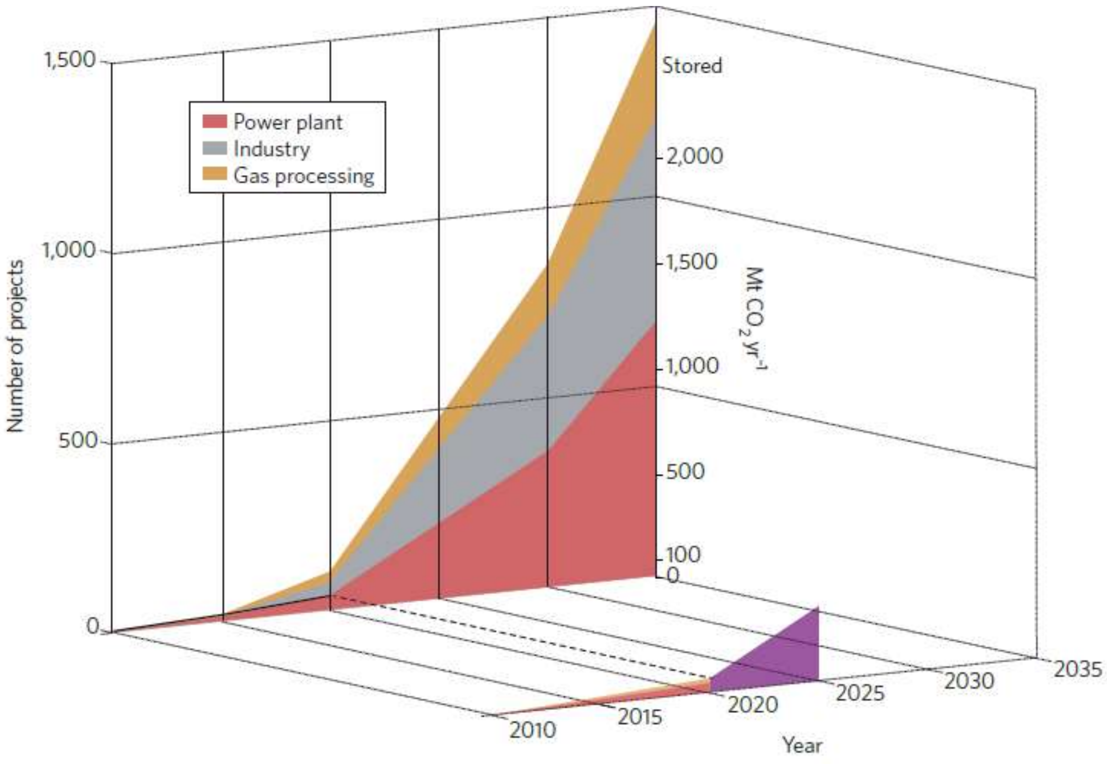


Figure 1.4: Prospects for CCS deployment (Scott et al. (2012), with permission of Nature Climate Change)

2.4 Supportive Canadian policy context for CCS

Canada has been a leader in CCS for over a decade. Canadian government and industry collaboration to develop financial and regulatory conditions in support of CCS were identified in the CCS Technology Roadmap (Natural Resources Canada, 2006) and the ecoEnergy CCS Task Force Report (2008). Three inter-jurisdictional objectives were to allocate $2B in new federal and provincial public funding to leverage industry dollars, to provide regulatory clarity, and, to support CCS within future greenhouse gas regulatory frameworks. The federal and provincial governments have allocated over $3B to CCS project development (Government of Canada, 2011). Internationally and bi-laterally, Canada also participates as a member of the Carbon Sequestration Leadership Forum (Carbon Sequestration Leadership Forum, 2013, Carbon Sequestration Leadership Forum, 2016); the International Energy Agency (2016a); the IEA Greenhouse Gas R & D Programme (2016); the Regional Carbon Sequestration Partnership Program (Office of Fossil Energy, 2016); the Clean Energy Ministerial (2016); and the U.S. – Canada Clean Energy Dialogue (Environment and Climate Change Canada, 2016).

In 2010, Canada's share of global CO_2 emissions was calculated at 1.8%, with an expected decrease to 1.6% in 2020 (Environment Canada, 2013). Our INDC under the 2015 Paris Agreement is 30% below 2005 emissions by 2030 (Government of Canada, 2016a). Unfortunately, Canada's GHG emissions trend has shown little reduction compared with 2005 levels (Environment Canada, 2013).

A component of a regulatory framework that could support development of CCS was enacted through the federal government's *Reduction of Carbon Dioxide Emissions from Coal-fired*

Generation of Electricity Regulations under the *Canadian Environmental Protection Act* (Environment Canada, 2012). Application of the regulation is intended to phase out high-emitting coal-fired generation by 2030 (a 10 year earlier phase-out than originally stipulated) (Government of Canada, 2016c) and promote a transition towards lower- or non-emitting generation such as high-efficiency natural gas, renewable energy, or fossil fuel-fired power with CCS. Beginning in 2015, new coal-fired units and units that have reached the end of their economic life must meet a 420 tonnes of CO_2 per GWh performance standard. Units that commit to implementing CCS could, under specific circumstances, receive emissions exemption up to 2025.

In 2016, the Government of Canada reached agreement with most provinces on a *Pan-Canadian Framework for Clean Growth and Climate Change* (Government of Canada, 2016d). Consistent with the coal-fired generation regulation, CCS is acknowledged as an approach for reducing emissions in the electricity sector, pointing to Saskatchewan's Boundary Dam project example (Chapter 3). As discussed further in Chapter 7, there could be implications for CCS with respect to the Framework's benchmark for carbon pricing beginning in 2018 (with the exception of Saskatchewan that has yet to agree): $10 per tonne, beginning in 2018 and rising by $10 per year to $50 per tonne in 2022.

At the provincial level, British Columbia's Climate Action Plan was published in 2008 with goals to reduce GHG emissions by 33% by 2020 and 80% by 2050 from 2007 levels (Government of British Columbia, 2008). Progress reports are completed every two years, as required by the *Greenhouse Gas Reductions Target Act* (Government of British Columbia, 2014). The 2012 interim target was achieved. The plan includes a revenue neutral carbon tax, introduced in 2008 at a rate of $10/tonne/$CO_2$eq, with $5/tonne annual increase (now $30/tonne). BC will hold the price on carbon at this level until the rest of the provinces catch up. CCS and CCS-EOR are included as a key driver for CO_2 emissions mitigation. Concurrent with this initiative, BC is implementing a 10-year Natural Gas Strategy (British Columbia Ministry of Energy and Mines, 2012) where, along with creating conditions for production increases, there is process underway to develop a CCS-specific regulatory policy framework (RPF) (Government of British Columbia, 2016, Province of British Columbia, 2014a, Province of British Columbia, 2014b). The BC government recognized that the existing provisions were not designed to manage particularities of long term CO_2 storage. The stated purpose of the RPF is "to identify and address any regulatory gaps; ensure that CCS is done safely to protect the public and the environment; and to provide transparency in CCS development" (Province of British Columbia, 2014b, p. 5). This initiative is discussed in detail in Chapter 2.

Alberta completed a regulatory framework assessment for CCS in 2013 (Alberta Energy, 2016). An expert-led and multi-stakeholder process reviewed technical, environmental, safety, monitoring, and closure issues for CCS. More recently, based on the advice of the Climate Change Advisory Panel (Government of Alberta, 2015b), the provinces' Climate Leadership Plan was announced in November 2015 (Government of Alberta, 2015a). Four major components are to transition from coal to natural gas or renewable power generation, implement a carbon levy and rebates, cap oil sands emissions, and reduce methane emissions from oil and gas operations. CCS and other unnamed technologies could be used to produce zero emissions from coal fired plants that continue to operate past 2030.

The government of Saskatchewan indicates that it is working with the federal government on the national climate strategy (Government of Saskatchewan, 2016). SaskPower's CCS-EOR project at the Boundary Dam coal fired electricity plant is Saskatchewan's primary investment in CCS.

In Nova Scotia, the CCS policy context falls within the *Environmental Goals and Sustainable Prosperity Act*, passed unanimously by the provincial legislature in 2007 (Province of Nova Scotia, 2012), and Climate Action Plan (Nova Scotia Government, 2009). The GHG emissions reduction goal is a minimum 10% from 1990 levels by 2020, with a target of 5 Mt/year by 2020. Electricity emissions caps are to take effect in 2010, 2015, and 2020. CCS Nova Scotia, a research consortium joint venture of the Province, Nova Scotia Power Inc., and Dalhousie University, is completing field research to expand understanding of the geology of the Sydney sub-basin as a potential site for a CCS project (CCS Nova Scotia, 2016).

In Canada, five large scale integrated projects are operating, under construction, or in the planning phase: two each in Alberta and Saskatchewan and one in British Columbia (Table 1.2). Three are CCS-EOR storage types: Saskatchewan's Weyburn-Midale Enhanced Oil Recovery Operations (3.0 $MtCO_2$/yr) and Boundary Dam Integrated CCS Demonstration Project (1.0 $MtCO_2$/yr), and the Alberta Carbon Trunk Line (~1.75 $MtCO_2$/yr) that is expected to be operating in 2017 (Massachusetts Institute for Technology, 2016). In Alberta, Shell's Quest Carbon Capture and Storage Project is a sequestration project for CO_2 captured at an oil sands upgrader facility where operations began in 2015 (1.08 $MtCO_2$/yr). Feasibility studies are completed for Spectra Energy's Fort Nelson CCS project in British Columbia, a saline sequestration project that could store up to 2 $MtCO_2$/yr from natural gas production. The application, review, and approval process for the first four projects are discussed in detail in Chapter 3, with special attention to risk assessment and risk management.

Table 1.2: Storage type and rated capacity ($MtCO_2$) for Canadian Large Scale Integrated Projects

Large Scale Integrated Project and Sector	Development phase	EOR ($MtCO_2$)	Saline Sequestration ($MtCO_2$)
Weyburn-Midale (US capture; Canadian EOR)	Operational	3/yr 17 since inception 30-40 projected (@2030) [Possibly 25 additional storage, post EOR operations]	
Boundary Dam Coal fired electricity	Operational	1.0/yr 30 total @2045	
Alberta Carbon Trunk Line - Industry	Construction (Operational ~2017)	1.5-2.0/yr initial 14.6/yr flow capacity	
Shell Quest Project Industry	Operational		1.2/yr 27 total @2040
Spectra Energy's Fort Nelson - Industry	Feasibility/ Planning		2.2/yr ~66 total @30 yrs
Total		5.5 – 6.0/yr >60-75 Mt EOR Possibly 30-40 storage	1.2 - 3.4/yr ~27 - 93Mt total

3 Human health and environmental hazards within the CCS value chain

Since inception, human health and environmental protection have been key goals within the safe and effective deployment of CCS. CCS projects have proceeded concurrently with an expanding knowledge base of hazard and risk issues within the operating and storage value chain, where risk is defined here as the combination of the likelihood and consequence of hazards that may create harm. For example, Wilson et al. (2003) identified geological storage hazards for the local project (CO_2 in the atmosphere or shallow subsurface; CO_2 dissolved in subsurface fluids; and geological displacement), and global environment (project leaks that return stored CO_2 to the atmosphere). Koornneef et al. (2012) and Pawar et al. (2015) further identified potential hazards for each chain component of integrated CCS systems, a list that includes air, soil, and groundwater contamination by CO_2, brine, or process contaminants, thus illustrating the complexity of health, safety, and environmental protection during project implementation. Jones et al. (2015) reviewed research with a focus on potential impacts to potable water resources and near surface (biosphere) systems in both the onshore and offshore projects.

Environment and health issues for capture processes include air emissions and dispersion (and associated land deposition with precipitation) of CO_2, nitrogen oxides, sulphur dioxide, ammonia, ethanolamine, particulate matter, mercury, halfnium, and hydrogen chloride/hydrochloric acid. Process upsets might also exhaust pollutants during capture and CO_2 stream compression and dehydration. Capture processes also include increased water consumption and wastewater discharges; solid waste and by-products; and an energy penalty. The last item refers to the increased energy input required to operate carbon capture and compression technologies compared with industrial or electricity plant operations without CCS, potentially increasing energy use for a coal fired plant by 25-40% (IPCC, 2005).

During transportation, potential hazards include pipeline or ancillary system failure. Accidental release of the CO_2 stream might be caused by rupture or puncture from corrosion (from impurities or water), construction or material defects (eg welds), ground movement, human error, or third party interference. Possible fatal and non-fatal human or wildlife exposures can result, especially where accumulation is in a topographic depression at surface or the bottom of a freshwater lake environment.

In preparing the injection site, hazards associated with well drilling include the loss of contaminated drilling mud at surface, which may also release chemical additives or saline water. Injection hazards during the operating period include intrinsic or induced hydraulic or thermal fracture of the caprock caused by increased pressures, with associated stream leakage; unexpected leakage along a spill point, fracture through the injection well, and well leakage because of a reduction of integrity or failure of the injection well casing Koornneef et al. (2012, p. 75). As with transport, human health hazards include exposure to CO_2 and other stream composition chemicals from accidents, malfunctions, and unintended events.

Storage hazards include CO_2, brine or heavy metal leakage from the sequestration reservoir into the geosphere, overburden, or biosphere (Figure 1.5). This could result in contaminated near surface soils, potable groundwater, surface water, or eventual release to the atmosphere (Jones et al., 2015, Koornneef et al., 2012, Pawar et al., 2015, Pearce et al., 2014, Wilson et al., 2003). Causes include a loss or reduction of integrity for the caprock, or capillary or molecular CO_2 or brine migration through the caprock, thereby permitting escape through fractures or faults leading to unexpected plume migration. Leakage may also occur more directly through exploration, injection, observation or abandoned wells. Research indicates that the impact of CO_2 contamination on groundwater chemistry is generally moderate, particularly in high-quality drinking water aquifers. However, migration of high-salinity brine into drinking water aquifers would have a more deleterious consequence (Pawar et al., 2015).

Another potential hazard is surface uplift and induced seismicity within the storage reservoir which may be caused by injection pressures. Unanticipated leakage may occur through caprock fracture or through a fault pathway, with CO_2 or brine contamination of drinking water. Earthquake tremors are a nuisance concern, but with possible property damage, thus also potentially affecting public acceptance.

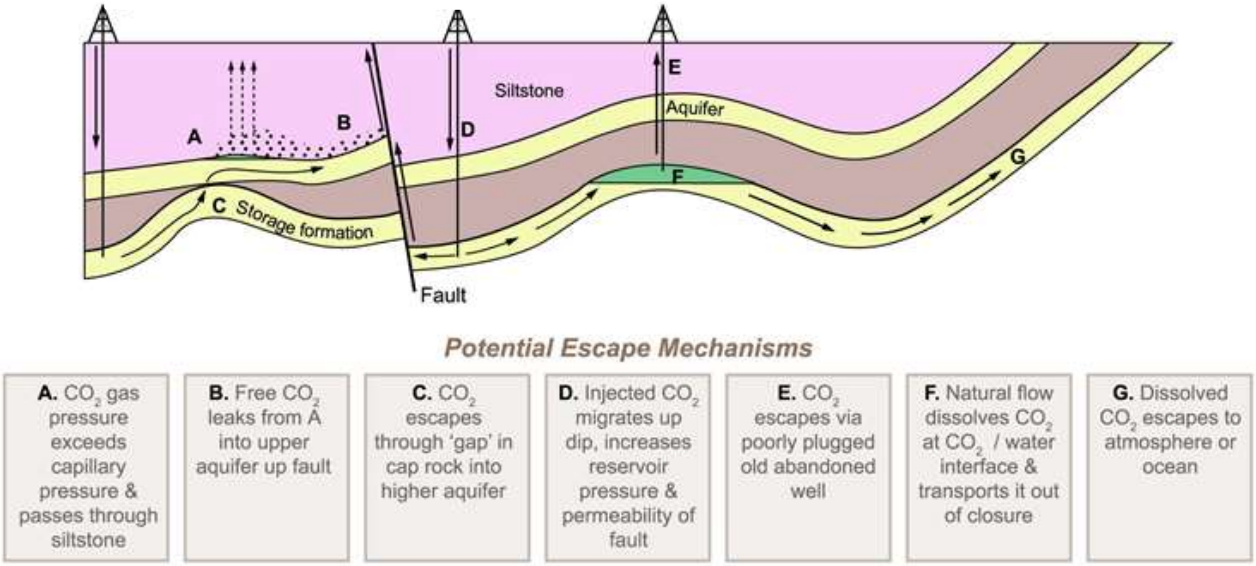


Figure 1.5: Potential CO_2 and brine leakage routes in injection and storage (Adapted from IPCC (2005), Figure TS-08)

Unanticipated CO_2 leakage is a risk to human health and the environment throughout the CCS value chain. This could both exacerbate global risks to population health and wellbeing, and decrease the potential for broad acceptance of CCS overall. However, the potential that CO_2 stored underground in a sequestration project could re-release, due to any type of failure in either the storage process or the geological formation, is one of the most serious issues that could be raised about CCS. It is understood that the rationale for CCS as a mitigation technology is based on the proposition that the gas, once injected underground, will stay there indefinitely. Leakage as a performance and containment risk could also result in less than expected sequestration benefit. It therefore represents a potentially significant environmental and health threat, as well as a waste of money.

In summary, an illustrative taxonomy identifies CCS hazards within value chain components (Table 1.3). The likelihood, severity, and risk management options for injection and storage hazards were assessed in the expert elicitation, findings for which are described in Chapters 4 and 5.

Table 1.3: Illustrative environmental and human health hazard taxonomy and risks for integrated CCS Projects

<table>
<tr><th colspan="4">CCS Value Chain Activity</th></tr>
<tr><th>Capture</th><th>Transport</th><th>Injection</th><th>Storage</th></tr>
<tr><td colspan="4">Physical Hazards</td></tr>
<tr><td colspan="4">CO_2 stream impurities</td></tr>
<tr><td>CO_2/amine/criteria contaminant air emissions</td><td>Pipeline failure</td><td>Injection wellhead or well casing failure</td><td>Unexpected plume migration</td></tr>
<tr><td>Amine/criteria contaminant land/water deposition</td><td>Associated systems failure</td><td>Caprock fracture</td><td>CO_2, brine or CO_2 saturated brine migration through caprock</td></tr>
<tr><td></td><td></td><td colspan="2">Induced seismicity</td></tr>
<tr><td></td><td></td><td colspan="2">Direct surface leakage – well leakage or far field</td></tr>
<tr><td colspan="4">Accidents, Malfunctions, Unplanned Events (Process Upsets)</td></tr>
<tr><td colspan="4">Human Health and Environmental Hazards</td></tr>
<tr><td colspan="4">CO_2 inhalation - occupational and/or public and/or wildlife morbidity/mortality</td></tr>
<tr><td colspan="4">Drinking water, soil, air contamination from amines, criteria contaminants, CO_2, or brine</td></tr>
<tr><td></td><td></td><td colspan="2">Surface uplift or earthquake</td></tr>
<tr><td colspan="4">Unanticipated CO_2 leakage rate to atmosphere contributing to climate change</td></tr>
</table>

4 Thesis overview

4.1 A population health model of the research problem

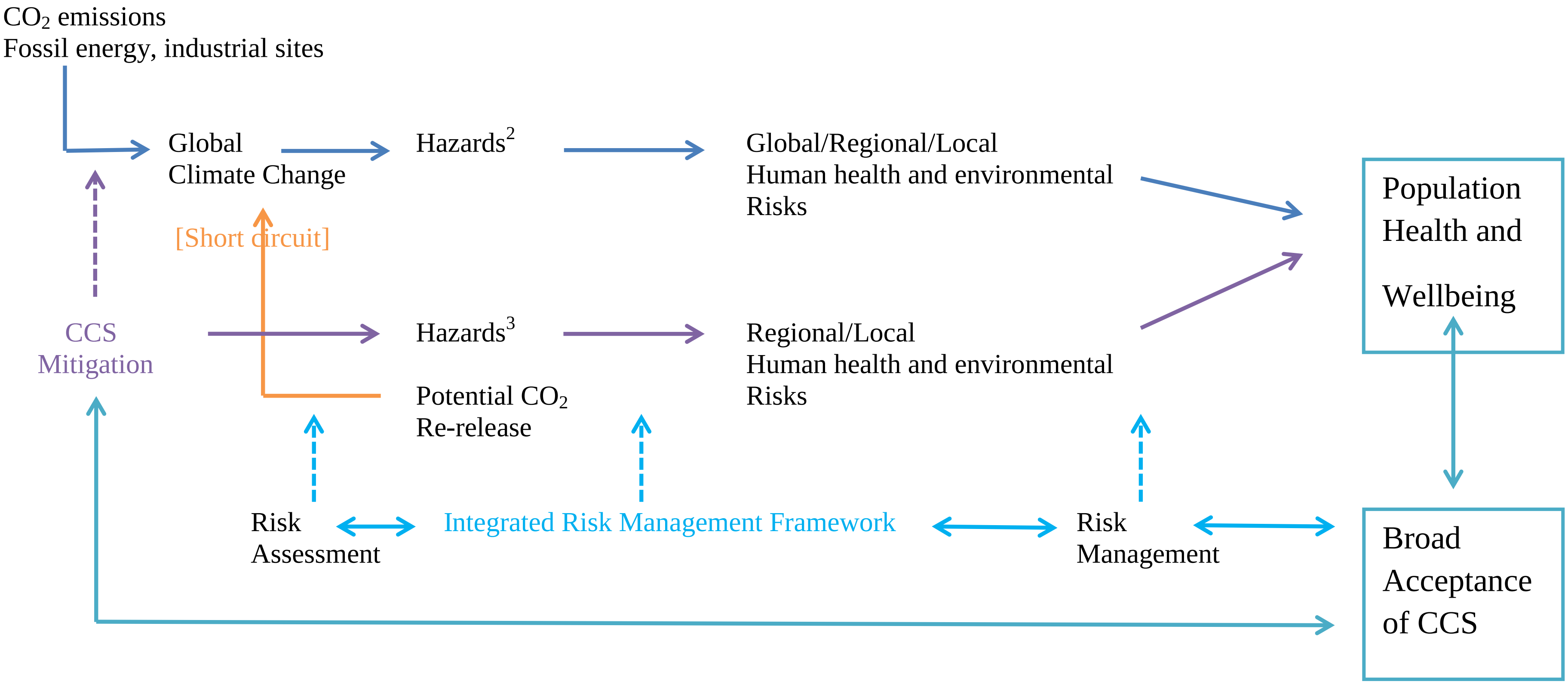
In a detailed review of risk management frameworks, Jardine et al. (2003) concluded that risk management processes should meet the decision making needs of the specific application. The integrated risk management framework for CCS in the Canadian context (IRMF) presented in Chapter 6 has been developed for saline sequestration CCS project types. This is the CCS approach favoured in international mitigation technology options (IEA, 2013a) because saline aquifers are the clear alternative for massive CO_2 sequestration, with a large capacity in suitable formations (Bachu, 2003, North American Carbon Atlas Partnership, 2012, US Department of Energy, 2015). CCS-EOR is not included in the potential application of the IRMF because these projects are viewed as an interim measure; sufficient monitoring, measurement, and verification to assess whether CO_2 storage is likely to be permanent remains to be undertaken (Bachu et al., 2013, Dixon et al., 2015). Internationally, CCS-EOR project types are not expected to assist with climate change mitigation over the mid- to long-term (IEA, 2013a). As suggested by IPCC (2005), the use of CO_2 in EOR projects is an expense to be minimized in operations where the goal is to extract additional fossil fuel. Conversely, large-scale CCS saline aquifer sequestration projects seek to safely maximize stored CO_2. EOR-CBM, salt cavern, and BECCS storage types are also excluded from the application of the IRMF because of limited capacity and greater uncertainty at the present time.

A conceptual framework of the considerations and linkages for the research project is illustrated in Figure 1.6. Based on Wilson et al. (2003) and beginning with the global sequence (top row, dark blue), CO_2 emissions from fossil fuels and industrial processes (left) are shown to contribute to global climate change, a source of social, environmental, and economic hazards. These create differential direct and indirect human health and environmental risks, which could manifest at the global/regional/local scale, ultimately affecting population health and wellbeing, as described at the beginning of this Introduction.

The CCS technology to mitigate CO_2 emissions that contribute to climate change is indicated in the middle of the left hand side of the figure (dashed arrow), as an intervention to affect this sequence. However, the middle row of the framework links CCS mitigation to other hazards and environmental and health risks. As described in Section 1.3, these stem from contaminant emissions in capture; abrupt CO_2 leakage in capture, transport, and injection; and intrinsic and induced geologic hazards in the injection and storage value chain components. Direct and indirect environment and health risks can result from these hazards, ultimately also affecting population health and wellbeing at the far right of the figure.

The intervention of an IRMF is indicated along the bottom of the figure. Double headed arrows depict the continuum of the risk assessment and risk management phases, with benefit to reduce hazards and risks throughout project development, thus also positively affecting population health and wellbeing. The connection of the IRMF to the widespread acceptance of CCS as a global climate change mitigation strategy is also shown (far right). Greater confidence in and local support for project implementation will enhance acceptance and successful implementation of this technology at both the local and global scales.

Figure 1.6: Conceptual framework of the research project



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[2] Social, environmental, economic hazards

[3] Capture, transport, injection, and storage hazards

A final note about the conceptual framework concerns the (vertical) orange arrow, the potential hazard of CO_2 re-release with a short circuit link to global climate change. Depending on the circumstance, this could exacerbate global risks to population health and wellbeing by linking to the top (global) panel, as well as decreasing the potential for broad acceptance of CCS at the right (direct link not shown).

4.2 Thesis outline

Written in journal article format, the next four chapters answer important research questions in the context of the development of an *Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context.*

Chapter 2 and Chapter 3 answer research questions related to current contextual issues in risk assessment and risk management of CCS:

- Chapter 2: What are the current provisions for risk assessment/risk management (RA/RM) in CCS regulations in leading jurisdictions?

  Frameworks to assess hazards and manage risks have advanced in both the regulatory and non-regulatory context concurrent with project implementation. Forbes et al. (2008), Stenhouse et al. (2009), and Condor et al. (2011b) completed early reviews of some of these contributions. Dixon et al. (2015) also provided detail on the historical development and inclusions of significant CCS regulations, but not focused specifically on provisions for risk assessment and risk management.

- Chapter 3: What has been the practice for RA/RM for large scale integrated CCS projects in Canada?

  The Canadian practice for risk assessment and risk management (RA/RM) during the application, assessment, and approval process of four LSIPs was completed for the first time. This is important for understanding the progress in risk assessment and risk management that has been made in two active Canadian provincial jurisdictions.

Chapters 4 and 5 address scientific understandings of hazards and related risk issues for CCS. In the absence of empirical data to resolve uncertainty for questions related to sequestration in saline aquifers, expert elicitation was used to advance understanding of relative risk and to quantify collective uncertainty judgements for difficult decision challenges. The elicitation instrument was designed by a CCS research team of which I was a part. Prior to the expert panel event, the protocol was reviewed and approved by the Research Ethics Board of the University of Ottawa. Elicitation materials are included in Appendix A.

- Chapter 4: What are experts' understanding and beliefs about risks and attendant uncertainties associated with injection and storage chain components of CCS?

  Risk assessment of capture and transport chain activities are better known and understood, while injection and storage chain activities have been found to be less well understood with attendant uncertainties (Damen et al., 2006, Koornneef et al., 2012). Even where risk in storage has been found to be low, Koornneef et al. (2012) suggested that the (ongoing) uncertainty regarding storage risk assessment has the potential to become a barrier for wide scale implementation of CCS if not properly addressed.

- Chapter 5: What are experts' understanding and beliefs about risks and attendant uncertainties associated with risk management of high impact low probability events related to CCS?

  The expert elicitation of scientific judgements also linked human health and environmental issues in risk assessment with a variety of risk management options that could be considered during the review and approval of deep geological saline sequestration projects worldwide. Indeed, as a principle of population health, coordinated action at multi-levels and multi-scales assists in protecting the determinants of health.

Also in journal article format, Chapter 6 presents the Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context.

- This chapter begins with a description of elaborated RA/RM frameworks developed by both government and non-government organizations, followed by the features of the IRMF, and considerations of its application within the next generation of risk science (Krewski et al., 2014). The IRMF for saline sequestration projects proposed here will provide a systematic and transparent process for project proponents and regulators to follow, with a checklist of actions and engagement opportunities in both the risk assessment and risk management phases of project implementation**.**

Not in journal article format, Chapter 7 completes the thesis with a summary of the findings from this research project focused on human health and environmental hazards and risk issues in CCS. Two additional barriers to widespread implementation of this climate change mitigation technology are also discussed: project costs and public concerns. The conclusion is completed with a risk management policy scenario. Key contextual issues and mechanisms are identified for future country deployment of CCS in both Organization for Economic Cooperation and Development (OECD) country and non-OECD country implementation, thus assisting with reliable and effective deployment of CCS for the benefit of both local and global populations.

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Chapter 2: Regulating the Risks of Carbon Capture and Storage: A Global Perspective

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Abstract

Carbon capture and storage (CCS) is included in the list of technologies that could reduce point source greenhouse gas emissions that contribute to climate change. In order to support worldwide development and implementation of this technology, global stakeholders continue to identify the need to address wide ranging regulatory issues such as carbon dioxide ownership, liability, and emission credits; health and environmental protection; public engagement; monitoring; and provisions specific to cross-border contexts. This article provides an update on regulating risks of CCS in Canadian and selected international jurisdictions, with emphasis on risk assessment and management (RA/RM) considerations. A comparative analysis finds wide variation in mandatory and voluntary provisions for the implementation of CCS at the international level. Future implementation of recommendations from comprehensive regulatory assessments in British Columbia and Alberta could strengthen RA/RM in these Canadian provinces.

Keywords

Carbon capture, regulatory framework, risk assessment, risk management, Canada, international.

1 Introduction

Carbon capture and storage (CCS) is included in the list of technologies that could reduce industrial point source greenhouse gas emissions that contribute to climate change (International Energy Agency [IEA], 2010b, 2013; Intergovernmental Panel on Climate Change [IPCC], 2014). Stakeholders have repeatedly identified the need for a legal and regulatory framework within international, regional, national, and sub-national jurisdictions to promote uptake of CCS projects worldwide (Baker &

McKenzie, 2011; CO_2 Capture Project [CCP], 2010, 2012; Condor et al., 2011; Carbon Sequestration Leadership Forum, 2013; Global Carbon Capture Storage Institute [GCCSI], 2010, 2011, 2013a, 2014; IEA, 2010a, 2010b, 2010c, 2011, 2013, US Environmental Protection Agency [USEPA], 2010). A wide range of regulatory issues that warrant consideration include carbon dioxide (CO_2) ownership, liability, emission credits, and project funding; health and environmental protection; public engagement; monitoring; and provisions specific to cross-border contexts. The IEA (2010a) (Table 2.1) suggested these will be addressed through existing laws and regulations, as they stand and with amendment, and through new regulations aimed at specific components of the CCS value chain.

This article provides an update regarding regulatory provisions that enable CCS in jurisdictions in Canada and internationally, with an emphasis on requirements for risk assessment and risk management (RA/RM). A comparative global analysis of RA/RM is then presented. Previous RA/RM analysis was completed for the London and OSPAR Conventions (Condor et al., 2011; Stenhouse et al., 2009); the then-draft European Union CCS Directive (Condor et al., 2011; Forbes et al., 2009; Stenhouse et al., 2009); then-draft USEPA Underground Injection Control Program rule (Forbes, 2009; Stenhouse, 2009); and national and sub-national provisions in Canada and Australia (Condor et al., 2011). More recently, Dixon et al. (2015) provides a review of legal and regulatory developments, with a focus on international jurisdictions outside of Canada. These regulatory developments are included here for completeness. The article in this issue by Larkin et al. (submitted-a), *An Integrated Risk Management Framework for Carbon Capture and Storage*, further details elaborated RA/RM frameworks developed by both regulatory and non-regulatory organizations. Also in this issue, Larkin et al. (submitted-b), *The Evolution of Regulatory Practice for CCS Projects in Canada*, consider the application of RA/RM in four large scale Canadian project approvals over the past fifteen years.

Table 2.1: IEA Key Regulatory Issues (Modified from IEA, 2010, pg.17)

Regulatory Issue	Broad Regulations	Existing Regulations Applied to CCS	CCS Specific Regulations	Emerging CCS Regulations
Full CCS Chain				
Protecting human health		X		
The role of environmental impact assessment		X		
Corrective measures and remediation measures			X	
Capture				
Composition of the CO_2 stream		X		
CO_2 capture			X	
Transportation				
CO_2 transportation			X	
Storage – Science				
Regulating site selection and characterization			X	
Authorization of storage site exploration activities			X	
Authorization of storage activities (Permitting)			X	
Authorization for storage site closure (Permitting)			X	
Storage and Monitoring				
Definitions and terminology applicable to CO_2			X	
Third-party access to storage site aaninfrastructure		X		
Project inspections			X	
Monitoring, reporting and verification			X	
Public Engagement				
Engaging the public in decision making		X		
International				
Transboundary movement of CO_2	X			
International laws re marine environment	X			
Emerging				
CCS ready				X
Using CCS for biomass-based sources				X
Understanding enhanced hydrocarbon recovery				X
Sharing knowledge and experience				X
Definition, Rights, Liability, Financial				
Classifying CO_2	X			
Property rights	X			
Competition with other users and preferential rights	X			
Liability during the project period			X	
Liability during the postclosure period			X	
Financial contributions to post-closure			X	
Providing incentives for CCS	X			
Scope of framework and prohibitions			X	

2 Canadian regulatory context

2.1 Canadian federal government

Prior to July 2012, Canadian CCS projects were subject to the *Canadian Environmental Assessment Act* (CEAA) (Government of Canada, 2012a), as administered by Natural Resources Canada where there was a potential financial contribution through the ecoEnergy Technology Initiative or Clean Energy Fund. This Act served, in part, to ensure that projects were considered in a careful and precautionary manner to avoid significant adverse environmental effects; to encourage responsible authorities to take actions that promote sustainable development and thereby achieve or maintain a healthy environment and a healthy economy; and to ensure opportunities for timely and meaningful communication and consultation with Aboriginal peoples and the public. The National Energy Board (NEB) had jurisdiction for pipelines crossing international and interprovincial borders. NEB regulations classified CO_2 pipelines as a type of commodity pipeline with no specific standards, where terms and conditions are determined on an *ad hoc* basis, as guided by applicable procedures for other pipelines and supplemented by specific analysis of the individual applications (International Energy Agency Greenhouse Gas R & D Programme [IEAGHG], 2010).

CEAA was amended in 2012 and is currently under review. Under the 2012 Act (Government of Canada, 2012b) if a project-type is included in regulations, the proponent must submit a project description to the Canadian Environmental Assessment Agency and a determination is made whether a federal environmental assessment is required. Potentially regulated “Physical Activities” that could be part of a CCS project include an oil or gas facility in a wildlife area; a fossil fuel-fired electrical generating station over 200 MW in size, or greater than 50% expansion resulting in 200 MW or more; expansion of a heavy oil or oil sands processing facility of defined capacity; and increased production capacity of more than 35% for an oil refinery, including a heavy oil upgrader of prescribed input capacity. The Minister of the Environment and Climate Change may also designate a project not identified in regulations, if there is the potential for environmental effects in areas of federal jurisdiction or public concerns about such effects. The NEB remains responsible for interprovincial and international pipelines.

If the ensuing environmental impact assessment (EIA) finds that a project is likely to cause significant adverse environmental effects, the federal Cabinet has decision making power whether these effects are justified in the circumstances. A decision statement is rendered to provide the decision and associated conditions with which the proponent must comply, whereby failure to fulfill the conditions represents a violation and contraventions can result in fines. There is also a mandatory follow-up program after each environmental assessment, intended to verify the accuracy of the predictions regarding potential environmental effects and to determine if mitigation measures are working. Furthermore, there are provisions for consultation and cooperation with other jurisdictions, as well as substitution of the federal for a provincial environmental assessment process. There are also opportunities for public participation through two prescribed public comment periods: while a determination is made whether an environmental assessment is required, and on the draft environmental assessment report for projects assessed by the Agency. Public hearings may occur during review panels and there is provision for panels to consider all written comments from the public.

With respect to regulated requirements for cooperation and communication with Aboriginal Peoples, the definition of "environmental effects" includes changes to their health and socio-economic conditions; physical and cultural heritage; current use of land and resources for traditional purposes; and structures, sites or things that are of historical, archaeological, paleontological or architectural significance.

While CEAA applied to several Canadian CCS projects considered by Larkin et al. (submitted-b), CEAA2012 has not applied to a CCS project to date.

2.2 British Columbia

The British Columbia Oil and Gas Commission (BCOGC) regulates the exploration and use of storage reservoirs, facilities, wells, and provincial pipelines, particularly for liquids that contain hydrogen sulphide. Their mandate is to provide for the sound development of the oil and gas sector, by fostering a healthy environment, a sound economy and social well-being; to conserve petroleum and natural gas resources; to ensure safe and efficient practices; and to assist resource owners to participate equitably in the production of shared pools of petroleum and natural gas. The Commission undertakes education and communication programs in order to advance safe and efficient practices in technological development. Community and industry expectations and process flowcharts are outlined on their website (British Columbia Oil and Gas Commission, 2016).

Several acts and regulations can be applied to CCS projects. The BC *Petroleum and Natural Gas Act* (Government of British Columbia [British Columbia], 2012) provides a definition of a storage reservoir and enables its tenuring, with provision for permitting, leases (including disposal well purposes), spacing, pooling and Crown Reserves. The *Oil and Gas Activities Act* (OGAA) Part 14 - Underground Storage (British Columbia, 2010) describes requirements for exploration licensing, designating a storage area, and leasing of storage reservoir. It clarifies ownership and the process used to be granted the right to use the pore space. The BCOGC has adopted the Canadian Standards Association Standard Z741 *Geological Storage of Carbon Dioxide* (CSA Group, 2012) pursuant to the Drilling and Production Regulation under the OGAA (BC Ministry of Natural Gas Development, 2014). The *Environmental Assessment Act* (British Columbia, 2002) applies to major projects or facilities; the *Environmental Management Act* (British Columbia, 2004a) aims to protect human health and the quality of water, land and air with respect to waste management and contaminated sites. The associated Waste Discharge Regulation (British Columbia, 2004b; BC Ministry of Environment, 2009) lists industries, trades, businesses, activities and operations that require authorization to introduce waste into the environment. To date, CO_2 has not been listed as a waste product.

The BC government recognized that these provisions were not designed to manage issues of long term CO_2 storage. As stipulated in the 10-year Natural Gas Strategy (BC Ministry of Energy and Mines, 2012b), development of a CCS-specific regulatory policy framework is underway through the Ministry of Natural Gas Development (BCNGD), with stated purpose "to identify and address any regulatory gaps; ensure that CCS is done safely to protect the public and the environment; and to provide transparency in CCS development" (BCNGD, 2014, pg 5). Issues identified in the discussion and comment paper included storage and disposal rights, general operations and permitting, monitoring, closure and post closure assurance, and long term liability and reservoir stewardship (Province of British Columbia, 2014a). Among the proposals relevant to environment and health RA/RM, the discussion paper suggested that CCS storage reservoir lease application would include: site characterization details; CO_2 stream composition; a description of measures to prevent significant leakage, unintended migration or other irregularities, as well as corrective measures/contingency plans in such an event; a proposed monitoring plan; health and safety emergency response plan; and community and First Nations' engagement plan, including consultations conducted as of the time of application (BCNGD, 2014). The discussion paper also suggested establishing a CCS review board (Storage Reservoir Stewardship Board) to verify these inclusions and that the Board would refer to third party experts to review site characterization data, validate site risk assessments, the monitoring and verification programs and mitigation plans. The proposed monitoring plan would be results-based and informed by site-specific risk assessments. A consultation summary report was published (Province of British Columbia, 2014b). The *Natural Gas Development Statutes Amendment Act, 2015* was passed, including amendments to the *Petroleum and Natural Gas Act* and the *Oil and Gas Activities Act* to enable CCS. Key provisions included authority of the BCOGC as the permitting agency, and regulations to improve transparency of oil and gas activities (Province of British Columbia, 2015). Additional amendments may be made in the future.

2.3 Alberta

CCS projects are underway in Alberta. The Alberta Energy Regulator (AER) (formally the Alberta Energy Resources and Conservation Board (ERCB)), is a quasi-judicial administrative tribunal acting as the single regulator of energy development, from application and exploration, to construction and development, and then abandonment, reclamation, and remediation. This includes allocating and conserving water resources, managing public lands, and protecting the environment over the entire life cycle of hydrocarbon resource development.

The AER has been regulating the disposal, storage, and injection of fluids to underground geologic formations in Alberta for over 20 years. To date, CCS projects have been treated as acid gas disposal activities under its Directives (Bankes and Ference, 2009). An application to dispose CO_2 would likely be approved if the AER is satisfied that disposal will not impact hydrocarbon recovery; the disposal fluid will be confined to the injection formation; offset owners within 1.6 km of the disposal well(s) have been consulted and have no objections or concerns to the disposal scheme (unit operators, approval holders, well licensees); and the applicant has the right to dispose into the requested formation.

The Acts and Directives that have been applied to CCS include:

- the *Oil Sands Conservation Act* (Province of Alberta [Alberta], 2013a) applied to capture activities;
- the *Oil and Gas Conservation Act* (OGCA) (Alberta, 2014a) applied to storage activities;
- Directive 051, Injection and Disposal Wells (AER, 1994);
- Directive 056, Energy Development Applications and Schedules (AER, 2014a), applied to well and pipeline development (pipeline design is based on CSA *Z662-07: Oil and Gas Pipeline Systems*);

- Directive 065, Resources Applications for Oil and Gas Reservoirs (AER, 2014b), applied to enhanced oil recovery schemes (EOR) and disposal/storage where CO_2 is considered an acid gas;
- Directive 071, Emergency Preparedness and Response; and
- other relevant Guides and Directives that apply to waste facilities and upstream oil and gas authorizations and consultation requirements.

Applications are posted publicly and AER hearings are scheduled where community concern is not resolved through the Appropriate Dispute Resolution process (AER, 2013). Interveners are accredited based on the location of their land holdings and the potential for a direct and adverse effect within a designated environmental protection zone. Fluker (2009) suggested that the then-ERCB did not address the socio-ecological impacts of energy projects because of its narrow interpretation of who meets the test to obtain standing and request a hearing.

Until October 2014, Alberta Ministry of Environment and Parks (AEP), formerly the Ministry of Environment and Sustainable Resource Development (ESRD), administered the *Environmental Protection and Enhancement Act* (EPEA) (Alberta, 2010a) and *Water Act* (Alberta, 2014b) as they would apply to the potential effects of CCS projects on land and water. In the transition from the ERCB to AER, upstream oil and gas regulatory functions under these acts were transferred to AER.

The EPEA and accompanying regulations described which activities required environmental impact assessment approvals and the process for obtaining them. Individual categories of activities include waste management; substance release; conservation and reclamation; miscellaneous (pesticides, designated materials, water wells); and potable (drinking) water. There are mandatory, exempted, and discretionary project types; or, where an activity is not specifically listed in the Regulation, an environmental impact assessment (EIA) process may be triggered when referred by another Environment Director or by the Proponent, who may request a decision on the need for an EIA report. There are six related regulations, two Codes of Practice, and twelve listed Standards and Guidelines. As described under CEAA2012, there were also provisions for federal/provincial cooperation in addressing these issues.

The AER webpage indicates a link to the Ministry of Environment and Parks with respect to documentation on the environmental assessment process (http://www.aer.ca/applications-and-notices/environmental-assessment). Where applied, EIA examines a project to determine what the environmental, social, economic, and health implications may be. A decision is made by the regulator as to whether the project is in the public interest and sets specific conditions under which the project can operate. There is a follow up program to monitor project implementation.

Alberta has also enacted several CCS-specific regulatory provisions. Through the *Carbon Capture and Storage Statutes Amendment Act* (Alberta, 2010b), an amendment to the *Mines and Minerals Act* (MMA) (Alberta, 2013b), and the Carbon Sequestration Tenure Regulation under the MMA (Alberta, 2011), instruments define and grant pore space, establish minimum depth for injection (greater than 1000m), and manage long-term liability. Monitoring, measurement, and verification (MMV) plans and closure plans are required in relation to a carbon sequestration lease. These plans must be approved and updated every three years, including management of long term liability. There is no specific reference or guidance on RA/RM, except for the MMV plans. However, the MMA enables RA to be required through regulation, as part of a CO_2 storage permit application (McCoy, 2014).

In 2013, Alberta completed a detailed Regulatory Framework Assessment (RFA) for CCS (Alberta Energy, 2013). The goals were to review and develop regulations for CO_2 sequestration that are comprehensive and transparent; to contribute to the acceleration of CCS activities in the province; and to underpin greater public acceptance of CCS projects. A multi-stakeholder, expert-led process considered technical, environmental, safety, monitoring and closure issues. The process focussed on CCS for sequestration, as it was determined that CCS for EOR required its own review, including transitioning from EOR to CCS.

Background reports prepared for the working groups included: Review of Carbon Capture and Storage Environmental Assessment and Project Approval Requirements in Ex-Alberta Jurisdictions; Literature Review and Assessment of Potential Impacts of Emissions from Carbon Capture and Storage Projects; Carbon Capture and Storage Leakage Scenario Assessment and Gap Analysis of Alberta Mitigation and Remediation Plan Requirements; Public Engagement and Stakeholder Consultation Assessment; and a Public Safety Survey for CCS (no longer available as a weblink).

The RFA Report included 71 individual recommendations and 9 conclusions, now being considered by the Ministry of Energy for potential implementation (Alberta Energy, 2016). These fall within four topic areas:

- Applications, Approvals, and Regulatory Framework

- Risk Assessment, Monitoring, and Technical Requirements
- Public Consultation and Notification, Surface Access, and Public Safety
- Site Closure and Long Term Liability

Given the extensive nature of the RFA process and outcomes, several of the Report's risk-related recommendations are included here. For example, guidelines for RA, as integral to the MMV and Closure plans, are recommended to be iterative, systematic, technically defensible, and transparent, with a publicly accessible process; modelling and simulations are to be undertaken (as applicable on a site-specific basis) to evaluate and predict the behaviour of the CO_2 sequestration complex and inform the RA; MMV records (including all iterative updates and comparisons of predicted behaviour of the sequestered CO_2 with measured performance) are to be retained for the life of the project to support MMV plans and closure certificate applications; and non-technical risks related to public acceptance of MMV should be identified and addressed by project proponents. It was suggested that the entire RM process be incorporated into the regulatory framework, including "informal assessment", although this assessment was not defined. It was also recommended that levels of acceptable risk be developed on a case-by-case basis, between the regulator and proponent (other stakeholders were not identified); that mandatory EIA be undertaken during a 3 year review of its application to CCS; that the public safety priority focus on transportation and injection; and that a detailed RA would inform MMV focused on CO_2 capture, injection, and storage.

The RFA also noted that air emissions from CO_2 capture processes (i.e., amine-based systems) and impacts to groundwater from CO_2 sequestration operations are both less well understood, and thus require further study. Other potential actions are to develop Environmental Protection Zone (EPZ) requirements specific to CCS projects for transportation and injection only; and the review and consideration of CSA Z741-12: Geological Storage of Carbon Dioxide (Canadian Standards Association, 2012).

With respect to communication and outreach, the report and appendices refer to the importance of transparency and public understanding of CCS as a new technology. Recommendations are to develop a CCS Regulatory Guidance Document as well as to develop industry-wide minimum requirements specific to CCS, with the possibility of enhancing the consultation and notification process for all stakeholders normally undertaken for oil and gas activities.

2.4 Saskatchewan

In Saskatchewan, a wide variety of project types are submitted to the Ministry of Environment (SaskMoE) for review under the *Environmental Assessment Act* (EAA) (Government of Saskatchewan [Saskatchwan], 2002). A determination is first made whether the project is a "development" under the Act. Assessment criteria for any project, operation, or activity or any alteration or expansion of any project, operation, or activity include:

- the effect on any unique, rare or endangered feature of the environment;
- substantial utilization of any provincial resource and in so doing pre-empt the use, or potential use, of that resource for any other purpose;
- emission of any pollutants or by-products, residual or waste products which require handling and disposal in a manner that is not regulated by any other Act or regulation;
- widespread public concern because of potential environmental changes;

- new technology that is concerned with resource utilization and that may induce significant environmental change; or
- a significant impact on the environment or that necessitates a further development which is likely to have a significant impact on the environment

Project descriptions are screened by other agencies. This process also serves to identify the range of non-environmental legislative and regulatory requirements. The proponent has an opportunity to answer any outstanding questions. The subsequent decision is to 1) provide clearance for the project, based on the description and proposed environmental protection commitments outlined in the proposal and the clarifications and restrictions developed through the review process; or 2) require an environmental impact assessment.

Once clearance or EIA approval is completed, the proponent may proceed to obtain other required permits and approvals for CO_2 transport under the *Pipelines Act* and associated regulations (Saskatchewan, 2011; Saskatchewan Ministry of Economy, 2014a) and injection and EOR under the *Oil and Gas Conservation Act* (OGCA) (Saskatchewan, 2014; Saskatchewan Ministry of Economy, 2014b). However, this is not mandatory under either legislation; some projects may be reviewed under EAA screening prior to or in parallel with the OGCA approval process.

The main purpose of the OGCA is to enable the greatest possible ultimate recovery of provincial oil or gas reserves, while protecting the environment with respect to operations of the oil and gas industry. The OGCA has applied to CO_2-enhanced oil recovery (EOR) operations. In 2011, an

OGCA amendment (Government of Saskatchewan, 2014) expanded regulation-making powers and clarified oversight for non-oil-and-gas substances, in particular with respect to the injection, storage and sequestration of carbon dioxide and other greenhouse gases in subsurface caverns (Maguire et al., 2011). The Minister is authorized to make orders respecting:

- the containment, storage, handling, transportation, treatment, processing, recovery, reuse, recycling, destruction, and disposal of oil and gas waste and non-oil-and-gas waste;
- the conditions under which drilling and producing operations may be carried out in environmentally sensitive areas and any special measures to be taken in those operations;
- well closures, decommissioning, abandonment, and site reclamation; and
- contributions to Oil and Gas Orphan Fund in the event that the owner of a well is unable to implement its obligations with respect to a specific well or facilities.

There are requirements for the owner/operator to ensure post-closure protection to prevent CO_2 leakage, as well as to properly decommission and remediate the surface area. However, ongoing monitoring or testing for leakage is not normally required from the licensee, except where reasonable risk exists; the Ministry will then require an on-going monitoring program. Details for making this determination were not available, but depend on an assessment of the circumstances. Remediation for leakage at a decommissioned and abandoned well site is the responsibility of the licensee in perpetuity.

Lastly, communications and outreach with stakeholders are not prescribed in Saskatchewan. Experience by the SaskPower proponent and Petroleum Technology Research Centre, for the

Boundary Dam capture project (Chapter 3), appeared to follow best practices, but no specific regulatory requirements.

3 International regulatory context

3.1 Cross-national jurisdictions

In 2006, the contracting parties to the International Maritime Organization's (IMO) London Convention adopted the *Risk Assessment and Management Framework for* CO_2 *Sequestration in Sub-Seabed Geological Structures* (RAMF) (IMO, 2006), in association with amendment to Annex 1 of the London Protocol to include CO_2 sequestration in sub-seabed geological formations. The framework is designed to allow characterisation of the potential risks posed by CO_2 sequestration on a site-specific basis and to enable the collection of all necessary information for developing a management strategy to address uncertainties and any residual risks. A second amendment to the London Protocol was adopted and further revised, the *Specific Guidelines on Assessment of* CO_2 *Streams for Disposal into a Sub-Seabed Geological Formations* (IMO, 2012). This provides advice on how to capture and sequester CO_2 in a manner that meets all the requirements of the London Convention and is safe for the environment, both marine and atmospheric, for the short- and long-term. These frameworks are for guidance only.

In 2007, contracting parties to the *OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic* adopted amendments to permit storage of CO_2 in accordance with Annex 1 to the Convention, 'Prevention and elimination of pollution from land-based sources'. Based on the London RAMF, the *OSPAR Guidelines for Risk Assessment and*

Management of Storage of CO_2 *Streams in Geological Formations* (FRAM) (OSPAR Commission, 2007) were also approved. The Guidelines are detailed in identifying and discussing the different elements of a RA framework to be applied to both onshore and other geological CO_2 storage projects (Stenhouse et al., 2009). A decision to grant a permit or approval shall only be made if a full risk assessment and management process has been completed to the satisfaction of the competent authority and that the storage will not lead to significant adverse consequences for the marine environment, human health, and other legitimate uses of the maritime area. Permitting requires a RM Plan (OSPAR, 2007). These guidelines are a mandatory requirement and are in force.

The European Union (EU) *Carbon Capture and Storage Directive* (CCS Directive) was approved in 2009, with sufficient transposition in 2011 to enter into force. The Directive establishes a legal framework for the environmentally safe geological storage of carbon dioxide to contribute to mitigating climate change (European Union, 2009). The purpose is for permanent containment, with no significant risk of leakage or harm, in such a way as to prevent or eliminate as far as possible negative effects and any risk to the environment and human health, and to prevent any adverse effects on the security of the transport network or storage sites (EU, 2009). Seven other pieces of EU environmental legislation were amended to remove legal barriers to geological storage of CO_2, such as the Strategic Environmental Assessment (SEA) Directive (EU, 1985), the Environmental Impact Assessment Directive (European Parliament, 2014) to assess risk to the environment in capture and transport, and the Directive on Integrated Pollution Prevention and Control that regulates the risks of CO_2 capture and streams to the environment and human health (EU, 2008). Several voluntary implementation guides for the

CCS Directive are published by the European Commission (EC) (EC, 2011a; 2011b; 2011c): Risk Management; Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures; Criteria for Transfer of Liability; and Financial Security and Financial Mechanism. Annex II of the Directive lists monitoring requirements. Other related EC publications include one opinion on adherence to the CCS Directive (EC, 2012) and the first report on the implementation of the Directive (EC, 2014). Furthermore, a required evaluation to consider the effectiveness, efficiency, coherence, relevance, and EU added value of the CCS Directive was completed (European Commission 2015).

The UN Framework Convention on Climate Change (UNFCCC) *Modalities and procedures for carbon dioxide capture and storage in geological formations as a clean development mechanism* (CDM) was adopted in 2011 (UNFCCC, 2011). Under the CDM, emission-reduction projects in developing countries can earn certified emission reduction credits for industrialized countries as part of their targets under the Kyoto Protocol. There are mandatory elaborated requirements for the selection and characterization of the geological storage site; risk and safety assessment for the full chain of CO_2 capture, transport, and storage, including surrounding environments; and monitoring.

3.2 Australia

At the national and sub-national levels, Australia Commonwealth and State CCS legislation and regulations apply to any greenhouse gas substance, therefore not limited to CO_2. The Commonwealth government is responsible for offshore operations greater than 3 nautical miles from land. Their regulatory framework is underpinned by the *Offshore Petroleum and*

Greenhouse Gas Storage Act (OPGGS Act) 2006 and regulations (Australian Government [Australia], 2009, 2011a, 2011b, 2011c, 2014a). The Department of Industry administers the Offshore Petroleum and Greenhouse Gas Storage (Greenhouse Gas Injection and Storage) Regulations 2011 (Australia, 2011a), where consideration of risk focuses on seepage and migration that could affect other petroleum resources. However, required site plans, storage, and monitoring plans could also be of benefit to human and environmental risk assessment and management. Transport is normally regulated through the Australian Pipeline standard, as required by the *Petroleum and Geothermal Energy Act*.

The National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) was established in 2012 and is responsible for regulating the health and safety, well integrity, and environmental management of all offshore petroleum facilities in Commonwealth waters, as well as in coastal waters where State powers have been conferred. With respect to health and safety, the OPGGS (Safety) Regulations 2009 (Australia, 2009) and OPGGS (Resource Management and Administration) Regulations 2011 (Australia, 2011b) outline requirements for operators to submit a Safety Case that describes hazards and risks, indicates how the risks are controlled, and the safety management system in place. Operators are to commit to reducing risks to a level that is “as low as reasonably practicable” (ALARP). Broad powers include dealing with serious situations and contingencies, including cessation of operations.

With respect to well integrity, the OPGGS (Resource Management and Administration) Regulations 2011 (Australia, 2011b) requires a well operations risk management plan, including consideration of well integrity hazard and any increases to existing well risks; lifecycle risk reduction; and monitoring and integrity assurance processes. Finally, the OPGGS (Environment) Regulations 2009 (Australia, 2014) sets out the content and criteria for acceptance of the Environment Plan required prior to undertaking GHG activities. This provides an evaluation of impacts and risks; an implementation strategy that ensures that any impacts are ALARP; and, a report on consultations. In addition to these mandatory regulatory provisions, several guidance documents for the preparation of submissions have also been produced (NOPSEMA, 2011a; 2011b; 2014a; 2014b).

State governments are responsible for both onshore sites and sites falling within a 3 nautical mile offshore limit. Near shore legislation typically mirrors that of the Commonwealth. Victoria was the first state to enact both onshore and offshore CCS regulatory framework. In Victoria, the *Greenhouse Gas Geological Sequestration Act* (State Government of Victoria [Victoria], 2008) and regulations (Victoria, 2009) address large-scale commercial and sustainable injection and permanent storage of greenhouse gas substances in the onshore. An injection testing plan must detail how risks to public health or the environment will be prevented and an environmental management plan, including environmental risk assessment, must be prepared in accordance with the regulations. Victoria will not accept liability after site closure. The GCCSI regulatory test toolkit (AECOM, 2013) has been applied in a mock project application, with recommendations for the short, medium and long term (AECOM, 2013).

Similarly, Queensland enacted the *Greenhouse Gas Storage Act* and Regulations (Queensland Government, 2010), including requirements, without elaboration, for injection test plans to assess whether there is any risk to public health or the environment, and risk mitigation.

South Australia amended the *Petroleum and Geothermal Energy Act* and associated Regulations (Government of South Australia, 2010) in order to specify the Environment Protection Authority and Safe Work South Australia as agencies that must be consulted in project approval. All regulated activities must be undertaken in accordance with a Statement of Environmental Objectives, developed on the basis of an Environmental Impact Report. The State also requires submission of Fitness-for-Purpose (FFP) risk assessments of facilities once every five years, with respect to public health and safety; the environment; and, where applicable, the security of the natural gas supply (Government of South Australia, 2012).

In Western Australia, the injection and permanent storage of GHG in underground geological formations is currently not regulated, with the exception of the Gorgon Gas Project via the *Barrow Island Act 2003.* Amendment to the State's *Petroleum and Geothermal Energy Resources Act,* that would permit onshore transport and storage of GHGs, is proceeding through the legislature (State Government of Western Australia, 2013; McCoy, 2014).

3.3 United States

In the United States, the Environmental Protection Agency's (EPA) *Underground Injection Control (UIC) Class VI Program for Carbon Dioxide Geologic Sequestration Wells* was approved in 2011 (USEPA, 2011a). The overall purpose of the UIC is to protect drinking water supplies, and addition of the Class VI Program was deemed necessary in order to address the relative buoyancy of CO_2, its mobility in the subsurface, its corrosivity in the presence of water, and the large injection volumes anticipated at CCS projects. There are no mandatory requirements for RA/RM. To date, detailed voluntary risk guidance has been published for well plan development and construction, well testing and monitoring, and area review evaluation and corrective action (USEPA, 2011b, 2011c, 2012a, 2012b, 2013a). Draft guidance on program transitioning from a Class II to Class VI well is also published (USEPA, 2013b). As part of Class VI permitting, RM may require an operator to submit site-specific project plans to address produced water use and disposal, closure, post-injection monitoring, mitigation, and remediation. States may apply for primacy enforcement responsibility.

A linkage exists between the UIC Class VI Program and US EPA Clean Power Plan *Rule for* CO_2 *emissions for existing fossil fuel-fired electricity plants* (USEPA, 2015). Although the rule does not involve regulation of any downstream recipients of captured CO_2, this must be transported to a storage site that complies with reporting obligations under the EPA's GHG Reporting Rule, Subpart RR. This requires storage site owners or operators to submit a monitoring, reporting, and verification plan to the EPA for review and approval (Dixon et al., 2015, GCCSI, 2014).

Three examples of CCS regulatory frameworks in US States, with particular focus on risk, are included here. Under the Kansas *Carbon Dioxide Reduction Act*, the State Corporation Commission adopted rules and regulations establishing requirements, procedures, and standards for the safe and secure injection of CO_2 and maintenance of underground storage of CO_2 in terms of both public health and safety or usable water (Kansas State Corporation Commission, 2010). The Mississippi *Geologic Sequestration of Carbon Dioxide Act* (State of Mississippi, 2011) established a regulatory framework that gives the Department of Environmental Quality and the State Oil and Gas Board the authority to regulate the storage of CO_2. Approval of reservoir storage requires, among other findings, that “there is no reasonable risk that the use of the reservoir for the storage of CO_2 will injure or endanger other formations containing fresh water, oil, gas or other commercial mineral deposits; … and that there is no reasonable risk that the proposed storage will endanger human lives or cause a hazardous condition to property”. This points to the USEPA Class VI Program regarding wells, although there is no RA/RM elaboration. Lastly, in North Dakota (State of North Dakota, 2009), Senate Bill 2095 relates to the geologic storage of CO_2 and gives authority to the North Dakota Industrial Commission over the construction, operation, and closure of a CO_2 storage facility. The law sets out the permitting requirements, criteria, fees, and process, as well as penalties for non-compliance. There is no RA/RM elaboration, except for a requirement for monitoring, and no guidance or regulations appear to have been developed. North Dakota was the first State to apply to the USEPA for Class VI primacy enforcement responsibility (McCoy, 2014) and no Class VI primacy applications have been approved (EPA, 2016).

4 Comparative analysis of RA/RM regulatory provisions in selected jurisdictions

There have been many significant contributions to understanding the regulatory context for CCS, as published by international government agencies, NGOs, and other researchers. Foremost among these are the International Energy Agency (IEA), IEA Greenhouse Gas R & D Programme (IEAGHG), Global Carbon Capture Storage Institute (GCCSI), the CO_2 Capture

Project (CCP), and previous work by University College London – Carbon Capture Legal Programme, now housed by GCCSI. For instance, the IEA established an annual legal and regulatory review in order to support development of CCS projects worldwide (IEA, 2010c; IEA, 2011; McCoy, 2014). Rather than being limited to report-based annual updates, the regulatory context for CCS in active jurisdictions was recently made available online through the CCS Law and Regulations Database (IEA, 2014). A user may search by jurisdiction or by issue; for example, CCS legislation is cross-listed with provisions regarding regulatory scope and definitions, land rights, exploration and injection permitting (including provision for environmental protection and impact assessment), operations and closing, and management of long-term responsibilities and liabilities. However, a quick review finds that not all relevant legislation is captured on the website, underscoring how challenging it is to understand the regulatory framework that really does apply to CCS in individual jurisdictions. For instance, in the case of Alberta, only two instruments are included: the *Mines and Minerals Act* and Carbon Sequestration Tenure Regulation, leaving the impression that a number of listed issues are not addressed by the province's regulatory framework. For Saskatchewan, only the *Oil and Gas Conservation Act* is included, whereas this update identifies the primacy of the *Environmental Assessment Act* as the screening tool for risk assessment and risk management, as described above.

Appendix B (Supplementary Material, Chapter 2) provides a comparative analysis of CCS regulatory provisions in the jurisdictions discussed here, particularly with respect to RA/RM mandatory requirements or voluntary activities. The level of practical elaboration on RA/RM frameworks is also shown. In general, specifications vary across global regions and mandatory requirements are elaborated less frequently than voluntary guidance. This is likely because government may require RA/RM broadly within legislation or regulation, but the proponent's or regulator's use of descriptive associated guidance is discretionary. The most comprehensive set of elaborated regulatory directives for CCS in a trans-national context is the storage collection promulgated by the European Union, with associated guidance developed by the European Commission. The 2011 UNFCCC inclusion of CCS as a clean development mechanism (UNFCCC, 2011) also includes mandatory and comprehensive RA/RM requirements for capture, transport, storage, and post-injection phases, with few notable gaps. Indeed, various UNFCCC representatives and observers believed that this framework will go beyond requirements for CDM and become the new standard for domestic or other international projects as well (IEA, 2012).

Overall, RA/RM in North America has been less prescribed than in Europe-based regional and international jurisdictions. For example, in contrast to the UNFCCC (2011) mandatory elaborated requirements, amendment to the *Alberta Energy Resources Conservation Act* and *Mines and Minerals Act* to facilitate CCS (also approved in 2011) did not include reference or guidance on RA/RM, except for a required Measurement, Monitoring, and Verification (MMV) Plan, but without elaboration (Alberta, 2010b). Similarly, the US EPA Underground Injection Control (UIC) Class VI Well Program does not include any RA/RM regulatory requirements (USEPA, 2011a). USEPA voluntary guidance is, however, extensive.

Given currently established constitutional powers, Canadian, Australian, and United States' regulatory frameworks for CCS are developed at both national and sub-national levels (provinces and states). In Canada, while provincial and federal governments may substitute environmental assessment processes under CEAA2012, oil and gas resource regulatory authority is solely a provincial matter. In Australia, State governments are mostly enacting parallel legislation to the Commonwealth lead. However, while all jurisdictions in Australia have a well-developed regulatory framework in place, there is a paucity of projects underway (McCoy, 2014). In the US, the key UIC Class VI Well Program is a federal rule, but States may apply for primacy enforcement responsibility.

This update also finds that specific triggers and activities determine the laws, regulations, and guidance that apply to each of the capture, transport, injection, EOR, or storage chain component activities. Newer additions to regulatory frameworks focus on injection and storage, while existing environmental assessment provisions are applied to capture and transport phase activities. Furthermore, risk assessment for human health is specified less often than environmental effects. In terms of risk management, the primary mandatory requirement is limited to monitoring. To date, only the Australian State of Victoria and Canadian province of Saskatchewan do not accept long term liability for carbon storage.

While RA/RM considerations such as uncertainty, stakeholder communication and consultation, and the goal of transparency are discussed sparsely in the regulatory context, both the BC and Alberta regulatory review processes in Canada identified transparency as an important goal. The latter issue is reported separately in this issue's paper, *Risk communication and public engagement in CCS projects: The foundations of public acceptability* (Leiss & Larkin, *accepted*). With respect to First Nations in particular in Canada, a 2014 Supreme Court of Canada ruling found that while economic development can still proceed on aboriginal land where title is established, this requires that the development has the consent of the First Nation and, failing that, that the government must make the case that development is pressing and substantial, and that it has met its fiduciary duty to the aboriginal group (Supreme Court of Canada, 2014).

For a review of the practical application of RA/RM in the approval process of four large projects in Canada, see this issue's paper, *The Evolution of Regulatory Practice for CCS Projects in Canada*. Going forward with respect to RA/RM and other issues, the effects of regulatory developments such as CEAA2012, as well as the recommendations from Alberta's CCS Regulatory Framework Assessment (Alberta Energy) and British Columbia's CCS Regulatory Policy Framework (BCNDG, 2014), are yet to be determined.

5 Conclusion

Regulatory initiatives continue to be deemed of utmost importance to the widespread planning and safe development of CCS projects worldwide. This paper provides an update on provisions that enable or apply to CCS projects in Canada and selected international jurisdictions, with an emphasis on requirements for risk assessment and risk management. These include the Canadian federal environmental assessment process, and the regulatory framework for the provinces of British Columbia, Alberta, and Saskatchewan. Internationally, RA/RM within the London Convention, the OSPAR Convention, the EU CCS Directive, and the UNFCCC Clean Development Mechanism are discussed as well as provisions for national and state governments in Australia and the United States. A comparative global analysis of RA/RM is also provided.

As suggested by the IEA (2010) and the review of the EC's CCS Directive (EC, 2014a), projects will continue to be approved through a combination of existing, amended, and new laws and regulations aimed at specific components of the CCS value chain. Results find wide variation in the mandatory and voluntary requirements for RA/RM across jurisdictions, with the most complete set of elaborated directives issued by the European Commission in support of the EU CCS Directive. Mandatory RA/RM in the UNFCCC CDM is also well described and comprehensive regulatory framework assessment and implementation is underway in the provinces of British Columbia and Alberta, Canada.

Indeed, the international climate change policy dialogue consistently acknowledges the important future mitigating role of CCS in emissions reductions (GCCSI, 2016; IEA, 2015; IPCC, 2014; UNFCCC, 2011). This review indicates that progress has been made in developing the regulatory context for CCS projects in regional and national governments over the past ten years. However, as suggested by global actors and discussed in this issue by Leiss and Krewski (submitted), *Environmental Scan and Issues Awareness: Risk Management Challenges for CCS*, this dialogue and activity has not yet translated into significant national progress on project implementation. A robust risk assessment and risk management regulatory framework will be increasingly important if the estimated and necessary 3,000 CCS schemes come to fruition, such that this technology makes the contribution to climate change mitigation that has been anticipated since its inception (Canadian Capture and Storage Association, 2012; IEA, 2015).

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Chapter 3: Evolution of Regulatory Practice for CCS Projects in Canada

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Abstract

Carbon capture and storage (CCS) pilot and demonstration projects began in Canada in the 1990s. This review of publicly available documentation considers the regulatory application and approval practice for four large Canadian projects that are either under construction or in operation. Results find that oversight of CCS projects is value chain specific and obtaining documentation can be challenging. However, technical risk assessment supporting approvals is moving forward, with an increasing range of chain component health and environmental risks being assessed using referenced approaches. Monitoring remains the primary risk management approach. Global risk estimation is not completed and unresolved issues about transparency in risk communication could have the potential to negatively impact broad public acceptance of CCS, and therefore project viability in the long run.

Keywords

Carbon capture and storage; regulatory practice; Canada; risk assessment; risk management; risk communication; Canadian Environmental Assessment Act; Saskatchewan Environmental Assessment Act; Alberta Energy Regulator

1 Introduction

Carbon capture and storage (CCS) pilot and demonstration projects began in Canada in the 1990s and substantial geological storage potential has been identified for this climate change mitigation technology (Natural Resources Canada [NRCan] et al., 2012). Today, four large scale integrated projects[4] (LSIP) are under construction or in operation. Three are principally carbon capture utilisation and storage (enhanced oil recovery (EOR)) project types: Saskatchewan's Weyburn-Midale Enhanced Oil Recovery (EOR) Operations and Boundary Dam Integrated CCS Demonstration Project, and the Alberta Carbon Trunk Line. Alberta's Quest Carbon Capture and Storage Project is a saline aquifer geological sequestration project type.

To investigate the evolution of regulatory practice in Canada, publicly available project applications, third party submissions, review, and approval documents are described, with emphasis on the regulatory process and considerations in risk assessment, risk management, and risk communication. Unstructured key informant interviews provided additional clarification. Analysis finds similarities and differences between provincial jurisdictions and project types, and identifies progress over a fifteen year study period. Potential obstacles to widespread implementation of CCS are also discussed.

Regulatory frameworks for CCS in Canada and selected international jurisdictions are described fully in *Regulating the Risks of Carbon Capture and Storage: A Global Perspective* (Larkin et al., submitted-a), particularly with respect to requirements for risk assessment and risk management (RA/RM) in acts or regulations that enable geologic sequestration. Differences exist in the mandatory and voluntary provisions that enable CCS, where mandatory requirements are not often elaborated and the use of guidance documents is discretionary. As well, RA/RM is less prescribed in North America than in European-based regional or international jurisdictions. In Canada, both CCS-EOR and saline sequestration project types are approved under oil and gas

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[4] LSIPs are defined as projects involving the capture, transport, and storage of CO_2 at a scale of at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO_2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014b)

related legislation, regulations, and directives that are in effect within the provincial jurisdiction. Three of the projects reviewed here were also subject to a screening process under the *Canadian Environmental Assessment Act.*

The analysis of regulatory frameworks (Larkin et al., submitted-a) and the present consideration of the evolution of regulatory practice applied to Canadian projects were used to inform the *Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context* in this issue (Larkin et al., submitted-b).

2 Regulatory review of four large Canadian CCS Projects

2.1 Weyburn-Midale Enhanced Oil Recovery (EOR) Operations, Saskatchewan

The Weyburn-Midale Enhanced Oil Recovery (EOR) Operations began in 2000 and is expected to continue through 2030. The Souris Valley Pipeline transports carbon dioxide (CO_2) from the Great Plains synfuels coal gasification plant in North Dakota to CO_2 miscible floods, operated by Cenovus Energy in Weyburn and Apache Corporation in Midale, Saskatchewan. Since inception, more than 17 Mt of CO_2 have been stored in conjunction with EOR at Weyburn; at the end of operations, this site is projected to store 30-40 Mt CO_2 (International Energy Agency Greenhouse Gas R & D Programme [IEAGHG], 2006; Petroleum Technology Research Centre, 2016). The infrastructure may then be used exclusively for CO_2 sequestration, providing an additional 25 Mt capacity (Cenovus Energy http://www.cenovus.com/operations/oil/weyburn.html). Over 2 Mt of CO_2 has been stored in conjunction with EOR at Midale and more than 10 Mt are expected to be stored over the 30-year life of the project.

The 260 km international transport pipeline from the Canada/US border to the Weyburn field was subject to screening under the *Canadian Environmental Assessment Act* (CEAA), as administered by the National Energy Board (NEB). The scope of the project was restricted to the 'applied-for facility', comprised of the pipeline, but excluding the miscible flood project. To facilitate public awareness prior to making the decision, the Board required the Proponent to publish notices in two national and seven regional newspapers. Only one letter, from Environment Canada, was received. Following the deadline, a second organization filed a letter arguing that the miscible flood project ought to have been included in the environmental assessment (EA); however, the Board did not find a reason to expand the scope of the review (NEB, 1998).

The CEAA review considered the estimated potential consequences of accidental airborne releases of CO_2 and hydrogen sulphide (H_2S) due to pipeline leaks or ruptures, and quantified the potential probability of impacts at receptor points along the route. The results determined the level of protection required for human health and safety such that these would be incorporated into the Emergency Response Plan (ERP). The NEB accepted Souris' recommendation that the Emergency Planning Zone (EPZ) within the ERP be based on an exposure threshold concentration of 100ppm H_2S, as was then determined as the concentration *Immediately Dangerous to Life or Health* (IDLH) (NEB, 1998). The EPZ then comprised the area within 1.5 km of the pipeline alignment. Proposed risk management of malfunctions and accidents included preparation of a draft ERP which discussed pre-emergency planning and education, operational safety precautions, emergency response procedures and agency coordination (NEB, 1998). CO_2 stream composition was also assessed in order to lower risks of contamination from residual substances if there was leakage into potable groundwater. The normal composition of the pipeline gas mixture was described as 97 percent CO_2 and 0.8 % H_2S, with not more than 2 % by volume of nitrogen or methane (NEB, 1998). The NEB public hearing addressed the adequacy of the public consultation process; the potential environmental and socio-economic effects of the proposed project; and the safety of the design and operation of the proposed facilities.

A second NEB CEAA application was in made in 2005 for a custody transfer and metering station needed to supply CO_2 from the Weyburn facilities to the Midale pipeline. This was subject to a public notification and consultation program commensurate with the scale and nature of the Project (NEB, 2005); the scope of this screening was limited to impacts associated with the station and not with the Midale pipeline as a whole (NEB, 2005). The sole affected landowner was the only person engaged in the process as it was deemed unnecessary to conduct further notification to the next nearest residence located over 2.8km from the project site. The Proponent also notified the Administrator of the Rural Municipality.

Both NEB screenings concluded that surface impacts on the environment were not significant and approval certificate conditions addressed environmental and general safety mitigation measures for pipeline design, pre-construction, construction, and post construction (operational) periods (NEB, 1998; 2005). Specifics included mitigation of topsoil erosion or compaction; a maximum 2.0 mole percent H_2S in the product stream; maximum moisture concentration entering the pipeline; pipeline inspection at the time of construction (but without a monitoring or follow-up program); performance data for the leak detection system prior to commencement of construction; criteria for the Emergency Protection Zone; and ongoing examination of the Emergency Response Plan as part of ongoing safety auditing function.

At the provincial level, several applications were made under the Saskatchewan *Environmental Assessment Act* (EAA): the 1984 Midale CO_2 Flood Pilot Project, the 1991 Midale field scale demonstration project, and the 2005 Midale EOR project and associated pipeline (IEAGHG, 2010). The single Weyburn EAA application in 1997 was for the 260km pipeline, compressors, flow lines, injection wells and other project infrastructure. In each case, the EAA concluded that environmental impacts were not significant and that the projects did not constitute a 'development' under the EAA. Applications were approved by clearance letter. The decisions also found that existing regulatory licensing requirements were sufficient to ensure that all components of these projects would be appropriately implemented (IEAGHG, 2010).

Details in the licensing application under the Saskatchewan *Oil and Gas Conservation Act* (OGCA) regulations in force at the time included the geological characteristics of the area; injection summaries of various research experiments and simulations; information on new and upgraded facilities; project monitoring and data collection; well location; construction and design (1997 only); internal and external corrosion protection plans; project schedule and expectations; emergency response plan (1991 only); and predicted costs (1997 only). These provided the basis for an analysis of projected recovery rates and behaviour of injected CO_2. No specific OGCA requirements were established for injection, potential for leakage and storage activities.

Midale 1991 and Weyburn 1997 approvals required operation of the project in accordance with the plans filed with the Ministry; approval of a field representative of the ministry prior to commencement of CO_2 injection and subsequent to any modifications to such installations; and annual progress reports. The Midale 2005 approval included additional conditions: to operate the project to minimize the possibility of negative impact on adjacent non-unit producing properties; to measure solution gas composition in production wells monthly and inject tracer to determine reservoir flow characteristics prior to CO_2 injection; to provide appropriate impact mitigation to adjacent units if required; and to undertake specific measures at identified wells, although details of this requirement are not documented. While the OGCA licensing approval applied to injection and EOR activities, there was no regulatory provision at the time for “waste” disposal (storage) and none was envisioned for EOR operations at inception (IEAGHG, 2010).

Additional provincial regulatory approval for the Weyburn and Midale projects included *Pipeline Act* regulations, shoreline permits, occupational health and safety regulations, waste handling, litter control, and *Clean Air Act* and Regulations (IEAGHG, 2010).

2.2 Boundary Dam Integrated CCS Demonstration Project, Saskatchewan

The Boundary Dam Integrated Carbon Capture and Storage Demonstration Project (BD) has been described as the first and largest integrated carbon capture demonstration project in the world (Saskatchewan Ministry of Environment [SaskMOE], 2013b). The goals of the project are to extend the operating life of the SaskPower coal-fired electricity plant unit by 30 years, increase efficiency, reduce SOx and NOx emissions, and capture approximately 1 Mt CO_2 per year. The key project operators are SaskPower for the capture facility at their Boundary Dam generating station and Cenovus Energy, the proponent for the transport pipeline (from SaskPower property line) to the injection/EOR operations, at the Weyburn field. Some CO_2 is also provided to the Aquistore research and saline sequestration monitoring project which is not discussed in detail here because it does not meet the definition of an LSIP with respect to the storage operations. Capture is expected to account for roughly two-thirds of the power project's estimated $1.24 billion cost. Although there was federal funding for this project ($240M), a CEAA screening trigger did not apply because the contribution was set up as a trust fund in the 2008 federal budget, for discretionary use by the Government of Saskatchewan for carbon capture and storage initiatives.

SaskPower submitted a capture project description for provincial EAA screening in 2009 (Government of Saskatchewan, 2002; SaskPower, 2009). Potential capture technologies were described at a high level and the application listed considerations that would be included in an Environmental Impact Statement (EIS), if one was to be required: a biophysical overview of the study region; a description of the socioeconomic environment; air dispersion modelling; noise assessment; hydrology; a public consultation program; as well as any other required studies. SaskPower noted that these studies would be undertaken if the Project was not deemed a development under the EAA because this data collection would be required for other regulatory approvals. Ancillary activities that would not be included in the assessment were listed as the CO_2 Pipeline, EOR operations, and water usage (because they represent separate developments, and may have other environmental approvals in place or anticipated). The application noted that decommissioning and site reclamation applications would occur at a later date.

BD project was not deemed a ‘development’ under the EAA and did not require an environmental impact assessment (EIA) (SaskMoE, 2009). The capture component received clearance based on the description and the environmental protection commitments of the project (SaskPower, 2009), subject to the clarifications and restrictions suggested by other Ministries as listed in the clearance letter (SaskMoE, 2009), including:

- Saskatchewan Watershed Authority support for proposed hydrology study and Industrial Branch of Ministry of Environment support for proposed air dispersion modelling (the Branch anticipated changes in ambient air quality with the three different technologies, partly as a result of lower stack height);
- Workplace Safety Unit regarding regulations to ensure safe use of chemicals and requirement that air concentration be kept below listed standards, particularly sulphur dioxide; and
- Mining and Engineering Services Branches of Ministry of Energy and Resources, regarding approvals for EOR, pipeline licensing, and field operations.

Subsequently, SaskPower completed an internal assessment of the three potential capture technologies and chose Cansolv Technologies’ proprietary amine based SO_2/CO_2 post combustion capture technology. An amended EAA application was submitted in 2013 (SaskPower, 2013), providing updated information for air emissions; CO_2 storage through Aquistore sequestration research project (SaskMoE 2014a; 2014b); deep waste water disposal well storage; and operation of a sulphuric acid producing plant generated through carbon capture activities. The latter three activities, as well as coal mining, ash lagoon operations, transport pipeline, EOR facilities and operations, and others, were discussed as ancillary developments requiring separate permitting.

The amendment included a brief biophysical and socio-economic overview of the local and regional environment, and focused on air dispersion modelling concentrations for criteria air contaminants (SO_2, NOx, CO, TSP, PM_{10} and $PM_{2.5}$, Hg and Cd) and effects of the amine-based technology (SaskPower, 2013). A decrease in ground level concentrations compared with the base case for these air contaminants was expected under several alternative operating scenarios, although predicted $S0_2$ concentrations were greater than applicable Saskatchewan standards in all but one scenario.

The Material Safety Data Sheets for the amine-based technology were also included in the application. In the absence of CCS process nitrosamine-specific data, N-nitrosodimethylamine (NDMA) was deemed a suitable surrogate for human health exposure and toxicity assessment based on an international review of the nitrosamine guidelines (SaskPower, 2013). Maximum amine and nitrosamine ground level concentrations were evaluated for eighteen vent dispersion scenarios. With anticipated emissions of 8 t/year and 10 kg/year, respectively, assuming a 90% capacity factor, negligible ground level impacts were anticipated, relative to Ministry of Environment approved guidelines of 5 ug/m^3 amine and 0.3 ng/m^3 nitrosamine. Indoor ventilation conditions were also assessed.

The amendment also included an assessment of an added water demand at Boundary Dam. Results found continued ability of the Rafferty Reservoir to supply users, including BD, the City of Estevan, and future development at SaskPower's Shand Generating Station.

With respect to risk management, SaskPower committed to complete a regional baseline and post monitoring results for amines and degraded products in air, water, and soil online. The application noted use of best management practices to avoid or mitigate minor impacts, particularly for water management at the Reservoirs. A short description of impacts and expected frequency of abnormal operating scenarios was presented in tabular format. These included stack emissions at start-up and shutdown; capture reduction to the federal regulatory target should electricity generation prove more advantageous than CO_2 sales (requiring only 60% rather than 90% capture rate); loss of CO_2 capture associated equipment (where it would be possible to run full SO_2 capture but without CO_2 capture); loss of SO_2 capture associated equipment (requiring shutdown with diversion of SO_2 contamination in order to protect CO_2 system); loss of acid plant (SO_2 emissions would return to current levels for duration of scenario); and reduced demand for the CO_2 product (off-taker demand to be managed through contractual agreements). The frequency of fluctuations in stack emissions was expected to be rare once operating stability is obtained.

Throughout the planning and development period, joint communications activities to engage and inform key audiences about all components of the project, including the CO_2 injection test well, were undertaken by SaskPower in conjunction with Petroleum Technology Research Centre (PTRC) and it's Aquistore sequestration research project (SaskMoE, 2014b). Several organizations formed the Aquistore Communications Steering Committee in 2011, including SaskPower, the PTRC, Enbridge Inc., SaskEnergy, SaskMoE, Schlumberger Carbon Services (SaskPower's consultant) and Consumers Co-operative Refinery Limited (CCRL) (SaskMoE, 2014b). Engagement efforts included kitchen table discussions with area landowners, public open houses, site tours, and media communications. An open house and grand opening of the capture plant occurred in 2014. The amended project application noted that the majority of comments received from directly affected stakeholders and others were favourable and supportive, that the information provided addressed relevant issues and concerns, and that no significant environmental impacts or concerns were identified from the public consultation process (SaskPower, 2013).

Based on the evaluation of the amended application against EAA project determination criteria, the global project was not deemed a development requiring an EIA. The clearance letter included terms and conditions under which the project could be undertaken, and specified that environmental protection measures be implemented in the manner described in application, and that the project comply with other federal, provincial and municipal regulatory requirements, and other administrative details (SaskMoE, 2013a). The reasons for this determination noted that the project would result in a net benefit to the environment (SaskMoE, 2013b). The project phase components would be subject to other regulatory requirements (pollutant emissions, transport and EOR chain component applications through the appropriate branches of the Ministry of Economy), the protection measures in the proposal, and the stipulations in the determination letter (SaskMoE, 2013b).

The Cenovus Energy pipeline has been licensed (Government of Saskatchewan, 2011) and the CO_2 will be used at the existing Weyburn EOR operations described above. The pipeline and injection scheme for the Aquistore sequestration research well have also been approved (SaskMoE 2014a; 2014b).

2.3 Alberta Carbon Trunk Line, Alberta

The Alberta Carbon Trunk Line (ACTL) is a 240 km high vapour pressure (HVP) pipeline and connectors project of Enhance Energy Inc. Initially, approximately 585,000 t/yr CO_2 will be captured from the Agrium Inc. Fertilizer Complex and 1.2 Mt/yr CO_2 from Phase 1 the North West Redwater Partnership's (NWRP) oilsands upgrader project, both located in Alberta's Industrial Heartland region. EOR injection is planned near Clive, Alberta by Fairborne Energy Ltd. The NWRP project has the potential to scale up to 3.6 Mt/yr CO_2 through later phases of development and the pipeline capacity is 40,000 t/d or 14.6 Mt/yr.

The Agrium and NWRP capture projects required notification of a change in process under the Alberta *Environmental Protection and Enhancement Act* (EPEA) (Government of Alberta, 2010), administered by the Ministry of Environment and Sustainable Resource Development (ESRD), without additional regulatory applications. This is because pure stream CO_2 will be dehydrated and compressed to ACTL specifications. Both plants will be operating as an improvement to emissions (Alberta Energy Utilities Board, 2007; Alberta Ministry of Environment, 2006). NWRP gasification operations will also minimize water and natural gas resource use, and reduce sulphur and trace metals emissions associated with conventional upgraders.

ACTL required a screening assessment under CEAA as a result of a potential federal funding contribution by NRCan. The EIS considered all of the physical works and activities required to construct, operate and decommission both the ACTL and the Clive/Bashaw injection and storage scheme (NRCan, 2012). The latter included up to twenty CO_2 EOR injection wells and 100 oil wells (converted and new). Valued ecosystem components (VECs) and the risk of potential residual adverse environmental effects from the pipeline were assessed qualitatively, based on criteria for magnitude, frequency, duration, geographic extent, and reversibility. Potential impacts included atmospheric and acoustic environments; soils, terrain and land use; vegetation and wetlands; wildlife; fisheries; historical resources; and social and economic issues. Other EIS sections considered accidents and malfunctions; effects of the environment on the project; environmental protection plan; and public and First Nations consultation.

Construction and operations activities for injection and EOR were assessed, including the integrity of existing and abandoned wells (the former with regard to their suitability for conversion to CO_2 service); drilling and completion of CO_2 injection and oil production wells; construction of CO_2 distribution and oil production flow lines; compression to recycle CO_2; monitoring mass distribution and migration of CO_2 in the reservoir; ongoing simulation and history matching, comparing actual project performance to modelling predictions; and ongoing updating of risk mitigation strategies and the Emergency Response Plan (ERP). However, no final engineering designs for injection and EOR were available at the time of the screening.

NRCan required a 30-day comment period based on the magnitude of the project, the fact that it is a first-in-kind project, and that it may be linked with additional CO_2 sources and injection sites in the future. Enhance Energy received requests for the draft screening report from ten individuals, and later provided copies of the final screening report.

Federal departments requested clarifications and provided comments based on their area of expertise (Canadian Environmental Assessment Agency, 2014). Health Canada initially responded with an inability to provide expert review due to the qualitative nature of the information, especially regarding air quality, noise, and human health effects. The Proponent stated that as there would be no new significant sources of continuous air emissions, there was very little potential for the Project to result in adverse effects on human health. NRCan commented that the level of detail for the injection and storage facility should have been as specific as that provided for the pipeline routing. The Proponent initially responded that this was proprietary information, but later invited government representatives to view information on this aspect of the project at their office. The Proponent also later provided a table summarizing the challenge, risk and mitigation strategy for CO_2 containment; CO_2 injection wells; CO_2 injection flowlines; drilling and completions (NRCan, 2012). No further assessment detail was provided. NRCan requested more detail on the Monitoring, Measurement and Verification (MMV) Plan, but this had not been completed at the time of the screening process. The Proponent noted that once plans were confirmed and negotiations were completed with the potential service providers, the company would make the MMV plan available to the public.

The CEAA screening decision found that the project was not likely to cause significant adverse environmental effects after mitigation measures for the pipeline, injection, and storage facilities normally implemented through Alberta’s Energy Resources and Conservation Board (ERCB) Directives (now Alberta Energy Regulator). Nevertheless, comments were provided with respect to the pipeline, release from injection and storage facilities, and accidents and malfunctions during construction, operations, and decommissioning (NRCan, 2012). For instance, it was suggested that the potential environmental effects of either a sudden release or a slow leak of CO_2 on soils, surface water, groundwater, air, and other environmental receptors would be negligible because of the relatively inert nature of the CO_2 being transported in the pipeline; however, CO_2 was considered a safety hazard for workers or public in vicinity of the pipeline (NRCan, 2012). CO_2 leakage from the storage reservoir was discussed for the decommissioning (post-closure) phase: the rate of leakage and total amount of CO_2 released from the reservoir would likely be a small fraction of the CO_2 stored, and effects would therefore likely be negligible.

Provincially, ACTL pipeline was also subject to the EPEA (Government of Alberta, 2010) with respect to a conservation and reclamation plan for soil, waste and water management practices and water crossings during the construction and reclamation periods (ESRD, 2013).

Lastly, ACTL and EOR activities were subject to ERCB Directives and regulations. More information is available with respect to land based than injection/EOR activities. Based on an expected pipeline flow rate of 15,000 t/day (the pipeline design is up to 40,000 t/day), a preliminary hazard assessment for CO_2 and co-materials (hydrogen (flammable) and carbon monoxide (toxic)), using dispersion modelling software in combination with ERCB Directive 71 guidance (for H_2S and HVP liquids), determined a 700 m Emergency Protection Zone (EPZ) adjacent to pipeline alignment. The study considered the release rate, meteorological conditions, concentration of concern (hazard endpoint, using National Institute for Occupational Safety and Health (NIOSH) for Immediate Danger to Life and Health (IDLH) (40,000ppm)) and release conditions. The Initial Isolation Zone was set at 20% of the EPZ and rounded to a distance of 200 m. The Emergency Awareness Zone was set at 150% of the EPZ and rounded up to 1,100 m. An H_2S concentration of 100ppm was cited in the report, but did not appear to be included in the determination of the ERP Zone. This assessment was provided by the Proponent as part of the ERCB application (Enhance Energy, 2012) and was not included with the reports and correspondence available as part of the CEAA screening (NRCan, 2012). It is unknown if this was an oversight.

The Directives also required the Proponent to provide a Project Information Package to landowners and occupants in the defined EPZ and to develop a site-specific ERP with affected stakeholders.

With respect to risk management, the pipeline portion of the ACTL project would be built to meet existing standards. The pipeline integrity program includes corrosion mitigation and monitoring, leak detection, and ERP. The Proponent engaged another firm to provide integrated solutions for work place quality, health, safety and environmental management programs, including emergency response, integrity management, and health and safety issues on a best practices basis.

The ERCB approved the application in 2011. There were no scheduled hearings because preliminary objections to the project were resolved. The Board determined the project was in the public interest. ESRD approval for the pipeline conservation plan was obtained in 2013 (ESRD, 2013).

2.4 Quest Carbon Capture and Storage Project, Alberta

Quest Carbon Capture and Storage Project (Quest) is the first large scale integrated CO_2 sequestration project in Canada. It is a joint venture between Shell Canada Energy (60%), Chevron Canada (20%) and Marathon Oil Canada Corporation (20%), the three companies who together formed the Athabasca Oil Sands Project. Quest value chain components include up to 1.2 Mt/yr CO_2 capture at Shell's Scotford bitumen upgrader using activated amine process; approximately 80 km transport pipeline and connectors; injection infrastructure at 3-8 well pads; deep saline sequestration in Basal Cambrian Sands (BCS) geological formation, approximately 2 km below surface; and a measurement, monitoring and verification (MMV) program (Shell, 2010a; 2010b; 2010c; 2010d; 2010e). Cumulative stored volumes could exceed 27 Mt CO_2 over the life of the project (greater than 25 years) (Shell, 2010a) with a 35% capture rate (MIT, n.d.) and overall reduction in CO_2 annual emissions of 15% relative to the existing upgrader (Shell, 2010b). The project is expected to cost $1.35B, with partial financing from the Alberta government ($745 million over 15 years) and federal Clean Energy Fund ($120 million) (Shell, 2010a).

Multiple acts, regulations, and directives applied to the review and approval of Quest (Table 3.1).

Table 3.1: Shell Quest regulatory framework[1]

Regulator	Regulatory Application - Chain Component			
	Capture	Transport	Injection	Storage
Agreement for Environmental Assessment Cooperation Alberta Environment – *Environmental Protection and Enhancement Act* Natural Resources Canada/Canadian Transportation Agency – *Canadian Environmental Assessment Act*	3 amine absorber towers, amine regeneration unit, multistage CO_2 compressor with coolers and separators, and a triethylene glycol dehydration unit; To increase nitrogen oxide limits from hydrogen manufacturing units (HMUs).	80 km steel pipeline from upgrader to proposed injection wells, including Conservation and Reclamation Plan	Environmental Impact Assessment Report for injection wells and storage	
Alberta Energy Resources Conservation Board [Now Alberta Energy Regulator]	To amend approval Section 13, *Oil Sands Conservation Act*	Part 4, *Pipeline Act* Directive 056: Energy Application for construction and operation of the pipeline	Directive 056 for well development Directive 051 for injection	Section 39, *Oil and Gas Conservation Act* Directive 065: Resource Application for Oil and Gas Reservoirs

[1] For details about the legislation, regulations and directives, see Larkin et al. (2014), *Regulating the Risks of Carbon Capture and Storage: A Global Perspective*.

Chain components were subject to CEAA screening (because of federal funds) and the EPEA, applied jointly under the federal/provincial agreement for environmental assessment cooperation. Furthermore, the EIA, together with requirements under Acts and Directives of the ERCB, formed the complete application to the ERCB, including: project description, impact assessments, measurement, monitoring and verification (MMV) plan and details about stakeholder consultations, among other sections. Throughout the 20 month review and approval process, subsequent documentation provided updates, amendments, errata, supplementary information requests (SIRs) by regulators, intervener submissions, and responses to these, totalling approximately 4,000 pages within 400 documents. Many documents remain posted on Shell Canada's website (http://www.shell.ca/en/aboutshell/our-business-tpkg/upstream/oil-sands/quest/about-quest.html) or can be obtained through Alberta Energy Knowledge Sharing website (http://www.energy.alberta.ca/CCS/3848.asp) or from Alberta Energy Regulator.

The EIA focused on the project's Area of Interest (AOI) – namely the sections of land for which a tenure lease agreement had been reached under Alberta's Carbon Sequestration Tenure Regulation (Government of Alberta, 2011). Within the AOI delineation, six risk issues were assessed: air quality, public health and safety, emergency response planning (transport and injection pads), injection well integrity, acid gas storage scheme, and accidents, malfunctions and unplanned events. Table 3.2 identifies the methodology, risks assessed, and proponent's conclusions for the human and environmental health issues considered (Shell, 2010d). Review of this material produced the following observations.

- Qualitative, semi-quantitative and quantitative risk assessment methodologies were used, often with a multi-step risk assessment (RA) approach.
- CO_2 was initially excluded from the air quality RA at the capture facility.
- Quantitative RA for the Pipeline and Injection Wells was made available later in the process, in response to a SIR.
- Although the Quest acid gas storage scheme RA is not available publicly, an Independent Panel Review (IPR) of the RA for this was made available later in the approval process in response to an SIR.
- Det Norske Veritas (now DNV GL) issued the world's first Certificate of Fitness for safe CO_2 storage to Quest.

The MMV plan (Shell, 2010e) development was ongoing throughout the approval process and continues through project development and implementation. Initial monitoring measures include three (shallow) non-saline groundwater monitoring wells for each injection well; at least three deep injection wells into the upper part of the storage complex; repeated 3-D seismic plume monitoring; and InSAR radar based technology to measure any ground deformation (ground heave).

Shell began outreach and consultation activities in 2008 (Shell, 2010a) and retained Pembina Institute's consulting arm (Pembina Corporate Consulting) to evaluate their program. Recommended enhancements were subsequently implemented. Under CEAA, NRCan required that public and aboriginal consultation activities be conducted, in part because the magnitude of the facility was considered a new technology (NRCan and Canadian Transportation Agency [CTA], 2012). No direct comments were received (NRCan and CTA, 2012). Federal authorities determined that the project was not likely to cause significant adverse environmental effects and that a ten-year follow up was required in order to verify predictions (NRCan and CTA, 2012). This will be based on the proposed MMV Plan and has been delegated to the proponent in consultation with others (NRCan and CTA, 2012).

Table 3.2: Shell Quest human health and environmental risk assessment and management

Issue	Approach[5]	Risks Assessed	Assessment Conclusion
Capture			
Air Quality	'Standard Assessment Approach' - Based on terms of reference, existing AENV Guidelines and Criteria. Consistent with other AQ assessments in region.	NOx, NOx as precursors to $PM_{2.5}$, PAI deposition, nitrogen deposition, ozone formation, regional haze	Increased NOx 3.1 t/d (1.9% in RAA) Compliant with Alberta Ambient Air Quality Objectives (AAAQO) and guidelines under normal operating conditions.
Public Health and Safety	Quantitative Human Health Risk Assessment – 4 step RA methodology endorsed by a number of regulators	Increased NOx, NOx as precursors to $PM_{2.5}$	Increased predicted concentrations of NOx and $PM_{2.5}$ are not expected to result in adverse health effects.[6]
Transport and Injection			
Emergency Response Planning (ERP)	Quantitative Risk Assessment used Published Exposure Limits, Modelling, risk acceptability based on land use - 7-step RA	CO_2 release into atmosphere in the event of accident or upset for Pipelines and Injection Wells	ERP 450m Maximum Risk of fatality within pipeline ROW calculated to be 2 chances in a million/yr[7]
Injection well	Oxand Risk Management Solutions Static and dynamic modelling for proposed Well #3	Plume migration along wellbore CO_2 mass leakage through well Well degradation	Risk-based quantification of 17 scenarios show that all scenarios have a low or very low risk score, according to Shell's risk criteria. No concern for long-term containment over 200 year period.
Storage			
Acid Gas Storage Scheme	Qualitative assessment of Site Selection and Characterization criterion (Shell2010a) From Review and Synthesis Draft Report to IEA GHG (2009)	Safety and Security of CO_2 Storage in the BCS	Shell's risk assessment is not apparently publicly available. Refers to DNV IPR.
	DNV Independent Panel Review (IPR)(Shell2011b) Based on CO_2Qualstore (DNV (2010, 2010b, 2010c))	Storage site characterization Risk and uncertainty assessment and management	The risk assessment activities have been carried out in a very comprehensive and systematic manner. Some deficiencies identified.
	DNV Independent Panel Review (IPR) (Shell2011c) Based on CO_2Qualstore DNV (2010)	Storage Development Plan	Evaluated and certified to be fit-for-purpose Includes actions to establish/ maintain confidence in 5 metrics

(Continued)

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[5] Shell documentation unless otherwise noted
[6] Regarding PM2.5, Evans (2013) shows that any increase will affect health
[7] ERCB Decision (ERCB2012)

Capture, Transport, Storage			
Accidents, Malfunctions, Unplanned Events (AMUE)	Qualitative risk assessment Combination of literature review and professional judgement. If available, quantitative analysis conducted - 4-step RA.	Effect of • Process upsets in CO_2 capture infrastructure • CO_2 pipeline rupture or injection well head failure • Release of CO_2, BCS brine or CO_2 saturated brine from the storage complex or injection wells on Valued Ecosystem Components (VEC) including Public Health and Safety, Aquatic Resources	No significant effects for all assessed VECs for each assessed AMUE.
Measurement, Monitoring and Verification (MMV)			
MMV Plan for Acid Gas Storage Scheme	Conceptual Semi-Quantitative Systematic Risk-based Approach to inform MMV Ongoing development throughout process based on ERCB Directives, CO_2 Qualstore (DNV2010)	Loss of conformance (Discrepancy between modelled and observed migration) Loss of containment (CO_2 and Brine migration)	RM in passive and active safeguards. No interaction expected between nonsaline groundwater and the Project during decommissioning and abandonment.

Under the ERCB regulatory process, consultation and notification continued through the decision making process for property owners within varying distances of the proposed activities (Shell, 2011a). As all community concerns were not settled through the ERCB's Appropriate Dispute Resolution (ADR) process, public hearings were required. Direct public participation at ERCB hearings is limited to accredited interveners based on the location of land holdings and having identified a direct and adverse potential effect. Five interveners representing three properties participated. Concerns included pipeline routing, safety and containment, injection, well water contamination, the effect of the project on future plans and property value, and compensation (ERCB, 2012).

Quest was approved with conditions (ERCB, 2012). The ERCB found the underground reservoir a suitable location for the long-term storage of CO_2, and that the combination of geological conditions, engineering design, operational practices and extensive monitoring program would mitigate any potential risks of project development (ERCB, 2012). The Decision discussed risk regarding third party industry activity in the AOI; legacy wells; long term integrity of injection wells; non-saline groundwater contamination affecting oil and gas industry activities; ground heave impacts on fracturing or increasing permeability of surface strata, potentially affecting potable water supply; loss of containment; and public safety (risk of fatality) for pipeline right of way, injection wells, and sequestration formation.

Twenty-one of the twenty-three conditions in the decision relate to monitoring activities. The Board emphasized that MMV needed to be adaptive. Shell was warned that additional requirements might be imposed as the project evolved, depending on how the plume performed

(Bankes, 2012). Bankes (2012) also notes that the MMV conditions were a result of a dialogue between Shell and the Board.

Other ERCB decision comments relate to protecting the potable water supply through completion requirements for injection wells. Furthermore, Bankes (2012) assessment of the decision found that the Board was satisfied that there was little risk of the injected substances migrating and reaching the legacy wells, and if it did that there was little risk that the induced pressure increases would lift the brine to reach protected groundwater aquifers.

3 Comparative analysis of regulatory practice

This review of publicly available documentation describes the ways in which human health and environmental hazards and risk issues were considered in the application, review, and approval of four large scale Canadian CCS projects: Saskatchewan's Weyburn-Midale Enhanced Oil Recovery (EOR) Operations and Boundary Dam Integrated CCS Demonstration Project; and Alberta's Carbon Trunk Line and Quest Carbon Capture and Storage Project. The comparative analysis first considers general aspects of regulatory oversight, including document availability, project boundaries, and range of risk issues assessed. Progress and deficiencies in risk assessment, risk management, and risk communication are then discussed.

3.1 Regulatory oversight and approach

In Canada, project development related to the oil and gas industry falls primarily within provincial jurisdiction. Regulatory oversight for the four large scale Canadian projects was therefore based on provisions contained within Alberta or Saskatchewan oil and gas- and environment-related legislation, regulations, and directives. Three projects were also assessed under the *Canadian Environmental Assessment Act* where a trigger was caused by an international pipeline development or a federal program funding contribution. Table 3.3 summarizes the provisions with respect to risk assessment and management, some of which have been updated over the period of these project approvals (Larkin et al., submitted-a).

Table 3.3: Primary regulatory oversight of Canadian projects[1]

Project and Goal	**Primary Regulatory Oversight**			
	CEAA Screening	**Alberta or Saskatchewan Provincial EIA**	**Alberta ERCB**	**Saskatchewan Licensing**
Approved 1997, 2005 Weyburn and Midale EOR Operations	Yes Transport	Clearance letter Transport	NA	Pipeline EOR
Approved 2009, 2013 Boundary Dam Integrated CCS Demonstration Project EOR; some Research	No	Clearance letter Global Project	NA	Pipeline EOR
Approved 2010-2013 Alberta Carbon Trunk Line EOR Operations	Transport Injection EOR	Transport C & R	Approved without hearings	NA
Approved 2012 Quest Carbon Capture and Storage Project Sequestration	Joint Application Federal/Provincial Capture, Transport, Injection, Storage		Approved with hearings	NA

[1] Acronyms:
CEAA – *Canadian Environmental Assessment Act*
C & R – Conservation and Reclamation Plan
EIA – Environmental Impact Assessment
EPEA – Alberta *Environmental Protection and Enhancement Act*
ERCB – Alberta Energy Resources Conservation Board
OGCA – Saskatchewan *Oil and Gas Conservation Act*

Regulatory oversight of CCS Projects is value-chain specific, where activities in capture, transport, injection, EOR, or storage determine the types of required applications and assessments. Identifying and accessing relevant assessment documentation for all value chain activities is therefore challenging. Furthermore, application and approval documents may be obtained from the proponent or regulator, depending on the project; some from web-based archives, some by direct contact, and some requiring payment for an information request.

Overall, *Canadian Environmental Assessment Act* screenings were more comprehensive in terms of multiple chain activities and ease of access to the document trail than those completed under provincial legislation, regulations, and directives. As described in Chapter 2, the federal government's CEAA includes the stated purpose to consider projects in a careful and precautionary manner. On the other hand, Saskatchewan's *Environmental Assessment Act* (EAA) applications were not posted. Here, the Ministry of Environment posts the Ministerial Determination and Reasons for Determination, but applications and review documentation require direct contact with a number of government offices and/or the project developer.

With respect to approach, Quest was based on the proponent's and regulators' defined 'area of interest' (AOI). Bankes (2012) suggested that neither the AOI nor its subset 'zone of interest' (ZOI) are "legal terms of art and … are not used in any of the relevant legislation or the key [ERCB] Directives". Bankes (2012) also suggested that the term is evidently important because it "controls the geographical scale of such things as lease configuration, the provision of notice, identification of legacy wells, geological characterization etc, and the scale (as one might expect) is much larger than that provided for cognate operations such as acid gas disposal projects". In Saskatchewan, if regulators deem a proposal not to be a development under the EAA based on specific review criteria, then a clearance letter is issued rather than requiring an environmental impact assessment. Proponents then proceed to chain activity licensing and permitting applications where documentation is not readily available and RA/RM is not detailed further.

The range of risk issues assessed during regulatory review and approval has grown over the past fifteen years – from air emissions (H_2S) that determine the emergency planning zones for a pipeline alignment (Weyburn Midale), through to six identified risk issues in Quest: air quality; public health and safety; emergency response planning (transport and injection pads); injection well integrity; acid gas storage; and accidents, malfunctions and unplanned events. Table 3.4 illustrates the issues assessed for each project. In the three more recent projects – Boundary Dam, ACTL, and Quest – where each project includes more than one assessed chain activity, publicly available documentation normally contained a detailed discussion about impacts and mitigation of surface-based activities and less information about potential effects of injection and EOR/storage. This may reflect two issues: operators and regulators have more experience with the assessment of industrial process emissions and pipeline hazards compared with less but growing experience in injection and storage phase activities (Koornneef et al., 2012; Pawar et al., 2015). Recently, Pawar et al. (2015) described the progress being made in risk assessment and risk management methodologies for CO_2 sequestration. Furthermore, this may be indicative of the proprietary nature of geological information within the industry. Regulators may be provided additional information verbally during the approval process (eg ACTL, Quest), but the specifics are not part of the documentation provided in a public document registry.

Table 3.4: Environmental and health risk assessment in CCS value chain activities for large Canadian projects[1]

Project	Capture	Transport	Injection	EOR/Storage
Weyburn-Midale EOR	NA	CEAA Screening H2S, CO_2 stream		
		EAB Clearance with defined EPZ (750m)		
Boundary Dam EOR	No CEAA Screening			
	Provincial EAB Global Clearance Letter			
	Clearance letter conditions NOx, SOx, PM_{10} and $PM_{2.5}$, other criteria contaminants Amines and by-products Water usage	Best practices Reclamation		
Alberta Carbon Trunk Line EOR		CEAA Screening		
	None	Detailed information Effect on Valued Ecosystem Components: Air and noise, soils and landuse, vegetation, wetlands, wildlife, historical resources, social and economic issues Accident and malfunction	Little information	
			Drilling and completions	Existing and abandoned wells Flow lines If leakage in decommissioning, CO_2 not inherently toxic; no contamination
	Alberta EPEA None required (improvement to current operations)	Alberta EPEA C & R		
		ERCB Hazard assessment re EPZ (700 m) CO_2, hydrogen, CO, H_2S, HVP RM – Pipeline to meet Regulatory standards and Monitoring		

(Continued)

<table>
<tr><th>Project</th><th>Capture</th><th>Transport</th><th>Injection</th><th>Storage</th></tr>
<tr><td rowspan="5">Quest
Sequestration</td><td colspan="4">Joint Fed/Prov Environmental Assessment (EPEA and CEAA Screening)
in conjunction with ERCB Regulations and Directives</td></tr>
<tr><td colspan="4">EIA
Accidents, Malfunctions and Unplanned Events
Effects on valued ecosystem components, public health and safety, aquatic resources</td></tr>
<tr><td rowspan="3">EIA/ERCB
Air quality
NOx, NOx as precursors to PM2.5, PAI, nitrogen, ozone formation, regional haze, CO_2

Public health and safety
NOx, NOx as precursors to PM2.5

Monitoring</td><td colspan="2">EIA/ERCB
Emergency Response Planning
Transport and Injection pads - (EPZ 450m)</td><td rowspan="2">ERCB
Site characterization and selection for acid gas storage scheme (Not publicly available)</td></tr>
<tr><td rowspan="2">Monitoring</td><td>ERCB Injection well integrity</td></tr>
<tr><td colspan="2">Measurement, Monitoring and Verification Plan to detect loss of conformance and loss of containment</td></tr>
</table>

[1] Acronyms - CEAA – *Canadian Environmental Assessment Act*, C & R – Conservation and Reclamation Plan, EAB – Environmental Assessment Branch, EIA – Environmental Impact Assessment, EPEA – Alberta *Environmental Protection and Enhancement Act*, ERCB – Alberta Energy Resources Conservation Board

3.2 Risk assessment

This review found a growing use of formal, systematic protocols for risk assessment and management in characterizing hazards, estimating risks, and specifying robust monitoring regimes. Nevertheless, the choice of methodologies and transparency is inconsistent across jurisdictions and across the different dimensions of CCS projects (siting, capture, transport, injection, storage, and monitoring). As noted above, overall, the level of detail in RA of surface-based activities such as air emissions modelling and transport pipeline development remains high and is greater than that provided for injection and storage activities. For example, Shell provided a description of the storage site characterization and selection, but did not provide the risk assessment publicly. ACTL only provided a summary table checklist of injection and storage risks, but without supporting documentation. In part, this may reflect the extensive experience operators and regulators have with the assessment of industrial process emissions and pipeline hazards compared with less but growing experience in injection and storage phase activities

Second, while Shell did not assess CO_2 leakage as a hazard initially and the RA of the pipeline and injection pads was not made available until later in the review process, Quest is the only project that calculated a risk of fatality within the pipeline right of way (maximum 2 chances in a million/year (ERCB, 2012)). Interestingly, the pipeline emergency protection zone has decreased over the years: Weyburn-Midale Souris pipeline was 750 m; ACTL was 700 m; and Quest was 450 m. The Boundary Dam amended application included assessment of the change in air emissions at the capture plant, but the off-take pipeline licensing application was not made available, and the associated EOR activities fall within the original Weyburn-Midale EOR Operations scheme.

3.3 Risk management

While CCS projects are approved within a regulatory framework, achieving and monitoring safe and effective operations is dependent on wide ranging risk management options, including regulatory, economic, advisory, community-based, and technological approaches (Krewski et al., 2007, Krewski et al., 2014). Examples of these are evident in this review of the four large scale Canadian projects. These and additional options for CCS are discussed fully in Larkin et al. (submitted-b).

In these four projects, developers and regulators point to meeting the requirements of existing provincial guidelines or directives as sufficient to mitigate or manage project activities at each phase of development. This review found that airshed air quality monitoring is proposed for capture projects, whereas pipeline monitoring and Emergency Response Plan (ERP)/Emergency Protection Zone enactment are primary risk management activities for CO_2 transport. In Alberta, ERP documents are deemed operational, to be approved by the ERCB after a decision was made to approve the project. Indeed, the Quest ERP was not finalized until after project approval. It was also determined that ESRD, through the EPEA, are not involved in planning for spill response (for instance, they are not provided the ERP during its development), but they must respond to an incident. Lastly, some regulatory approvals require notification and reporting although follow up is not always required. The specifics of these submissions, if existing, are deemed operational and are not part of applications or approval processes.

In Alberta, Measurement, Monitoring and Verification (MMV) is the principle RM approach discussed in detail, whereas in Saskatchewan monitoring is approved as RM, but detailed plans are not readily available. A variety of monitoring technologies have been proposed and approved for injection and EOR/storage. Given Alberta's requirement for a MMV Plan and Closure Plan under the Carbon Sequestration Tenure Regulation (Government of Alberta, 2011), development of the MMV Plan was a principle activity for Quest in which risk management is being informed by a semi-quantitative risk-based approach. Refinement of Quest MMV continues through project implementation. This is an example of the regulatory RM framework requiring sufficient capabilities in monitoring as a technological RM approach. As stated in the ERCB decision (2012), "Shell submitted that it designed its project to minimize risk to the environment and the public, and it believes its MMV plan provides early detection of potential problems and verification of the effectiveness of corrective measures taken" (pg. 54). A detailed Closure Plan will also be developed as the project progresses.

Measurement and reporting of EOR project performance and containment has not been required; project developers are again concerned with safeguarding proprietary information with respect to the use of CO_2 as a cost to be avoided in accessing oil and gas in the miscible flood operations (Dixon et al., 2015; Jenkins et al., 2015). As suggested above, geological information remains closely guarded by project developers.

In terms of decision content, regulators review and accept the proponent's assessments, with or without clarifications. In ACTL, there was some frustration evident in the federal departmental review where many details were provided for transport risks, and few regarding injection and storage assessment. For Quest, the ERCB accepted Shell's proposed spatial boundary of the study zone (Area of Interest), a delineation discussed above. In Boundary Dam, the RA use of surrogate NDMA for amines and by products was accepted, although further research by the proponent is also underway. Also, although the proponent selected and explained their choice of risk assessment methodologies, the presentation of results varied and did not always promote public understanding. One example, the aforementioned presentation of risk of fatality within the pipeline right of way, was illustrated in graphs and figures within Shell's application and described numerically by the ERCB in its decision. With respect to decommissioning and closure, proponents indicate and regulators agree that these project phase details will be developed at a later date.

3.4 Risk communication

In terms of risk communication and public outreach, proponents undertook and reported on regulatory requirements for public consultation about project activities. This normally included a selection of mechanisms to notify and consult with property owners and identified stakeholders within pre-determined (regulatory-based) distances. Local and regional public outreach was initiated and continues for both Quest and the Boundary Dam project.

As the first LSIP saline sequestration project in Canada, the review of Quest documentation demonstrated a number of risk communication issues. In terms of process, the Shell Quest application, review and approval was complicated to follow. The number of applications under two regulatory regimes (environmental assessment and ERCB applications) was likely demanding, confusing and frustrating for the proponent, regulators, and the public as well. Risk topics were difficult to track through mixed topic supplementary information requests (SIRs) for each chain component (examples at Shell 2010f; 2011a; 2011b; 2011c), and the content of each document was not well described by the titles. Transparency, described as (1) ease of access to information and (2) the fullest possible disclosure of all decision inputs in risk assessment and management decision-making, is also viewed as problematic. An industry association suggested that Shell's outreach had been exemplary (Fink, 2010); however, the analysis presented here finds that some risk information was either not well presented, not provided in a timely manner, or not made available at all. For instance, the Quantitative RA for Pipeline and Injection Wells and DNV's Independent Panel Review (IPR) Report of Shell's RA of Acid Gas Storage Scheme were both made available approximately one year into the ERCB review, in response to two SIRs. The document dates and their purpose in Shell's preliminary project assessment indicate they were completed much earlier. On a separate matter, one might question the noted Independent Panel Review of Quest, given the known relationship between the Proponent and the IPR manager, Det Norske Veritas (now DNV GL). In Saskatchewan, on the other hand, there appears to be no central repository/availability of project documentation, although requests are usually responded to positively when made to either project developer or regulator.

One final comment concerns the language used to describe the benefits of CCS in project announcements. Projects often equate the amount of CO_2 captured in terms of the equivalent number of cars taken off the road (between 200-500 thousand cars per project per year). This may or may not be meaningful to the public debate about CCS as a mitigation strategy. As well, CO_2-EOR project descriptions generally include estimates of the number of barrels of crude oil that can be developed in a miscible flood. This contrasts with the interests of those advocating for absolute decreases in fossil fuel production/dependency through alternative energy sources and energy conservation.

4 Conclusion

This review of publicly available documentation describes the regulatory practice for four large Canadian CCS projects either under construction or in operation: Weyburn-Midale Enhanced Oil Recovery (EOR) Operations, Boundary Dam Integrated CCS Demonstration Project, Alberta Carbon Trunk Line, and Quest Carbon Capture and Storage Project. As CCS develops, integrated projects will continue to be approved through a combination of existing, amended and new laws and regulations aimed at specific components of the CCS Chain, as outlined by Larkin et al. (submitted-a) and expected by international agencies (European Commission, 2014; IEA, 2010). Nevertheless, narrow regulatory interests form an apparent disconnect between the announcement of integrated projects and the nuts and bolts of assessment.

Conclusions that can be drawn from this review find that RA/RM is ‘moving forward’ in approvals technically: an increasing range of chain component health and environmental risks are being assessed using referenced approaches. However, while proponents explained their choice of risk assessment methodologies, and there is an increasing range of risks being assessed, documentation can be scattered rather than presented comprehensively across risk topics, and the presentation of results would not always promote public understanding. Hence, individual risk assessments are deemed acceptable, without project developers or regulators discussing comprehensive risk estimation. An integrated RA/RM framework of the type proposed by Larkin et al. (submitted-b) has not been used as a guide.

Furthermore, documented approval processes experienced slow and/or incomplete public release of risk assessment information. Indeed, unresolved issues about transparency in risk management decision making for CCS may have a negative impact in the future on public acceptance and therefore on project viability in the long run. This issue is discussed in detail by Leiss and Larkin (submitted).

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Chapter 4: Uncertainty in Risk Issues for Carbon Capture and Geological Storage: Findings from a structured expert elicitation

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Abstract

Carbon capture and geological storage (CCS) is identified within the portfolio of mitigation options for climate change. Each value chain activity of large scale integrated projects (capture, transport, injection, and storage) includes uncertainties and hence potential risks with respect to both environmental and human health protection. With a focus on injection and storage, a structured elicitation of international experts provides quantified judgements and uncertainties, and understanding of relative risk of CCS activities. In the 0-50 year, 51-499 year, and >500 year time periods, the expert panel suggested an almost equal likelihood of storage leakage occurring, with a marked decrease from minor to major to catastrophic leakage (approximately >1 in 30; 1 in 10^3; 1 in 10^4, respectively); for the same time periods, the judgement of likelihood for major leakage that would result in measurable negative effects on human health or the environment was the same (approximately 1 in 10^3). Insights could stimulate further scientific deliberations about the reliable and effective deployment of this complex and interdisciplinary technological process. A companion paper discusses complementary findings for issues in CCS risk management.

Keywords

Carbon capture and storage, expert elicitation, risk assessment, uncertainty, public health, environmental protection, performance, containment, injection, sequestration

1 Introduction

Carbon dioxide (CO_2) is a greenhouse gas (GHG) that has been identified as a significant driver of climate change, with 65% of GHG emissions attributed to CO_2 in 2010 (IPCC, 2014b). From an estimated 27 GtCO_2eq/year emissions in 1970, GHGs are trending towards or may exceed 55 GtCO_2eq/year through 2030, even with implementation of the full range of unconditional and conditional components of intended nationally determined climate change mitigation actions (United Nations Framework Convention on Climate Change, 2016). This amount of emissions has been modeled to result in an atmospheric concentration of 580-720 ppm CO_2eq, higher than the 450ppm that could limit average global temperature increase to +2.0^{o}C by 2100, the international Paris Agreement target (United Nations Framework Convention on Climate Change, 2015).

In an effort to cut CO_2 emissions from point source fossil fuel and industrial process sites – such as coal and natural gas electricity generation facilities, and cement, steel, fertilizer and oil upgrader facilities – carbon capture and geological storage (CCS) technology has been included within the portfolio of mitigation options for climate change (IEA, 2009, IEA, 2013a, IPCC, 2005, IPCC, 2014b). Up to 3,000 saline aquifer sequestration projects could contribute 13% cumulative CO_2 emission reductions worldwide through 2050 (GCCSI, 2014a, IEA, 2015a).

Large scale integrated CCS projects include four value chain activities: CO_2 capture and compression to supercritical fluid phase, transport by pipeline, underground injection, and permanent storage in deep geological formations. Potential environmental and human health hazards have been identified for each of these activities, with greater experience and understanding of risk assessment for capture and transport compared with less but growing experience for injection and storage activities (Koornneef et al., 2012, Pawar et al., 2014, Pawar et al., 2015).

The findings from a structured expert elicitation described here contribute understanding of relative risk of these value chain activities and quantify collective uncertainty judgements across experts for a number of environmental and human health issues related to CCS risk assessment. The elicitation was focused on performance and containment hazards and associated risk in injection and storage, where insights could stimulate further scientific deliberations. The elicitation also considered issues in CCS risk management, with a focus on low probability high impact events, findings for which are detailed in a companion paper in this issue (Larkin et al., *submitted-d*). (See Appendix A for invitation and instrument).

The following sections first explain the terminology and approach used in this analysis, including the CCS technology, an overview of technical, environmental, and health issues associated with the technology, and previous findings from expert elicitation.

CCS technology and terminology

Pre-, post-, and oxyfuel combustion represent the three main capture technologies proposed for CCS, as applied to power generation and industrial facilities. Capture activities also include compression to a supercritical fluid phase. For purposes of the present discussion, transport is limited to pipelines. Deep well injection occurs at wellheads located within the storage complex.

Given the need for thousands of deep saline aquifer CO_2 sequestration projects for CCS to contribute its full potential to climate change mitigation, this storage type was the focus of the elicitation. Questions related to carbon capture utilisation and storage (CCUS) in enhanced oil

(EOR) or enhanced coal bed methane (CBM) recovery operations were included in a limited way. EOR projects use CO_2 in miscible flood operations that enable incremental oil production. CO_2 is reused and remains in open pore space previously occupied by fossil resources. These projects are described and promoted as proof of concept, demonstrating that CO_2 remains stored underground over an extended period of time. The less common CBM field pilot projects inject CO_2 into coal seams where most remains permanently stored (Massachusetts Institute for Technology, 2016).

Technical, environmental, and human health hazards

A Special Issue of *International Journal of Greenhouse Gas Control* (Gale et al., 2015) provided a comprehensive review of developments in CCS on the tenth anniversary of the publication of the IPCC *Special Report on Carbon Capture and Storage* (IPCC, 2005). Seventeen papers considered progress and gaps in such topics as CO_2 capture technologies; CO_2 storage (where findings suggest the potential for safe operations is likely where sites are properly selected, characterized and managed); environmental impacts of CCS (noting an ongoing gap in quantitative methods for end-to-end risk assessment of human health and the local environment); risk assessment methods; and progress in monitoring techniques. Developing economic and policy considerations for CCS and public acceptance were also included.

Technical hazards relate to site performance and containment, both of which have the potential to affect the successful operation of the project. As described by Pawar et al. (2015), performance issues include insufficient injectivity or storage capacity during site assessment and injection phase activities. Substantial research has been devoted to identifying and verifying the main processes for each of these risk categories. Reviews were completed by, for example, Bachu (2015) regarding storage efficiency, and Birkholzer et al. (2015) and Celia et al. (2015) regarding migration, trapping, and containment in deep saline aquifers.

With respect to containment, CO_2 and brine hazards may manifest during the injection and post-injection (storage) period, possibly creating risks for the environment and human health. Environmental issues were identified by Wilson et al. (2003) in a geological storage hazard taxonomy that included CO_2 in the atmosphere or shallow subsurface; CO_2 dissolved in subsurface fluids; geological displacement; and leakage that could return stored CO_2 to the atmosphere, with global ramifications. The list of environmental hazards was extended by Koornneef et al. (2012) and Pawar et al. (2015) to include air, soil, and groundwater contamination by CO_2, brine or process contaminants affecting the natural environment. Additionally, the biosphere hazards assessed by Bowden et al. (2013a) further included effects on wildlife, prairie, recreation, and industry assets related to air, soil, and water contamination. Jones et al. (2015) discussed improved understanding of potential environmental impacts of CO_2 leakage on drinking water resources and near surface ecosystems for both onshore and offshore CCS projects.

Potential human health hazards include occupational or public inhalation of supercritical CO_2, potentially resulting in morbidity and mortality, and induced seismicity effects on built infrastructure. As well, potential re-release of stored CO_2 could contribute GHG emissions back to the atmosphere with attendant health effects of an exacerbated climate change scenario. From a population health perspective, the natural and built environment are included as determinants of human health, defined as the circumstances in which populations are born, grow up, live, work and age (Commission on Social Determinants of Health, 2008). CO_2 or brine effects on drinking water, soil, and air contamination, as well as wildlife and habitat, may therefore also be considered health hazards.

Structured expert elicitation

CCS in saline aquifers is a new technology, with just two large scale projects operating over the past 10 years, and a third operating since 2015 (Massachusetts Institute for Technology, 2016). As such, CCS is a good candidate for a structured expert elicitation, an approach that has been shown to be of value where there is limited information and experience, large uncertainties, and risks are theoretically very low (Aspinall, 2010). Previously, structured expert elicitation has been applied to wide ranging issues of collective importance (Cooke and Goossens, 2008), including nuclear applications; water pollution; the aerospace sector; volcanoes; and in health risk related to chronic wasting disease (Oraby et al., In press); prion disease (Tyshenko et al., 2012, Tyshenko et al., 2011) and global foodborne disease burden (Hald et al., 2016).

Gerstenberger and Christophersen (2016) combined a structured expert elicitation with Bayesian Belief Networks analysis in a research project to demonstrate the use of these methods in assessing the probability that the CO2CRC Otway Stage 2C experiment (Australia) would meet its goals of detecting and stabilizing a CO_2 plume using a 4D seismic monitoring survey. Their findings focused on the implications of the impacts of the methods moreso than the implications for the project, suggesting that the Classical Model for structured expert elicitation provides a more defensible and useful procedure compared with informal methods, particularly because of the "transparent and unbiased weighting scheme and the influential role it plays in encouraging experts to be open minded during the elicitation by its emphasis on uncertainty in one's own knowledge" (Gerstenberger and Christophersen, 2016, p. 328). Using non-structured elicitation, geological aspects of containment risk for the Otway project were also quantified (Watson, 2014). The normalized risk quotient for the likelihood of more than ten leakage events was lower than the target risk quotient in all cases.

Other non-structured expert elicitations have been used in CCS and CCUS project risk assessments (Pawar et al., 2015), to discern selected geosphere and biosphere risks of the IEAGHG Weyburn-Midale CO_2 Monitoring Project (Bowden et al., 2013a, Bowden et al., 2013b) and the evolving perceptions of risk for two model CCS projects in Scotland (Polson et al., 2012). For Weyburn-Midale, risk workshops were used to develop a risk register and a quantitative assessment of the consequence and likelihood of geosphere containment risks (Bowden et al., 2013b). The process demonstrated that it is likely that approximately 30 Mt CO_2 could be expected to be stored safely in the EOR project for an extended period of time. Results were linked with semi-quantitative risk assessment for the biosphere where, among several findings, the project posed an acceptable level of risk to public safety; well pathways pose the greatest biosphere risk; and public amenity assets - sensory perception, agriculture, and property/infrastructure - are most at risk due to movement of CO_2 into channel aquifers (Bowden et al., 2013a, p. S307). In Polson et al. (2012), experts first indicated mostly low risk perception for features, events, and processes (FEPs) in their risk register for two model saline aquifer reservoirs, and new information reduced uncertainty further during the course of the project. However, experts also displayed a change in risk perception for some issues in the absence of new information, with authors suggesting a need to understand the factors that may have contributed to this difference.

2 Methods

A panel of twelve international experts, recognized as authorities in the field, was convened over two consecutive part-days in March 2015 to elicit understanding and beliefs about risks and uncertainty in CCS, with emphasis on injection and storage and risk management of low probability high impact (LPHI) events. Five members work in academia and seven in public research agencies. They brought expertise in hydrology and fluid mechanics, geomechanics, geophysics, well integrity, simulation and mathematical modeling, risk assessment, and monitoring (affiliation and expertise detailed in Appendix C).

Prior to the elicitation, a draft elicitation instrument was reviewed and tested by additional experts in CCS injection and storage, following which some modifications were made and one question was removed. The facilitated elicitation then took place using video conferencing facilities hosted by the University of Ottawa. Panel members were located in Canada, the United States, Europe, Australia, and Saudi Arabia. One participant withdrew voluntarily after the first day citing insufficient familiarity with the subject matter. The responses provided by that participant are excluded from the analysis.

Experts understood the elicitation was concerned with a generic risk scenario and did not constitute a risk assessment or management exercise for a specific project scenario. Before beginning the elicitation, a crucial step was to establish that participants had a common understanding of terms and conditions embedded in the elicitation instrument, arriving at the following agreed terms:

- Risk referred to probability and consequence of an adverse effect combined.
- The term “CO_2 leakage” represented both leakage and seepage scenarios, and questions did not differentiate between point source leakage or diffuse leakage over a large area.
- CCS leakage failure scenarios included:
    - minor leakage (light and slow, escaping repository);
    - major leakage (requiring intervention to mitigate effects); or
    - catastrophic leakage (with significant infrastructure damage or evacuation).
- The amount of leakage could be considered in terms of:
    - the percentage of the mass injection rate of CO_2;
    - the percentage of total injected CO_2 mass; or
    - the total mass of leaked CO_2 per year.
- Injection concerned well operations, including the facility, wellbore, and near wellbore zone.
- Storage included conditions away from the wellbore that may affect the integrity of repository.
- CCS projects were expected to be developed in low to medium population density areas, remote from major urban centres.
- The elicitation did not attempt to assess judgements as to what constitutes an “acceptable” level of risk.

Questions of clarification and interpretation were permitted throughout the process; some definitions and contextual understandings were refined during the course of the elicitation. During the virtual plenary session, experts completed each question individually using pre-formatted spreadsheet response tables, which were submitted by the experts to us at completion. Throughout, experts were also given the opportunity to record their thoughts and reasoning and to comment on the elicitation process.

Three question formats were used to elicit responses to questions on CCS risk assessment issues.

1) *Paired comparisons.* Experts completed the upper triangular part of preference matrices to compare relative risks of capture, transport, injection, and storage; long-term risks of storage options; distinct causes of local health and environmental hazards in low/moderately populated areas; and mineral reactivities. Pairwise preference semi-quantitative ranking was obtained by probabilistic inversion of the importance ordering choices using the Unibalance software (Macutkiewicz and Cooke, 2006, Tyshenko et al., 2011). Experts' internal consistency was evaluated in assessing pairwise preferences.

2) *Numerical uncertainty distributions*.

   According to the Classical Model of Cooke (Cooke, 1991, Cooke, 2009, Cooke, 2013) experts first completed a series of (eighteen) calibration questions on technical CCS issues in site performance and containment; these were variables with values known from the literature, which experts would not be expected to know precisely, but should be able to capture within credible uncertainty distributions (90% range). This calibration exercise enabled distinct performance weights to be given to individual experts based on their accuracy and ability to judge uncertainties (Aspinall, 2008, Aspinall and Cooke, 2013, Cooke, 1991). This method remains the only technique currently available that has the attribute of genuine empirical control on the resulting individual performance scores. For a detailed description, see Cooke (1991), Cooke and Goossens (2008), and Tyshenko et al. (2011). For target items, experts' elicited quantiles were aggregated with these weights to form a new distribution: the Performance Weight (PW) solution, expressing the group view on the item median value and uncertainty distribution. This is a mathematically valid and auditable procedure for arriving at a rational consensus on the group view (Cooke, 1991). Two calibration questions that related specifically to capture and transport were discarded from the performance weight calibration, because responses did not contribute information to help discriminate between experts.

Experts responded to numerical uncertainty distribution target questions with a central value (median) best judgement (50^{th} percentile) and the 90% credible range (lower limit 5^{th} percentile and upper limit 95^{th} percentile). Target questions considered the likelihood of leakage in three time periods, the likelihood of major leakage that would result in significant effects on the local environment or human health, storage capacity and injectivity, and seismicity. Responses to calibration and target questions using this format were processed using the EXCALIBUR software package.

3) *Likert scale rating.* A 5-level Likert scale was used to elicit expert opinion on the likelihood and severity of twenty-nine hazards within four hazard groups: well leakage, injection,

intrinsic storage hazards, and induced storage hazards. The same scale was used by Polson et al. (2012) (Table 4.1). The mean expert score was calculated, along with its standard error in order to provide a measure of uncertainty in expert opinion.

Table 4.1: Likelihood and severity descriptors for Likert scale rating of hazards.

Level	Likelihood - If there were 100 similar projects, frequency of this hazard element would occur …	Severity – Change in state
1	Improbable - Probably not at all, never	Light - No modification to initial state
2	Unlikely - Fewer than three times among the 100 projects	Serious - Modification to initial state within acceptable limits
3	Possible - 5–10 times among the 100 projects	Major - Modification to initial state above acceptable limits but without damage
4	Likely - In around half of the 100 projects	Catastrophic - Modification to initial state above acceptable limit with repairable damage
5	Probable - In most or nearly all of the projects	Multi-Catastrophic - Considerable modifications to initial state which is not catastrophic repairable with existing technologies

A third facilitated video conference provided the expert panel with an opportunity to review preliminary findings. Experts agreed that several questions required further clarification. An explanatory document, including a rationale for re-elicitation and formatted response tables, was then distributed electronically and experts submitted responses to these final elicitation questions on an individual basis (Appendix A). These questions re-considered the likelihood of storage leakage scenarios, a regulated threshold for leakage, and safe storage lifetimes. A new question considered the likelihood of a measurable negative environmental impact or adverse public health impact, given five levels of hazard severity.

3 Results

Performance weights based on calibration question responses were not applied to paired comparison and Likert scale responses. Target question response detail is provided in Appendix C (Supplementary Material, Chapter 4).

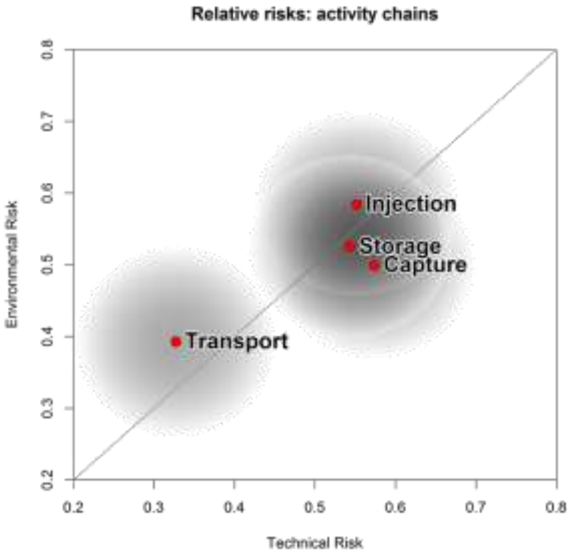
3.1 Pairwise preference semi-quantitative ranking scores

Results from the expert panel judgements on pairwise comparisons (PCs) of relative risk are presented graphically, with tabulated results provided in the supplementary material. Ellipses depict approximate 95% confidence areas for factor ranking scores. For cases with alternative scenarios or options, horizontally extended ellipses indicate greater variance in ranking scores for the option on the x-axis, relative to rankings for the y-axis option; vertically extended ellipses indicate greater variance vice versa. In terms of differentiation between different risks, off-diagonal markers indicate that the rank scores differ for the two alternative risk sources, and rank scores clustering near 0.5 indicate the group's responses do not provide evidence to differentiate between risks. When this happens, the corresponding coefficients of agreement or concordance are very low, indicating an absence of any systematic trait in the experts' choices (Supplementary Material).

PC1: In order to rank the relative risk of four chain activities of integrated carbon capture and storage projects (capture, transport, injection, and storage), we need you to indicate which you consider to present the greater risk. Technical (Q1), environmental (Q2), and health risks (Q3) are considered separately.

In all three cases (technical, environmental, health), rank scores in general did not separate decisively or systematically. However, in the case of technical risk and environmental risk (Figure 4.1a), transport is ranked well below the other three activities (capture, injection, and storage) in the CCS value chain. In the case of health risk and technical risk (Figure 4.1b), storage and transport both rank below capture and injection, with the technical risk of storage ranking higher than health risk. In comparing environmental risk with health risk (Figure 4.1c), experts' rank scores were greater for injection than transport, but did not differ in each case (on diagonal). Capture was judged to present a potentially greater health risk and storage a greater environmental risk.

(a)



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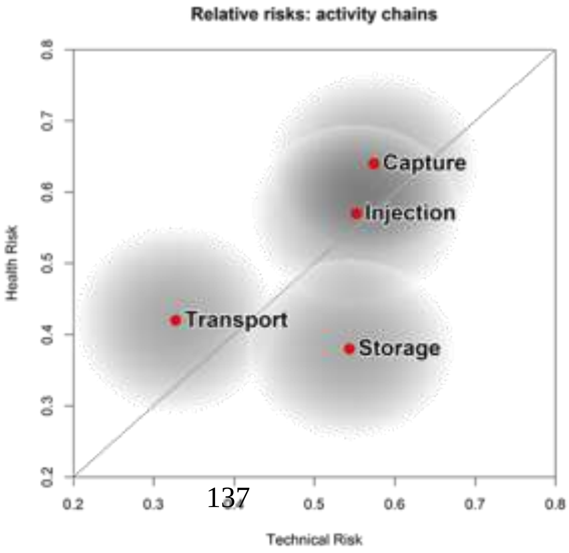

(c)

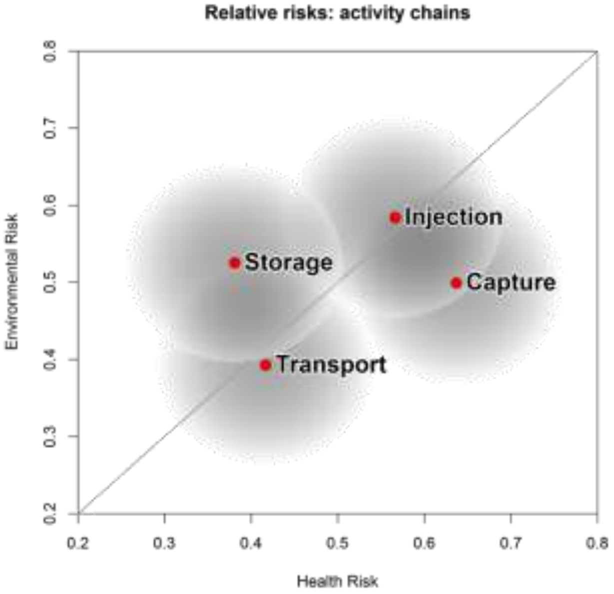

Figure 4.1 (a-c): Pairwise preference matrix of relative risk for capture, transport, injection and storage: (a) environmental compared with technical risk, (b) health compared with technical risk, and (c) environmental compared with health risk

PC2: In order to rank the overall relative risk of the three main types of storage options (saline aquifer; coal bed methane seams; enhanced oil recovery), we need you to indicate which you consider to present the greater risk over the long term (>100 years)?

Saline aquifer sequestration, coal bed methane seams, and enhanced oil recovery operations have been identified as three main geological CO_2 storage options. The long-term risk was not differentiated in the pairwise preference responses (Figure 4.2). Note the very narrow scaling for rank scores and the uncertainties in rank score values (as represented by the overlapping vertical ellipses) (see also Supplementary Material). This indicates experts' did not rank one storage option as being of greater long term risk than another.

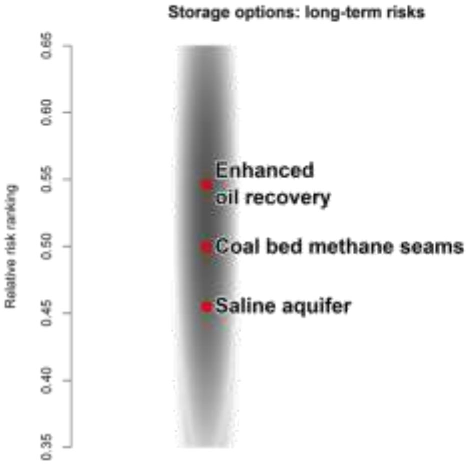

Figure 4.2: Relative long-term risk ranking of three storage options

PC3: In order to rank the relative risks of distinct causes of local health and environmental hazards in a low to moderately populated area, we need you to indicate which you consider to present the greater risk.

- *Brine,* HCO_3*, or elevated gas-phase* CO_2 *migration into the shallow subsurface and near-surface environment.*
- *A seismic event of magnitude M > 5 on the Richter scale.*
- *Explosive re-release of* CO_2 *to the surface.*
- *Cap rock integrity loss due to hydraulic fracturing caused by CCS project.*

Responses indicate that experts ranked 'hydraulic fracturing caprock failure' as a lower potential hazard compared with 'brine/gas migration in the subsurface/near surface environment', 'explosive CO_2 release to the surface', and 'seismic event >M5' (Figure 4.3).

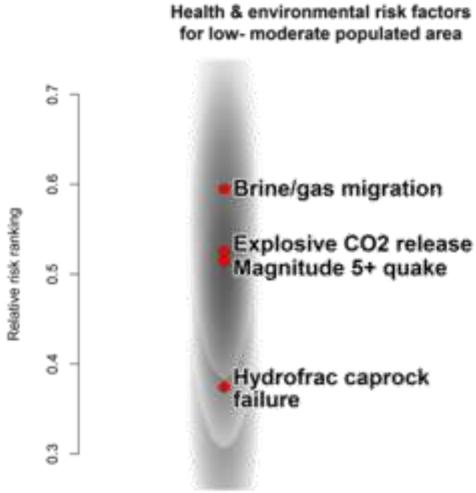

Figure 4.3: Relative risk of distinct causes of local health or environmental hazards in a low-moderate populated area

PC4: [In the tables], we need you to indicate the relative reactivity of five naturally occurring minerals with CO_2 in the pure supercritical state and CO_2 in the dissolved state.

There is good evidence that the group held coherent and self-consistent views for these choices. As shown in Figure 4.4, the minerals all plot close to the diagonal in rank order, with clear separations between most. The findings reflect values that are computable in PHREEQC (Parkhurst and Appelo, 2013), one of two computer simulation models most commonly applied to interpret groundwater changes at injection sites (Jones et al., 2015). This lends confidence that this question type provides legitimate findings for judgements of relative risk for less well-known factors.

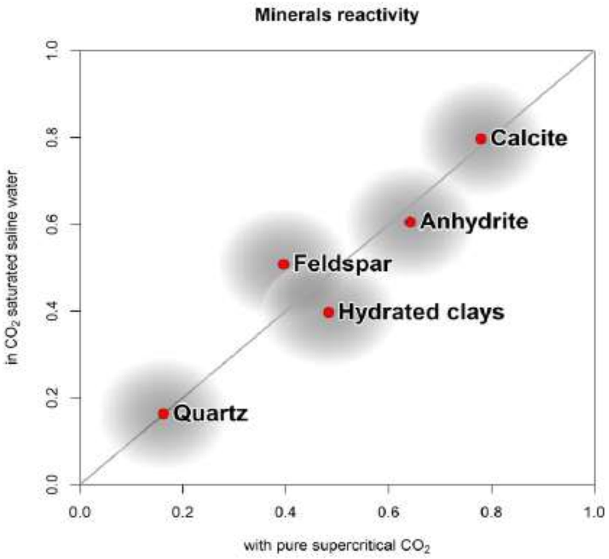

Figure 4.4: Pairwise preference matrix of relative reactivity of five naturally occurring minerals with CO_2 in pure supercritical and dissolved state

3.2 Numerical uncertainty distributions

The median performance-weighted responses and 90% credible intervals for target questions are reported in numerical form (Table 4.2). A range graph plot, with individual expert responses, performance-weighted responses, and equal-weighted responses (Figure 4.5(a-c)); and a composite plot of comparative piece-wise uncertainty distributions (Figure 4.6) provide examples of the figures that are included for each question in the Supplementary Material (Appendix C). An R suffix in target question numbering indicates the question was re-elicited.

Table 4.2: Median performance-weighted responses and 90% credible intervals provided by the experts to target questions (R in question number denotes re-elicitation.)[8]

Target Question (unit of response)	Median Value	90% Credible Interval
TQ19-21. (0-50 yrs) In the Capture phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of		
a) minor leakage (1 in X)	1 in 1	1 in 2,100 to 1 in 1
b) major leakage (1 in X)	1 in 125	1 in 1.0x10^{6} to 1 in 10
c) catastrophic leakage (1 in X)	1 in 1,100	1 in 1.5x10^{7} to 1 in 100
TQ22-24. (0-50 years) In the Transport phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of		
a) minor leakage (1 in X)	1 in 105	1 in 135,000 to 1 in 2.4
b) major leakage (1 in X)	1 in 1,050	1 in 550,000 to 1 in 31
c) catastrophic leakage (1 in X)	1 in 10,400	1 in 2.2x10^{6} to 1 in 79
TQ25-27. (0-50 years) In the Injection phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of		
a) minor leakage (1 in X)	1 in 130	1 in 2,400 to 1 in 1.5
b) major leakage (1 in X)	1 in 1,290	1 in 23,700 to 1 in 7.5
c) catastrophic leakage (1 in X)	1 in 15,700	1 in 270,000 to 1 in 69
TQ28R-30R. In the first 50 years of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios [in storage] (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?		
a) minor leakage (1 in X)	1 in 13	1 in 1,520 to 1 in 1.4
b) major leakage (1 in X)	1 in 1,030	1 in 96,400 to 1 in 35
c) catastrophic leakage (1 in X)	1 in 10,300	1 in 1 million to 1 in 83

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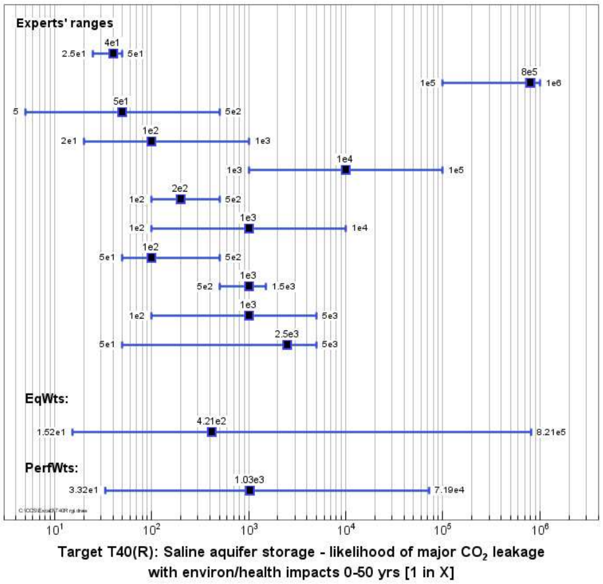
[8] Exact meaning should not be ascribed to the precision of these reported results – they should be regarded as indicative.

TQ31R-33R. From year 51-499 of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios [in storage] (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?		
a) minor leakage (1 in X)	1 in 9.9	1 in 2,070 to 1 in 2
b) major leakage (1 in X)	1 in 890	1 in 16,100 to 1 in 57
c) catastrophic leakage (1 in X)	1 in 11,300	1 in 1 million to 1 in 595
TQ34R-36R. From year 500 onwards of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios [in storage] (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?		
a) minor leakage (1 in X)	1 in 27	1 in 8,340 to 1 in 2
b) major leakage (1 in X)	1 in 1,200	1 in 172,000 to 1 in 100
c) catastrophic leakage (1 in X)	1 in 12,500	1 in 1 million to 1 in 1,020
TQ40R-42R: In a typical saline aquifer storage site, what is the likelihood of major CO_2 leakage that would result in measurable negative environmental impact or adverse public health impact in each of the time periods (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?		
a) 0-50 yrs	1 in 1,030	1 in 71,900 to 1 in 33
b) 51-499 yrs	1 in 1,050	1 in 1 million to 1 in 61
c) 500+ yrs	1 in 1,140	1 in 1 million to 1 in 103
TQ48: What is the worldwide capacity for geological CO_2 sequestration in saline aquifers ($GtCO_2$)?	28 Gt	0.1Gt to 76,000 Gt
TQ49: What is the ultimate CO_2 sequestration capacity in solution as a percent (%) of a deep saline aquifer (%)?	1.2%	0.2% to 33%
TQ50: What percentage of a theoretical repository capacity for a reasonable quality saline aquifer would you generally expect could be accessed by carbon dioxide placement using horizontal wells (%)?	7.5%	1.0% to 76%
TQ51: In a CO_2 injection scheme in deep saline aquifer (~1 $MtCO_2$/year), what is the modal distance from the injection well that is likely to be affected by salt precipitation (metres)?	7.6 m	1 m to 175 m

T40-42Rev: In a typical saline aquifer storage site, what is the likelihood of major CO_2 leakage that would result in measurable negative environmental impact or adverse public health impact in the (a) 0-50 year, (b) 51-499 year, and (c) >500 year time period (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

(a)



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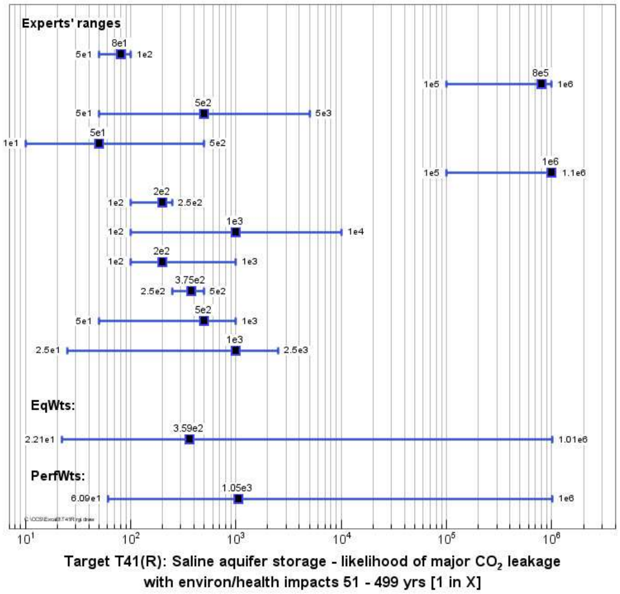

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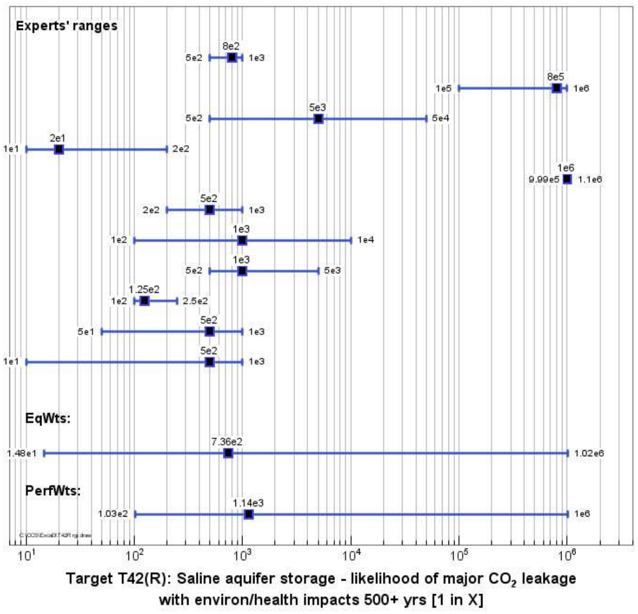


Figure 4.5 (a-c): Range graph plots, with individual expert responses, performance-weighted responses, and equal-weighted responses (T40-42R, Table 4.2)

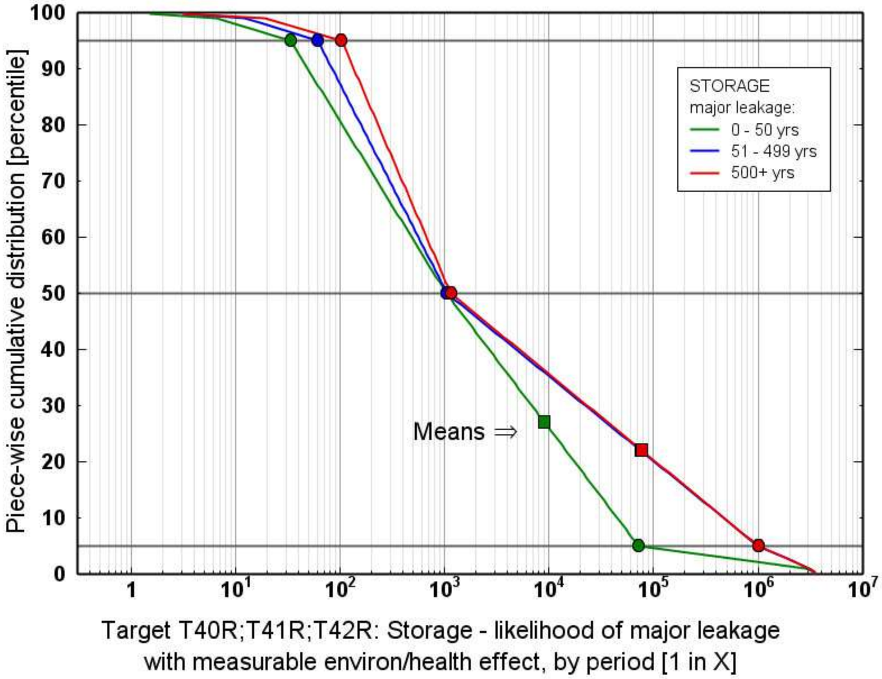


Figure 4.6: Composite plot of comparative piece-wise uncertainty distributions (T40-42R, Table 4.2)

Numerical uncertainty distribution target questions focused on seismicity are excluded from the analysis because responses to questions concerning this important issue appear to indicate that a focused elicitation of experts in this field of study could assist with quantifying these judgements. Gerstenberger et al. (2015) also found that research related to induced seismicity is in early stages and that additional research is needed to better understand these risks. White and Foxall (2016) provided a review of challenges and progress in risk assessment of the induced seismic hazard. Target questions asking the likelihood of a measurable negative environmental impact or adverse public health impact at five levels of hazard severity are also excluded from the analysis: pooled solutions about these impacts were uninformative and clear dichotomies between individuals' responses suggest there were ambiguities of understanding within the group. It was not possible to resolve these fully in the re-elicitation that was undertaken, and these issues therefore remain open for further investigation.

a) Likelihood of minor, major, or catastrophic CO_2 leakage

TQ19-36R: In each of the four chain components of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood (1 in X) of

a) minor leakage *b) major leakage* *c) catastrophic leakage*

Experts began with a common understanding of leakage scenarios. Capture and transport leakage likelihood uncertainty from performance weight (PW) solutions (on log scales) increases significantly from minor to major to catastrophic leakage (TQ19-24, Table 4.2). For injection, leakage likelihood uncertainty (on log scales) also increases overall from minor to major to catastrophic leakage, although much less so than for capture or transport (TQ25-27).

The median response was essentially the same for the likelihood of storage leakage in the three time periods (0-50 yrs, 51-499 yrs, over 500 yrs), for each of minor, major, and catastrophic event types (>1 in 30; ~1 in 10^3; avg ~1 in 11,300) (TQ28R-TQ36R, Table 4.2). The PW upper likelihood limit of minor leakage was essentially the same in all time periods (>1 in 2), as was the lower likelihood limit for catastrophic leakage (1 in 10^6). However, experts' likelihood uncertainty distributions suggest that "two schools of thought" exist, with response groupings indicating that some experts suggest higher likelihoods and others who suggest much lower likelihoods (Supplementary Material). Experts' PW uncertainty was greatest for the likelihood of catastrophic leakage in 0-50 year operating period.

b) Likelihood of major leakage in a saline sequestration site that would result in measurable effects on the environment or human health

TQ40R-42R: In a typical saline aquifer storage site, what is the likelihood of major CO_2 leakage that would result in measurable negative environmental impact or adverse public health impact in each of the time periods (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

In this triplet of questions, experts understood that the site would be properly selected, characterized and designed; that major leakage would require an intervention to mitigate effects; and that a measurable effect on the environment or human health would be detectable. In each time period, the median likelihood is essentially the same (1 in 10^3) (TQ40-42R, Table 4.2; Figures 4.5(a-c) and 4.6). Experts' views were divided into groups expressing higher and much lower likelihoods over all timeframes (Figure 4.5(a-c); see also Supplementary Material). PW solutions are tighter and thus more informative than equal weight (EW) solutions for the two longer timescales.

c) Storage capacity and injectivity

TQ48: What is the worldwide capacity for geological CO_2 *sequestration in saline aquifers (*$GtCO_2$*)?*

The uncertainty distribution for the worldwide capacity for geological sequestration in saline aquifers is wide, with median response 28 Gt and 90% credible range from 0.1 Gt to 76,000 Gt (TQ48, Table 4.2). PW findings display a lower median than EW pooled responses.

TQ49: What is the ultimate CO_2 *sequestration capacity in solution as a percent (%) of a deep saline aquifer?*

The uncertainty distribution for sequestration capacity in solution as a percent of the aquifer is also wide: median 1.2%; 0.2% to 33% credible range (T49, Table 4.2). Responses to this question suggest two schools of thought about this target item (Supplementary Material).

TQ50: What percentage of a theoretical repository capacity for a reasonable quality saline aquifer would you generally expect could be accessed by carbon dioxide placement using horizontal wells (%)?

The median percentage is 7.5%, approximately half the EW solution but uncertainty distributions are quite similar (TQ50, Table 4.2, Supplementary Material).

TQ51: In a CO_2 injection scheme in deep saline aquifer (~1 $MtCO_2$/year), what is the modal distance from the injection well that is likely to be affected by salt precipitation (metres)?

Experts' judgement on the modal distance from the injection well that is likely to be affected by salt precipitation indicates a lower median distance (~7.6 m) and smaller uncertainty bounds than EW (TQ51, Table 4.2; Supplementary Material).

3.3 Likert scale rating of likelihood and severity of hazards

Experts' judgement was elicited for the likelihood and severity of twenty-nine hazards in well leakage, injection, and intrinsic and induced storage circumstances. The impact was understood to be physical damage to infrastructure or the geological formation. The mean rating for each hazard, with standard error as a measure of uncertainty in expert opinion, is provided in Figures 4.7-4.8. Results categorized by the four hazards groups are provided in the Supplementary Material. In some cases, the elicitation description was more specific than the features, events, and processes considered in the unstructured expert elicitation (Polson et al., 2012). Hazard risk ranking was calculated as likelihood × severity of experts' mean response (Figure 4.9). Only the unknown and unlocatable well hazard scored as high risk based on the cutoffs used by Polson et al. (2012) (>10).

Combined likelihood and severity of experts' mean response is summarized in a risk matrix form (Figure 4.10). It is interesting to note that the display of experts' mean responses within the risk matrix does not necessarily match risk ranking values. For instance, reduced injectivity due to plume oil interaction is low risk quantitatively and medium risk on the matrix; similarly, unknown and unlocatable wells scored high risk quantitatively, and medium risk on the matrix. This illustrates the differences that can arise as a function of the cut-off value given to risk categories.

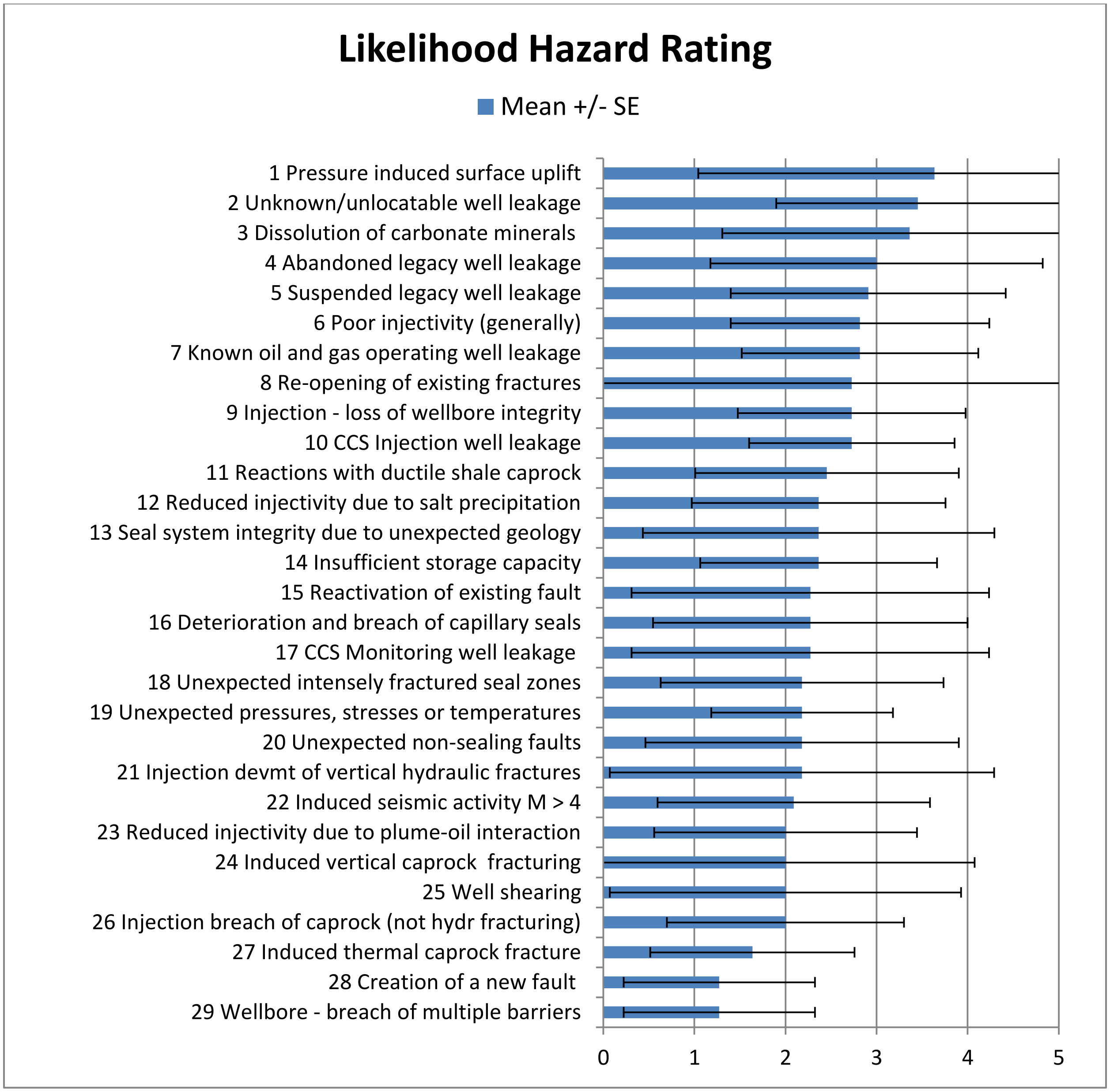


Figure 4.7: Mean expert likelihood rating of twenty-nine potential hazards, including standard error as a measure of uncertainty in expert opinion. [Ratings range from: improbable (1); unlikely (2); possible (3); likely (4); probable (5).]

Figure 4.8: Mean expert rating of the severity of twenty-nine potential hazards should they occur, including standard error as a measure of uncertainty in expert opinion. [Ratings range from: light (1); serious (2); major (3); catastrophic (4); multi-Catastrophic (5).]

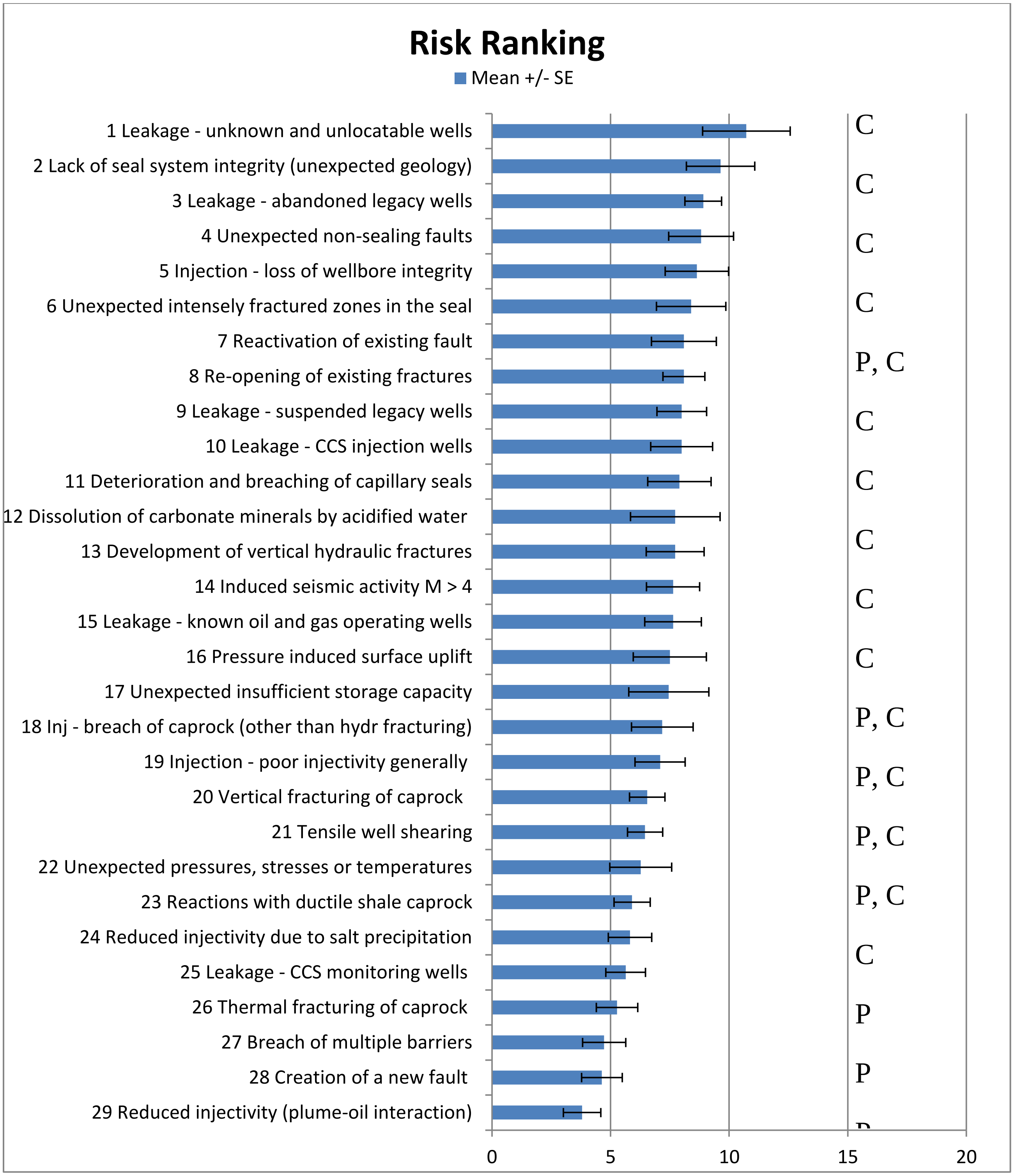
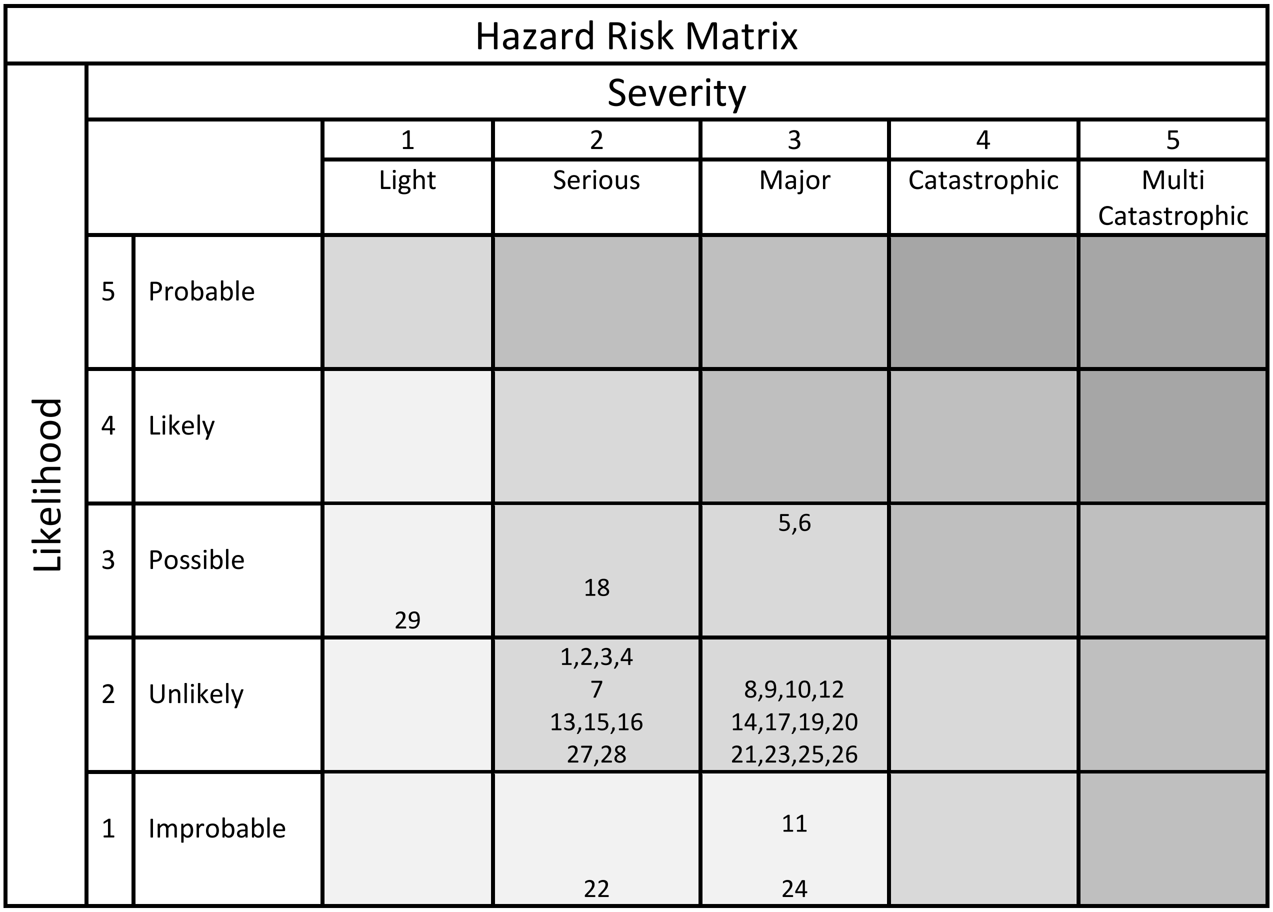


Figure 4.9: Risk Ranking (L X S of mean rating) for twenty nine hazards in well leakage, injection, intrinsic storage and induced storage circumstances. L × S value of less than 5 is considered low risk; hazards in the range 5 ≤ L × S < 10 are medium risk; 10 ≤ L × S < 20 hazards are high risk; and ≥20 are very high risk. Column on right indicates principal risk category: containment (C) or performance (P)



Hazard Risk Matrix

Likelihood		Severity				
		1	2	3	4	5
		Light	Serious	Major	Catastrophic	Multi Catastrophic
5	Probable					
4	Likely					
3	Possible	29	18	5,6		
2	Unlikely		1,2,3,4 7 13,15,16 27,28	8,9,10,12 14,17,19,20 21,23,25,26		
1	Improbable		22	11 24		

Figure 4.10: Risk matrix indicating mean response likelihood and severity combination for all hazards. Top row of each square – Well hazards: 1 CCS Injection, 2 CCS Monitoring, 3 Known Oil and gas operating wells, 4 Suspended legacy wells, 5 Abandoned legacy wells, 6 Unknown and unlocatable wells; 2nd row - Injection hazards: 7 Poor injectivity, 8 Loss wellbore integrity, 9 Vertical hydraulic fractures, 10 Breach of caprock (other than hydraulic fracturing), 11 Breach of multiple barriers; 12 Tensile well shearing; 3rd row - Intrinsic storage hazards: 13 Unexpected insufficient storage capacity, 14 Unexpected non sealing faults, 15 Unexpected pressures, stresses or temperatures, 16 Reactions with ductile shale caprock, 17 Deterioration breach of capillary seals, 18 Dissolution of carbonate minerals, 19 Unexpected intensely fractured zones in the seal, 20 Lack of integrity in the seal system due to unexpected geology; 4th row - Induced storage hazards: 21 Vertical caprock fracturing, 22 Thermal caprock fracturing, 23 Re-opening of existing fractures, 24 Creation of new fault, 25 Reactivate existing fault, 26 Induced seismic event M>4, 27 Reduced injectivity due to plume-oil interaction, 28 Reduced injectivity due to salt precipitation, 29 Pressure induced surface uplift

4 Discussion

In 2015, an international panel of experts participated in a structured elicitation on risk and associated uncertainties in CCS. With a focus on saline aquifer geologic sequestration, target questions considered injection and storage chain components of integrated projects, and low probability high impact events. A limited number of questions considered capture and transport chain activities and other storage options.

Target questions are not intended to be used for risk assessment of any specific project. Rather, this exercise was a first attempt to quantify an expert panel's opinions about selected technical, environmental, and human health hazard and risk issues related to CCS that can be anticipated to arise during CCS project assessment, review, and approval processes.

Eleven international experts agreed *a priori* about CO_2 leakage scenarios; injection and storage activity boundaries; that the envisioned integrated saline sequestration project would use transport by pipeline; and the storage site, developed in a low to medium population density area, would be properly selected, characterized, and designed. Furthermore, it was understood that wellbores would be properly completed and sealed for the duration of the storage period.

Previously, Pawar et al. (2015) provided a thorough review of advances in methodologies for risk assessment and risk management of CO_2 sequestration. Using the same typology, this discussion considers findings related to performance and containment hazard/risk issues.

4.1 Global capacity and performance risk

The expert panel's median best estimate for global capacity for sequestration in saline aquifers, the backdrop to CCS as a mitigation technology for climate change, indicates room for approximately 28 $GtCO_2$ (uncertainty 0.1 – 7.6E+04 $GtCO_2$) (TQ48, Table 4.2). In 2005, an IPCC Special Report also discussed capacity estimates worldwide, with a lower estimate of 1000 $GtCO_2$ and upper estimate uncertain, possibly 10^4 $GtCO_2$ (IPCC, 2005, p. 221). In the intervening period, the 2015 expert panel appears to have a different view of this potential. However, the IEA (2013c) suggested CCS deployment would see approximately 123 $GtCO_2$ captured and stored through 2050, storage that is within the expert panel's credible range.

Deep saline aquifers are considered the most widely available candidates for geological CO_2 sequestration, with approximately 800 major sedimentary basins estimated to exist worldwide (Bachu, 2003). Storage resource estimates calculate the fraction of pore volume available and accessible for storage by CO_2 injection via drilled and completed wellbores (Bachu, 2015, US Department of Energy, 2015). With variable levels of detail, national and regional storage atlases exist for the US (US Department of Energy, 2015), North America (North American Carbon Atlas Partnership, 2012), Norway (Norwegian Petroleum Directorate, 2013), and Brazil (Ketzer et al., 2014). An online storage resource catalogue has been developed in the United Kingdom (The Crown Estate and British Geological Survey, 2016). Indeed, an effort to quantify the worldwide capacity for geologic sequestration has been identified as a necessary activity, with CO_2 storage sites potentially designated strategic national assets (IEA, 2015a). Estimates for saline formation sequestration capacity are provided in Table 4.3.

Table 4.3: CO_2 saline formation storage resource estimates (potential volume)

Country	Storage resource estimates (Gt)		
	Low	Medium	High
USA (US Department of Energy, 2015)	2,379 (2015) 1,610 (2012)	8,328	21,633 (2015) 20,155 (2012)
Canada (North American Carbon Atlas Partnership, 2012)	28	110	296
Mexico (North American Carbon Atlas Partnership, 2012)	100		
Norway (Norwegian Petroleum Directorate, 2013)		4.4	
IEA projection for CCS (IEA, 2013c)		Cumulative 123 by 2050	

Using these geological resources effectively depends on managing performance risks for injectivity and storage capacity. CCS projects are expected to achieve injection rates that support storage objectives. For example, large scale integrated saline aquifer sequestration projects are generally conceived to inject upwards of 1 Mt CO_2 each year for the duration of their operating period.

Experts' views on hazard issues in the performance risk of injectivity were elicited using three question formats. Based on pairwise preference semi-quantitative ranking, experts held similar views regarding the reactivity of five minerals with CO_2 in pure supercritical and dissolved state (Figure 4.4). From most to least reactive under the two defined conditions, rank order unambiguously located calcite and quartz at the top and bottom rank order of reactivity.

Experts also provided quantitative judgements for the modal distance that could be expected for salt precipitation. This reaction can cause a reduction in permeability and thereby have a negative effect on injectivity and pressure. Experts' performance weight median response was approximately 7.6m from the wellbore, with a 90% credible uncertainty range from 1 to 175 m

(TQ51, Table 4.2). In the Shell Quest sequestration project located in the Western Canadian Sedimentary Basin (Alberta, Canada), simulations indicated an approximate effect of 15 m (Shell Canada Limited, 2011a).

Experts also assessed the likelihood and severity of several injection hazards using a Likert-scale question format. Risk ranking was calculated as mean rated likelihood multiplied by mean rated severity (Figures 7-8). With the exception of injection hazard "loss of wellbore integrity" which ranked 5th of 29 performance and containment hazards, all other injection hazards did not rank high: CCS injection well leakage (9th); injection – development of vertical hydraulic fractures (12th); injection – breach of caprock (other than hydraulic fracturing) (17th); poor injectivity (generally) (18th); tensile well shearing (21st); reduced injectivity due to salt precipitation (24th); and reduced injectivity due to plume-oil interaction (29th). Some of these performance hazards are also considered containment hazards (Figure 4.9).

Performance risk for CCS also concerns achieving storage capacity in the project's geologic formation (Bachu, 2015, IEA, 2013a, Pawar et al., 2015). In understanding this to be a question of solubility, experts' median response suggested approximately 1.2% ultimate sequestration capacity, with performance weight uncertainty of approximately 0.2 to 33% (TQ49, Table 4.2). Researchers previously suggested approximately 2-3% of the total effective volume in a deep saline aquifer can be utilized for CO_2 storage (van der Meer, 1993, 2006). Bachu (2015) grouped numerous storage efficiency factors into several categories: characteristics of each of the storage aquifer, confining aquitards, and storage operation, as well as regulatory determinations that establish the volume of rock assigned to a project. As such, both Bachu (2015) and the IPCC ten years earlier (IPCC, 2005), suggested that a range is expected depending on the storage site characteristics and temporal considerations. The suggestion of two ‘schools of thought’ for this question within the present panel is not surprising. The theoretical repository capacity that could be accessed using horizontal wells drilling strategy was higher, estimated by experts as 7.5% of pore space replaced with supercritical CO_2, with uncertainty ranging from about 1-75% (TQ50, Table 4.2). The use of this technology was envisioned in 2005 as a way to increase the injection rate while drilling fewer wells (IPCC, 2005).

Unexpected insufficient storage capacity as a performance hazard was assessed in the Likert scale question format, ranking 14th in hazard likelihood and 18th in severity, with relatively low uncertainty compared to other hazards (Figures 4.7-4.8); risk ranking was 15th of 29 risks (Figure 4.9). Risk ranking of other storage related performance hazards includes dissolution of carbonate minerals (11th); pressure induced surface uplift (19th); unexpected pressures, stresses, temperatures (22nd); and reactions with ductile shale caprock (23rd).

Furthermore, while injectivity and intrinsic and induced storage capacity issues may limit project performance, sequestration sites could also be limited by economic or regulatory constraints (Bachu, 2015, Dixon et al., 2015).

4.2 Focus on human health and the environment

Ensuring public health and environmental protection are important goals in project planning, implementation, and eventual decommissioning of CCS sites. In general terms, the experts did not differentiate relative risk between three long term storage options of enhanced oil recovery

(EOR), coalbed methane (CBM), and saline aquifer sequestration (Figure 4.2). Currently, 76% of operating CCS projects are EOR, accounting for 81% of the capture rate worldwide (Massachusetts Institute for Technology, 2016). This is an increase from the 72% of operating and executing projects in 2014 (GCCSI, 2014b).

The experts also compared technical, environmental and health risk in capture, transport, injection, and storage in general terms. Relative risks for the environment or technical domains were not strongly differentiated within each of these activities, although transport by pipeline was ranked as the lowest risk (Figure 4.1a). For technical as compared to health risk, strong evidence separated health risk rankings of capture and injection relative to transport and storage. Storage was seen as a greater technical risk than health risk (Figure 4.1b). Further, experts' rank scores clearly differentiated capture as a greater potential health risk than environmental risk (Figure 4.1c and Supplementary Material); injection and transport were viewed of equal potential risk to the environment and health, with injection a greater risk to both. Storage was viewed as a greater potential risk to the environment than health. These findings could reflect experts' range of technical expertise in CCS compared with more limited expertise in potential health impacts of CCS.

With respect to elicited distinct causes of local health or environmental hazards, expert rankings did not discriminate between brine/gas migration in the subsurface/near surface environment, explosive CO_2 release to the surface, and seismic event >M5 (Figure 4.3). However, caprock integrity loss due to hydraulic fracturing was ranked a lower relative hazard. In Likert-scale format, likelihood and severity of migration (as several listed containment hazards), seismic event >M4 (a different cutoff than the relative risk question format), and caprock fracture hazards (as vertical caprock fracturing, thermal caprock fracturing, and breach of caprock (other than hydraulic fracturing), were also rated. Within the list of 29 hazards, none of these ranked a high risk (Figures 4.9-4.10), although there was a range of uncertainty in the group's judgement of each risk (Figure 4.9).

4.3 Performance and containment - leakage

Wide ranging injection and storage performance and containment hazards have the potential to create the conditions for CO_2 leakage during CCS operations and long term sequestration period. Leakage to the biosphere could occur though channels associated with a borehole or through a geological fault area (Paulley et al. (2012), cited in Jones et al. (2015)).

In assessing the likelihood and severity of 29 hazards related to well leakage, injection, and intrinsic and induced storage circumstances, the mean ratings of the expert panel did not surpass level 4 (likely, catastrophic) for any hazard and the greatest uncertainty did not necessarily match the highest mean rated hazard (Figures 4.7-4.8). One hazard, development of vertical caprock fractures in injection, had high uncertainty for both likelihood and severity. On the other hand, as both a performance and public perception risk issue, pressure induced surface uplift had the highest mean likelihood and lowest severity of the 29 hazards, with a risk ranking of 17th overall (Figure 4.9).

The risk ranking and risk matrix (Figures 4.9-4.10) emulate the findings of Bowden et al. (2013a) and Bowden et al. (2013b) in their consideration of the Weyburn-Midale EOR project

(Saskatchewan, Canada). In the present study, unknown and unlocatable wells were the greatest containment risk, and abandoned legacy well leakage ranked 3rd (Figure 4.9). Similarly, Quintessa's database of Features, Events and Processes (Quintessa Ltd., 2013) suggested it would be difficult for project developers to "detect a substandard well abandonment before the beginning of CO_2 injection to the designed reservoir", particularly an unknown well within the assessed storage zone. Several well leakage hazards ranked high on the list of 29 hazards, and as both a performance and containment risk, "injection - loss of wellbore integrity" ranked 4th overall.

The expert panel also completed quantitative judgements on the likelihood of leakage scenarios during each chain component of a large scale sequestration project (TQ19-36R, Table 4.2). Leakage was interpreted as "detectable". During the 0-50 year operating period, some experts' judged minor leakage as a virtual certainty in capture and transport, with likelihood uncertainty increasing significantly from minor to major to catastrophic events (TQ19-24, Table 4.2). Koornneef et al. (2012) found the highest failure scenario flow rate was for the transport activity. Based on existing studies from natural gas pipeline incidents, Duncan and Wang (2014) summarized the likelihood of failure of CO_2 pipelines at 1.2×10^{-4} to 6.1×10^{-4} km^{-1} yr. The study suggested this has been overestimated by 2-3 orders of magnitude for events that could result in fatalities or injuries. As the present panel of experts may be less well versed in issues of capture and transport than injection and storage, further elicitation with specialists in these particular domains could assist with quantifying uncertainty judgements.

Uncertainty for the likelihood of leakage during injection increased, but much less markedly than for capture and transport, with an order of magnitude increase in probability between minor, major, and catastrophic events (TQ25-27, Table 4.2). Previously, Bachu and Watson (2009) reviewed failures for CO_2 and acid gas well injection in Alberta, Canada, finding that the incidence of well failures was greater before 1994 regulations and suggested that drilled for purpose CO_2 injection wells, under an appropriate regulatory framework, will reduce and prevent well failures.

Given the protracted temporal dimensions of CCS, with sequestration anticipated for periods of 1,000 years or more, numerical uncertainty distributions for leakage likelihood in storage were broken down and elicited for the 0-50 yr operating period, as well as for 51-499 yr and 500+ year storage periods. Experts' responses suggest a similar median likelihood (with marked decrease) for each of minor, major, and catastrophic leakage in each of the three time periods (>1 in 30; 1 in 10^3; 1 in 10^4, respectively) (Table 4.2). Elicitation findings also appear to suggest some difference of opinion exists among the experts. Response groupings are evident in this analysis, with some experts suggesting higher likelihoods and others much lower likelihoods (Supplementary Material). This is especially evident for minor leakage across all timescales.

Leakage amounts, rates, and probabilities have been estimated previously by a number of investigators (Supplementary Material). Pawar et al. (2015) provide several examples of leakage risk assessment applications, including a quantitative leakage likelihood assessment for aspects of the Otway Project, Australia (Watson, 2014). For more than ten risk events, a normalized quantitative risk quotient was determined by experts, as a function of probability and impact relative to the target risk leakage limit of 1% over 1000 years.

Previous research suggested that the risks associated with injected CO_2 will likely decline with time and on longer timescales (10^3–10^4 yr) (Benson, 2007, Koornneef et al., 2012). CO_2 should become permanently immobilized, though the percent trapping contribution is expected to vary over time: primary mechanisms in the operating period (structural, stratigraphic, and hydrodynamic trapping); extending to secondary mechanisms in closure and post-closure period (residual phase, solubility, and mineral trapping mechanisms). While performance is focused on achieving injection targets and storage capacity, poor containment could permit the CO_2 plume to extend to geologic formations that were not well assessed, with an unknown level of attendant risk. Indeed, CO_2 will continue to migrate for some time after injection due to residual pressure gradients. This allows the CO_2 to come in contact with a great area of the caprock, in time making the likelihood of encountering a leakage pathway higher. Nevertheless, the effects of re-release could be time-dependent, with less serious climate effects if occurring in the long term (IPCC, 2005, Wilson et al., 2003). In Alberta, Canada, Shell's Quest sequestration project documentation estimated zero leakage from storage (Shell Canada Limited, 2011b).

The elicitation delved deeper into experts' views regarding the likelihood of major leakage in a saline sequestration site that would result in measurable effects on the environment or human health. The term 'measurable' was understood to represent 'detectable'. In this triplet of questions, experts' judgement of the risk of leakage was essentially the same over the three time periods, that is, 1 in 1000 or 0.1% (TQ40-42R, Table 4.2). Previously, and as a potentially extreme effect, Roberts et al. (2011) suggested the risk of death from exposure to CO_2 leakage from natural CO_2 seeps is about one in 100 million/year and that an engineered CCS storage site would be even safer, given the project planning and monitoring requirements. (This research was based on deaths from natural CO_2 seepage in Italy as a result of volcanic activity.)

With respect to environmental impacts of CO_2 leakage, Jones et al. (2015) found few published quantified data for leakage scenarios and suggested this is because of high uncertainty, especially in predicting deep geological flow; however their review also found no "direct evidence of significant leakage from existing storage sites" (p. 353). Bellarby (2012) suggested where geologic migration might not necessarily reach the biosphere, rates could be so low as to be undetectable and hence not of major concern. Koornneef et al. (2012) suggested failure of the underground CO_2 storage system would have limited environmental consequences, thus suggesting a low risk; however, significant uncertainty in the assessment of this risk has the potential to become a bottleneck for wide scale implementation of CCS if not properly addressed. The findings from the elicitation appear to indicate that at a general level uncertainty for leakage and its negative effects remains high.

Leakage events remain a performance and containment hazard of serious concern in terms of public perception of the risks of CCS technology overall. As these events may occur as a consequence of well leakage, injection, intrinsic or induced storage hazards, acceptable leakage rates and impacts need to be determined (Stenhouse et al., 2009). On the other hand, the overarching purpose of CCS could be negated should substantial amounts of CO_2 release back to the atmosphere. Expert elicitation target questions for risk management, as discussed in the companion article considered: long-term retention of CO_2; a regulated threshold for likelihood of minor, major or catastrophic storage leakage; safe storage lifetimes; the proportion of environment and human health risk management and costs within CCS project operations (from both regulatory and liability points of view); effectiveness of risk management options for six low probability high impact events; and the storage monitoring period. Together, findings are of great value in planning the safe deployment of future CCS facilities.

5 Conclusion

Risk assessment and management has developed as a matter of judgement in probability and uncertainty since publication of the so-called “Red Book”, *Risk Assessment in the Federal Government: Managing the Process* (National Research Council, 1983). In the case of carbon capture and storage, projects have proceeded concurrently with an expanding knowledge base over the past twenty years. At a project level, Gerstenberger and Christophersen (2016), in their reporting of a CCS-related expert elicitation, reiterated the notion that all relevant uncertainties should be considered if practitioners are to obtain a robust and credible estimate of the risk.

The elicitation reported here did not consider a specific project site. Its purpose was to quantify, in a preliminary way, uncertainty in hazard and risk issues that are expected to be discussed during future sequestration project assessment, review, and approval processes. This paper considers issues and results relating to the elicited assessment of risks, while a companion paper in this issue describes complementary findings for risk management (Larkin et al., *submitted-d*).

Analysis of the expert group's individual pairwise choices indicate persisting uncertainty, as manifest in low coefficients of agreement/concordance for risk ranking in technology, environment, and health in each of capture, transport, injection, and storage; relative long term risk of three storage options; and relative risk of several distinct causes of local health or environmental hazards in a low-moderate populated area. On the other hand, consistent views were provided for the pairwise preference matrix of relative reactivity of five naturally occurring minerals with CO_2 in pure supercritical and dissolved state.

Based on the Classical Model of Cooke (Aspinall and Cooke, 2013, Cooke, 1991), quantitative estimates of uncertainty in performance and containment risk issues indicate a wider credible range for equal weight (EW) compared with performance weight (PW) in almost all questions. Among the findings, the PW credible range indicates a decreasing likelihood of minor, major, catastrophic leakage in capture, transport, injection, and storage over three timeframes; wide uncertainty in worldwide saline aquifer storage capacity (0.1 – 76,000 Gt); wide uncertainty in ultimate sequestration capacity of CO_2 in solution, as a percent of a deep saline aquifer (0.2–33%), increasing to 1-76% with the use of horizontal well drilling strategy; and wide uncertainty in the modal distance potentially affected by salt precipitation (1-175m). PW median judgements indicated that minor leakage is a virtual certainty in capture; the likelihood of minor, major, and catastrophic storage leakage is almost equal but decreasing over three timeframes; the likelihood of leakage resulting in measurable effects on the environment or human health is essentially equal for three time periods (0.1%); and that 28Gt worldwide storage capacity may be less than required for potential CO_2 mitigation using saline sequestration, as envisioned by the IEA through 2050 (cumulative storage of up to 123 $GtCO_2$) (IEA, 2013c).

These judgements may change as further information becomes available and for specific project proposals. The Supplementary Material provides examples of individual's responses that have a smaller range of uncertainty than the group as a whole, in some cases suggesting "two schools of thought" within the expert panel. Examples include storage leakage likelihoods over three time periods and the global sequestration capacity in saline aquifers. In principle, these apparent dichotomies might be resolved by further, more detailed exploration of issues and contributory factors. On the other hand, Garthwaite et al. (2005) (cited in Gerstenberger et al. (2015, p. 156)) suggested "extreme probability events are inherently very small numbers and thus are particularly difficult for experts to conceptualize and to give reasonable estimates thereof".

Some informational 'noise' of this nature may also be expected given the limited experience in CCS to date. Throughout the elicitation process, the expert panel was invited to offer comments on the questions and on the process itself. One panel member suggested that at this particular point in time, perhaps experts in CO_2 *storage* do not yet exist. CCS is a new interdisciplinary technology, where experts' judgements in some cases appear to indicate no clear shared opinion (no definitive, reliable, exact number). Some panel members suggested additional important CCS topics that could be investigated in a focused elicitation include induced seismicity, thermo-hydro-chemical-mechanical coupled processes, and the risks and benefits of CCS within broader climate change mitigation options.

Observations on the elicitation process

The Classical Model for structured expert elicitation is a well-established approach that provides a defensible and useful procedure for gauging expert opinion in matters where there exists considerable uncertainty (Aspinall, 2008, Aspinall, 2010, Cooke, 1991, Cooke, 2013, Cooke, 2015). Concerns about expert bias are reduced through an anonymized elicitation procedure with a formal, transparent, and auditable processing of responses and a performance-based weighting scheme for pooling judgements. This encourages experts to be open minded in responding with their estimates and uncertainties, based on their own personal knowledge, expertise, and experience.

The choice of calibration questions and experts' knowledge with respect to these topics is a critical success factor for the elicitation. As with previous elicitations using this method, the goal is to provide calibration questions that reflect and fairly represent the specialist knowledge necessary for the expert elicitation target questions (Gerstenberger and Christophersen, 2016) . While the range of expertise on the panel was broad, CCS is a new technology with complex risk issues over lengthy periods of time. The wide ranging target questions may not have been within the purview of all the participants and, if they felt it appropriate, experts were permitted to decline to answer particular items.

Given that this exercise was not site dependent, the elicitation instrument and open discussion attempted to ensure the same understanding among experts of the problem context, definitions, and question content; that is, that experts had the same picture in their mind as they responded individually to the elicitation instrument. Experts suggested that these understandings could have been repeated more often as the instrument was completed. A re-elicitation attempted to address issues in understanding that became apparent from the Classical Model analysis. Nevertheless, unresolved ambiguity for some target questions could be reflected in the uncertainty distribution illustrated in the responses. While this elicitation was successful in linking international experts through video conferencing (thus also reducing the carbon footprint of the event), the re-elicitation was completed individually whereas a second plenary session might have assisted with further developing the common understanding for this series of questions. Gerstenberger et al. (2015) also found useful results and the possibility of obtaining better responses using an iterative process involving feedback and more than one expert meeting.

Nonetheless, we suggest our findings provide a valuable basis, and opportunity, to reflect on the collective set of judgements when saline sequestration projects are developed and reviewed. The present results provide considerable insight into how experts view the potential technical, environmental, and health risks associated with the four value chain components for carbon capture and storage (capture, transport, injection, and storage). These judgements will be useful in planning future deployments of this technology at different sites around the world, and in evaluating CCS as a viable technology for mitigating fossil energy and industrial point source CO_2 emissions, facilities that are major contributors to climate change.

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Chapter 5: Risk Management in Carbon Capture and Geological Storage: Insights from a structured expert elicitation

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Abstract

With a focus on risk management (RM) in injection and storage for carbon capture and geological sequestration (CCS), an expert elicitation of scientific judgements quantified collective uncertainty ranges for a number of difficult environmental and human health risk challenges. Results suggest similarities and differences in opinions, an outcome that may be reflective of both the newness and the complexity of this technology. A suitable monitoring period was estimated at about a century; however, uncertainty was three orders of magnitude, with an upper (5th percentile) value of almost 1000 years. For selected low probability high impact georisks, only site selection and monitoring were considered “very” effective RM options. Monitoring, well integrity studies, emergency response plan, automatic emergency shut down system, and training were considered “very” or “extremely” effective in managing two risks more directly related to human health. Experts responded with a wide uncertainty spread for a regulated threshold of minor, major, and catastrophic leakage. A companion paper discusses elicitation findings for issues related to risk assessment.

Keywords

Carbon capture and storage, expert elicitation, risk management, injection, sequestration, health, environment

1 Introduction

Carbon capture and geological storage (CCS) has been identified as a mitigation option for climate change. This technological process can reduce carbon dioxide (CO_2) emissions at point source fossil fuel and industrial process sites such as coal and natural gas electricity generation facilities, or cement, steel, fertilizer and oil upgrader facilities (International Energy Agency [IEA], 2009, IEA, 2013a, IPCC, 2005, IPCC, 2014b). In 2010, CO_2 from fossil fuel and industrial processes was estimated at 32 $GtCO_2e$/year, accounting for 65% of total annual anthropogenic GHG emissions, and up from 55% in 1970 (IPCC, 2014b).

The overarching purpose of CCS is long term retention of CO_2 in deep geological formations, where large scale integrated projects (LSIPs) have the capacity to store at least 800,000 tonnes of CO_2 annually for a coal–based power plant or at least 400,000 tonnes of CO_2 annually for other emissions from intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2016b). Estimates suggest that up to 3,000 dedicated large scale geological sequestration storage projects, storing a cumulative 123 $GtCO_2$, are necessary worldwide if CCS is to achieve a projected 13% reduction in CO_2 emissions by 2050, and thus making a measurable contribution to climate change mitigation (GCCSI, 2014a, IEA, 2013a).

CCS projects include four value chain activities: CO_2 capture and compression to a supercritical state, pipeline transport, deep wellbore injection, and permanent storage in geological formations (i.e., saline aquifers). While addressing the global environmental and human health impacts of climate change, the overarching goal for CCS project proponents and regulators is to ensure local safety and environmental protection while storing CO_2 for the long term. Indeed, environmental and human health hazards have been identified for each of the value chain activities. When CCS projects were first initiated, risk assessment and management of capture and transport chain activities were better known and understood than injection and storage components (Damen et al., 2006, Koornneef et al., 2012). Today, research and experience are improving understanding and reducing uncertainty in the latter activities (Pawar et al., 2014, Pawar et al., 2015).

With a focus on injection and storage in saline aquifer sequestration projects, an expert elicitation of scientific judgements was convened in an effort to quantify collective uncertainty judgements for a number of complex environmental and human health risk challenges related to CCS. The present paper provides findings related to risk management, including options for addressing low probability high impact events. The elicitation also considered issues in risk assessment, findings for which are detailed in a companion article (Larkin et al., *submitted-e*).

Structured expert elicitation

Structured expert elicitation has been shown to be of value where there is limited experience and large uncertainties, but where risks are considered very low (Aspinall, 2010). CCS, in particular sequestration in saline aquifers, is a relatively new technology that falls within these parameters.

Since the early 1990s, structured expert elicitation has been used to discern risk ranking, uncertainty, and risk management options for wide ranging issues of societal importance (Cooke and Goossens, 2008, Oraby et al., In press, Tyshenko et al., 2012, Tyshenko et al., 2011). With respect to CCS, this approach has been recommended within a suite of tools to be used in risk assessment (Gerstenberger et al., 2013). It was also applied in a research project, in combination with Bayesian Belief Networks analysis, in considering the detection and stabilization of a potential CO_2 plume in the CO2CRC Otway Stage 2C experiment (Australia) (Gerstenberger and Christophersen, 2016) .

Elicitation parameters

The portion of the facilitated expert elicitation reported here focuses on environmental and human health risk management issues for saline aquifer sequestration projects, particularly with respect to injection and storage and management of low probability high impact (LPHI) events (See Appendix A for instrument). Carbon capture utilization and storage (CCUS) projects are also operational, particularly for enhanced oil recovery (EOR) operations that use CO_2 in a miscible flood. Another CCUS project type is enhanced coal bed methane (CBM) recovery operations, where injected CO_2 remains permanently stored in the coal. CBM are the least common CCUS projects undertaken to date (Massachusetts Institute for Technology, 2016).

Environmental and human health issues associated with CCS have been discussed in broad terms by Wilson et al. (2003) and included both local environmental risks (CO_2 in the atmosphere or shallow subsurface; CO_2 dissolved in subsurface fluids; and geological displacement) and the risk to the global environment, should project leaks re-emit stored CO_2 to the atmosphere. More recently Koornneef et al. (2012), Bowden et al. (2013b), and Pawar et al. (2015) expanded the spectrum of environmental risks for the natural environment: CO_2, brine or process contaminants can affect air, soil, and groundwater quality. Bowden et al. (2013a), in their list of biosphere risks, extended this further to include wildlife, prairie, recreation, and industry assets related to air, soil and water issues. Jones et al. (2015) reviewed research and experience regarding the potential impacts of CO_2 leakage on potable water resources and ecosystems.

Project level human health hazards include exposure to supercritical CO_2 and the effects of induced seismicity on built infrastructure (Koornneef et al., 2012). Morbidity and mortality can result from inhalation of elevated CO_2 concentrations in the atmosphere, should there be a sudden release of the supercritical CO_2 stream. Seismicity could affect human populations should the built infrastructure become weakened. Furthermore, re-release of CO_2 could worsen GHG concentrations in the atmosphere, thereby contributing to climate change, with concomitant environmental and health risks. This is also germane from a population health perspective, as environmental conditions are an important determinant of health.

2 Methods

The elicitation methods are described in detail in the companion article that provides findings with respect to important issues in risk assessment (Larkin et al., *submitted-e*).

In brief, twelve international experts participated in the structured expert elicitation using video conferencing over two consecutive part-days in March 2015. Five participants from government research centres and seven from academia had extensive expertise in varied aspects of geoscience, risk assessment, and monitoring (for additional expert detail, see Appendix D). The group first arrived at a common understanding of terms and context, with an emphasis that the elicitation did not concern a specific project site but that the location of a project would be away from major urban centres. Other understandings included leakage types and failure scenarios and the boundary between injection and storage activities. Additional questions of clarification and group interpretation were permitted throughout the process. Experts completed and returned elicitation target questions individually within distributed spreadsheet file response tables.

Partial results for one participant, who withdrew voluntarily from the elicitation after the first day, are not included in the analysis.

The risk management target questions had two formats:

a) *Numerical uncertainty distribution.* In preparation for numerical uncertainty distribution target questions, the elicitation began with expert calibration under Cooke's Classical Model (Cooke, 1991). This step provided a distinct performance weight (PW) for each expert statistically based on their ability to judge uncertainties, as established by their accuracy (best judgement) and uncertainty informativeness (90% credible range) for eighteen questions for which the answers were known. The Cooke Classical Model is the only currently available technique that enables genuine empirical control such that the result of the PW median solution and associated uncertainty distribution is a valid representation of the group view (Aspinall and Cooke, 2013, Cooke, 1991, 2013).

Experts then answered target questions with best judgement responses for the quantity in question (50th percentile), as well as the 90% credible range (lower limit 5th percentile and upper limit 95th percentile). Risk management questions considered the regulated threshold for likelihood of storage leakage, safe storage lifetimes, long term retention, storage monitoring period, and relative effort and project costs that should be focused on risk management. Calibration and target question responses in this format were processed using the EXCALIBUR software package (Cooke, 1991, Cooke and Goossens, 2008, Tyshenko et al., 2011).

b) *Likert scale rating.* A 5-level Likert scale was used to elicit expert opinion on the effectiveness of six risk management (RM) options for five low probability high impact (LPHI) events. A description for each level of effectiveness was provided: not at all effective (1); minimally effective (2); moderately effective (3); very effective (4); extremely effective (5). Prior to providing their responses, the experts added an additional level: (6) “0/Not applicable”.

The rated LPHI events were: large migration out of pore space, caprock fracture, induced seismic event M>4, massive release of CO_2 resulting in human fatalities, and catastrophic wellhead injection failure. The RM options were: site selection, well integrity studies, emergency response plans, monitoring, automatic emergency shut down system, and training (operating procedures). Expert panel responses in this section were also converted to equivalent pairwise preference matrix form, and re-processed with the Unibalance Probabilistic Inversion algorithm (Macutkiewicz and Cooke, 2006).

Likert scale responses and associated paired comparisons were not weighted based on calibration question responses used in the numerical uncertainty distribution format. However, pairwise preferences were checked for internal consistency.

Following completion of the structured elicitation, a third facilitated video conference session provided experts with preliminary findings. Some of these findings, combined with expert comments, suggested further clarification of some items would be beneficial. An explanatory document (Appendix A) summarizing the rationale for such clarifications was distributed electronically and all experts completed and submitted responses to the re-elicitation target questions on an individual basis.

3 Results

3.1 Numerical uncertainty distributions

Table 5.1 provides the median performance-weighted responses and 90% credible intervals provided by the experts for risk management target questions. Appendix D (Supplementary Material, Chapter 5) includes figures with individual expert responses, performance weight (PW), and equal weight (EW) distributions, along with composite plots of comparative piece-wise uncertainty distributions for linked target items, representing the three quantiles (i.e. 5th, 50th and 95th percentiles) of aggregated performance weighted judgements. Figures 5.1 and 5.2 provide examples of these representations. Re-elicited questions include R suffix in numbering.

a) Regulated threshold for likelihood of minor, major or catastrophic storage leakage

TQ37R-39R - Preamble:

Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 *annually for a coal–based power plant, or at least 400,000 tonnes of* CO_2 *annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).*

What should be the regulated threshold for the likelihood of minor, major or catastrophic storage leakage in a LSIP sequestration project (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

Table 5.1: Median performance-weighted responses and 90% credible intervals provided by the experts to target questions (R in question number denotes re-elicitation.)[9].

Target Question (unit of response)	Median Value	90% Credible Interval
TQ37R-39R. What should be the regulated threshold for the likelihood of minor, major or catastrophic storage leakage in a LSIP sequestration project (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?		
a) Minor leakage	1 in 202	1 in 39,600 to 1 in 2.7
b) Major leakage	1 in 4,060	1 in 337,000 to 1 in 40
c) Catastrophic leakage	1 in 399,000	1 in 1.1 million to 1 in 338
TQ43R: How long will a typical saline aquifer storage site remain safe, where safe means 95% or more facilities will not fail in the time periods you specify (years)?	12,700 yrs	8.6 million yrs to 166 yrs
TQ44R: How long will a typical saline aquifer storage site remain safe, where safe means 50% or more facilities will not fail in the time periods you specify (years)?	125,000 yrs	80 million yrs to 5,130 yrs
TQ45R: How long will a typical saline aquifer storage site remain safe, where safe means 5% or fewer facilities will not fail in the time periods you specify (years)?	1 million yrs	780 million yrs to 15,100 yrs
TQ46: In a typical large scale integrated <u>saline aquifer</u> storage project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)	99.8%	87% to 100%
TQ47: In a typical large scale integrated <u>enhanced oil recovery</u> storage project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)	99.85%	54% to 100%
TQ55: What should be the storage project monitoring period (years)?	92 yrs	8 yrs to 990 yrs
TQ56: Considering potential negative impacts of CCS on either the environment or human health, what proportion of risk management should be focused on mitigating environmental impacts as opposed to human health impacts (0-100%)?	12%	1.1 % to 69 %

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[9] Exact meaning should not be ascribed to the precision of these reported results – they should be regarded as indicative.

TQ57: On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)?	5.5 %	1.1% to 17 %
TQ58: Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?	11 %	1.1 % to 25 %

Having agreed to an understanding of three CCS leakage failure scenarios, Table 5.1 indicates a decreasing median regulated threshold moving from minor, to major, to catastrophic scenarios, as well as wide solution uncertainty spread for all three scenarios. However, there is some separation into high and low risk ‘schools of thought’ in all three cases (Supplementary Material). It appears there are significant differences of opinion within the expert panel, perhaps indicating that this risk management option has not been previously considered thoroughly or in detail by the participants.

b) Safe storage lifetimes at ‘low-end’, ‘median’ and ‘high-end’ safe storage periods

TQ43R-45R - Preamble:

Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 *annually for a coal–based power plant, or at least 400,000 tonnes of* CO_2 *annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).*

Assuming no fundamental change in technology, what is the safe storage lifetime of a typical saline aquifer storage site at the following confidence levels? Please give three durations to express your uncertainty.

TQ43R: How long will a typical saline aquifer storage site remain safe, where safe means 95% or more facilities will not fail in the time periods you specify (years)?

TQ44R: How long will a typical saline aquifer storage site remain safe, where safe means 50% or more facilities will not fail in the time periods you specify (years)?

TQ45R: How long will a typical saline aquifer storage site remain safe, where safe means 5% or fewer facilities will not fail in the time periods you specify (years)?

The experts' median period for facilities remaining safe is 12,700 years, 125,000 years, and 1 million years (95% or more; 50% or more; and 5% or fewer facilities, respectively) (TQ43-45R, Table 5.1). Experts' judgement median values showed less uncertainty than EW solutions (Supplementary Material). One expert indicated lifetimes one-to-two orders longer than other panel members, an individual judgement that extended the uncertainty in all cases (Supplementary Material).

c) Long-term retention of CO_2

TQ46: In a typical large scale integrated saline aquifer storage project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

TQ47: In a typical large scale integrated enhanced oil recovery storage project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

The most widely-quoted long-term retention target for storage of carbon dioxide is 99% of injected CO_2 remaining underground for 1,000 years (IPCC, 2005). In this question, experts understood retention to be within the identified storage formation immediately adjacent to the injection wells.

The group median estimate judgement is essentially the same for both saline aquifer sequestration and EOR operations, with approximately 99.83% and 99.85% of injected CO_2 expected to be retained. The uncertainty band is wider for EOR than for saline (TQ46-47, Table 5.1).

d) Storage monitoring

TQ55: What should be the storage project monitoring period (years)?

Next to site selection, CO_2 monitoring to test for containment and performance in CCS projects is the primary risk management activity, where an iterative process to calibrate and update risk assessments and monitoring plans is included in many regulatory-based risk management frameworks and non-regulatory guidance documents (Larkin et al., *submitted-a,* Larkin et al., *submitted-c*). Jenkins et al. (2015) provide a review of the progress in monitoring and verification in the ten years since the IPCC *Special Report on Carbon Capture and Storage* (IPCC, 2005).

Experts' uncertainty judgement suggests a coherent view, with median estimate 92 years monitoring activity, i.e. about a century (TQ55, Table 5.1; Figure 5.1).

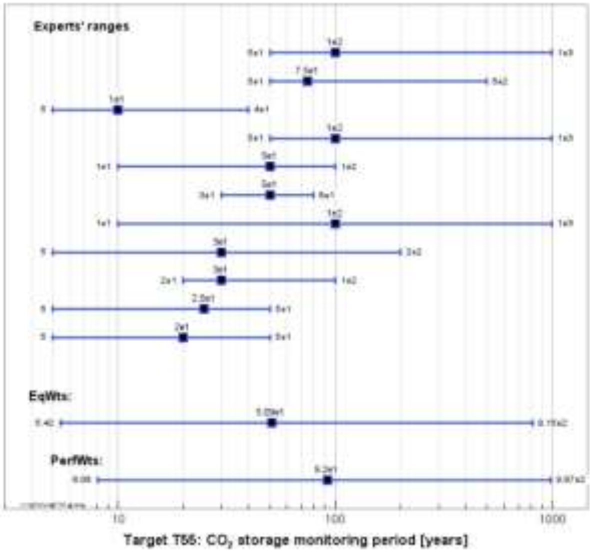


Figure 5.1: Individual expert responses, performance weight (PW), and equal weight (EW) distributions: TQ55: What should be the storage project monitoring period (years)?

e) A triplet of questions considered the proportion of environment and human health risk management and costs within CCS project operations. Experts limited the estimate to injection and storage implementation, thereby excluding exploration, construction, capture and transport activities.

TQ56: Considering potential negative impacts of CCS on either the environment or human health, what proportion of risk management should be focused on mitigating environmental impacts as opposed to human health impacts (0-100%)?
TQ57: On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)?
TQ58: Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?

Findings indicate uncertainty distribution of approximately 1-70% of RM that should be focused on the environment as opposed to human health impacts, with a median estimate of approximately 12% (TQ56, Table 5.1).

Experts' median estimate is that approximately 5.5% of project costs should be mandated by regulatory agencies to protect the environment and human health. This can be compared with experts' response on the percentage budget that should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts, such that the company is reasonably secure against gross negligence claims in any post-failure litigation. Here, the median estimate is approximately 11% or double the suggested regulated amount (TQ57-58, Table 5.1; Figure 5.2).

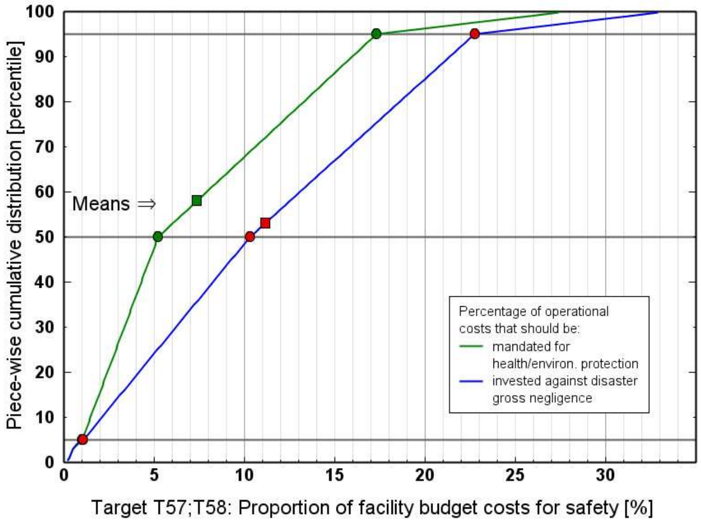


Figure 5.2: Composite plot for of comparative piece-wise uncertainty distributions for linked target items, representing the three quantiles (i.e. 5th, 50th and 95th percentiles) of aggregated performance weighted judgements: TQ57: On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)? TQ58: Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?

3.2 Likert scale effectiveness ratings of risk management options

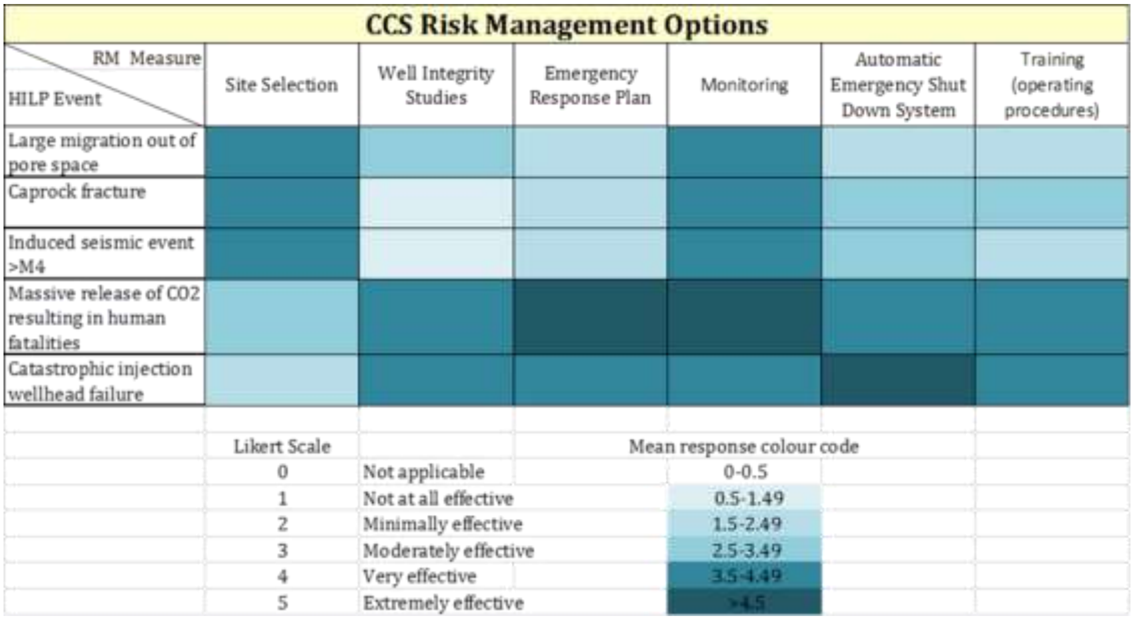
RM2: This question is focused on risk management of high impact low probability (catastrophic) events. For questions related to leakage, please note that the nature of the leaked substance (e.g., CO_2, brine, or another contaminant) is not the focus of the question; rather, the question focuses on a leakage of any kind.

Please rate the effectiveness of each of the following methods to manage risk of high impact low probability (HILP) (catastrophic) events using the following 5-point Likert scale: not at all effective (1); minimally effective (2); moderately effective (3); very effective (4); extremely effective (5); not applicable (6).

Experts rated the effectiveness of site selection, well integrity studies, emergency response plan (ERP), automatic emergency shut down system, and training (operating procedures) in managing the five low probability but high impact events discussed below. Prior to their response, experts arrived at an understanding that “large migration” includes all scenarios such as through a wellbore or geological fault.

Findings are displayed in a heat matrix of mean ratings (Figure 5.3). With the exception of site selection, all risk management options were considered “very” or “extremely” effective in managing risk of potential massive release of CO_2 and catastrophic wellhead failure. Only site selection and monitoring were considered “very” effective risk management options for georisks, namely large migration out of pore space, caprock fracture, and induced seismic events >M4. Monitoring was considered moderately or very effective for all LPHI events.

The pairwise preference matrix form of risk management options for pairs of LPHI indicate that for most scenarios, the group collectively identified definite preferences in ordering for risk management measures (Appendix, Chapter 5). The one scenario for which there is no clear consensus on effective measures is ‘fatal massive CO_2 release’. Supplementary Material also provides: (1) bar charts showing mean of responses for effectiveness of risk management options for each LPHI, with the standard error of the mean score providing a measure of uncertainty in expert opinion; and (2) pairwise preference matrix form of risk management options for pairs of LPHI.



CCS Risk Management Options

RM Measure / HILP Event	Site Selection	Well Integrity Studies	Emergency Response Plan	Monitoring	Automatic Emergency Shut Down System	Training (operating procedures)
Large migration out of pore space	█	▓	▒	█	▒	▒
Caprock fracture	█	░	▒	█	▓	▓
Induced seismic event >M4	█	░	▒	█	▓	▒
Massive release of CO2 resulting in human fatalities	▓	█	■	■	█	█
Catastrophic injection wellhead failure	▒	█	█	█	■	█

Likert Scale		Mean response colour code
0	Not applicable	0-0.5
1	Not at all effective	░ 0.5-1.49
2	Minimally effective	▒ 1.5-2.49
3	Moderately effective	▓ 2.5-3.49
4	Very effective	█ 3.5-4.49
5	Extremely effective	■ >4.5

Figure 5.3: Mean effectiveness rating of six risk management options for five low probability high impact events: large migration out of pore space; caprock fracture; induced seismic event M>4; massive release of CO_2 resulting in human fatalities; catastrophic injection wellhead failure.

A large migration of CO_2 out of the pore space could extend the plume to geological formations and anthropogenic features that were not assessed, thereby increasing the risk to performance and containment success. Jenkins et al. (2015, p. 334) suggested that “the complex interplay of highly reflective thin layers, tuning effects, variable fluid saturation and mixing patterns, various modes of signal attenuation still renders full understanding of the plume highly challenging".

Caprock is the sealing formation of low permeability rock that is a critical feature for CO_2 containment at a CCS site (IPCC, 2005). Its damage through caprock fracture, potentially caused by injection pressures, would open a pathway into or through the formation potentially enabling stored CO_2 or brine to reach the surface environment.

Induced seismic events with magnitude M>4, potentially caused by injection pressures, could result in unanticipated leakage scenarios through a fractured caprock or release through a fault pathway. In addition to potential CO_2 or brine leakage that could affect drinking water, felt earthquake tremors are a concern with respect to public acceptance because of property damage or nuisance (White and Foxall, 2016). Birkholzer et al. (2015) linked slips on existing faults to broken seals. Both Pawar et al. (2015) and Celia et al. (2015) noted ongoing difficulty in risk assessment of induced seismicity, in part because of limited data sourced from large operations. White and Foxall (2016) reviewed technical difficulties associated with achieving effective risk assessment and risk management of induced seismicity, as well as progress to address them. Discussion included fault identification; microseismic event detection, location, and characterization; estimating earthquake recurrence and influence of injection; ground motion prediction; and structural and community vulnerability (White and Foxall, 2016).

A massive release of CO_2 resulting in human fatalities could occur during capture, transport, injection, or storage activities, the latter through an existing wellbore. While normal air concentrations of CO_2 are typically less than 1%, the relatively large volume, concentrated and pressurized CO_2 stream in CCS could pose a hazard to humans and other living organisms. The National Institute for Occupational Safety and Health defines an ambient CO_2 concentration of 4% as immediately dangerous to life and health (IDLH) (Centers for Disease Control and Prevention, 2016), whereas the target purity of the supercritical CO_2 stream is 97-99.9% depending on the capture technology. Stream impurities, such as hydrogen sulphide, may also affect human health and the near surface biosphere (Koornneef et al., 2012).

Similarly, catastrophic injection wellhead failure could affect project workers, contaminate the local environment, reduce or shut down project performance, and exacerbate public concern. Quintessa Ltd. (2013), the online CO_2 database of features, events and processes, describes this event as an "uncontrolled flow of fluid (liquid, gas or supercritical fluid) into the injection wellbore, followed by [rapid] transport of the fluid to a shallower geological formation (underground blowout) or to the land surface or seabed."

4 Discussion

Environmental and human health risk management for CCS projects considers potential performance and containment hazards in an effort to ensure large scale integrated projects operate as planned. CO_2 capture, transport, injection, and geological storage need to be effectively and safely deployed by operators while operators and regulators need to minimize the likelihood and severity of local hazards and related risk issues. These include contamination of air, soil, or water resources from process contaminants, CO_2, or brine; human, wildlife or livestock morbidity and mortality from exposure to highly concentrated CO_2; and induced seismicity causing surface uplift or earthquake, with damage to infrastructure. The goal of permanently sequestering CO_2 emissions and mitigating climate change, with associated benefits to the global environment and population health, could also be negated should there be higher than expected CO_2 leakage rates.

A wide variety of risk management options should be considered and applied to an integrated, interdisciplinary technology such as CCS. As a principle of population health, coordinated action at multi-levels and multi-scales assists in protecting the determinants of health. While not comprehensive in terms of risk management options for CCS (also see Larkin et al. (*submitted-a*) in this issue), elicited target items are situated within five categories of action proposed by Krewski et al. (2007) and Krewski et al. (2014) under the REACT framework that considers regulatory, economic, advisory, community-based, and technological options (Table 5.2). A number of options require action by stakeholders under more than one category of action.

Table 5.2: Elicited risk management options associated with five categories of action

<table>
<tr><th colspan="5">Risk Management Options</th></tr>
<tr><th>Regulatory</th><th>Economic</th><th>Advisory</th><th>Community-based</th><th>Technological</th></tr>
<tr><td colspan="5">Regulated leakage likelihood threshold</td></tr>
<tr><td colspan="2">Regulated mandated cost allocation</td><td colspan="2">Proponent’s cost commitment</td><td></td></tr>
<tr><td>Site selection</td><td></td><td colspan="3">Site selection</td></tr>
<tr><td>Emergency Response Plan</td><td></td><td colspan="2">Emergency Response Plan</td><td></td></tr>
<tr><td>Automatic emergency shut down</td><td></td><td></td><td></td><td>Automatic emergency shut down</td></tr>
<tr><td>Well integrity studies</td><td></td><td>Well integrity studies</td><td></td><td>Well integrity studies</td></tr>
<tr><td></td><td></td><td colspan="3">Training</td></tr>
<tr><td colspan="5">Monitoring</td></tr>
</table>

4.1 Focus on environmental and human health protection

Two primary concerns for CCS performance, containment, and public perception risk management in injection and saline aquifer sequestration are CO_2 or brine leakage (seepage) to the biosphere. For the shorter operations period, the group's performance-weighted median response suggests 88% of effort should be focused on human health compared with environmental protection (TQ56, Table 5.1). Experts also suggested greater health than environmental risk in capture compared with storage (Larkin et al., *submitted-e*). As an economic risk management option, experts' central estimate was that 5.5% of injection and storage project costs should be mandated by regulatory agencies for both environment and human health protection, with a 90% credible range ~1%-17% (TQ57, Table 5.1). Based on 2010 US$ analysis of the FutureGen project's Environmental Impact Assessment, Trabucchi et al. (2012) suggested the damages to human health and the environment from pipeline ruptures and subsurface leakage could be less than 1% of total estimated project costs over a 100-year operating period, but that the range in damage estimates would be site dependent.

Experts' numerical uncertainty distribution for the fraction of CO_2 expected to be retained for the long-term (1,000 years) indicates the same median estimate judgement (99.8%) for both saline aquifer and EOR projects (TQ46-47, Table 5.1). This is in keeping with the IPCC *Special Report on Carbon Capture and Storage* (IPCC, 2005), where a summary of evidence for retention and release rates suggested more than 99% of CO_2 would be retained over the first 1,000 years. In 2005 and 2007, experts set the acceptable project leakage rate at 1% over 1,000 years for the Otway research project (Watson et al., 2014). Similarly, the containment risk target within a geosphere risk assessment workshop for the Weyburn-Midale EOR project was 99%

retention of total injected mass of CO_2 over 1,000 years (Bowden et al., 2013b). However, the expert panel's 90% credible interval was greater for EOR, with the lower limit having greater variability than upper limit values (TQ46-47, Table 5.1). At the low/5th percentile, that is a 1 in 20 judged likelihood, experts' suggested 87% and 54% of CO_2 would be retained in saline aquifer sequestration and the EOR project type over 1,000 years, respectively. Wilson et al. (2003) and IPCC (2005) suggested the effects of re-release are time-dependent, with less serious effects if anticipated leakage occurs in the long term. Nevertheless, re-release of unanticipated volumes of CO_2, for reasons described by Meadowcroft and Langhelle (2009, p. 284) as basic knowledge failure, practical knowledge failure, or significant regulatory failure, could affect the role of CCS in emissions reductions, thereby exacerbating public acceptance as well as anticipated population health benefits of climate change mitigation.

Responses to our set of elicitation questions on what should be the regulated threshold for the likelihood of minor, major, or catastrophic storage leakage suggested wide ranging views, possibly suggesting that this risk management strategy has not (yet) engaged the thinking of the expert panel in the way presented. A regulated threshold for leakage scenarios could be developed, as are used in risk management for industrial emissions of contaminants to air, soil, and water. In their review, Koornneef et al. (2012) did not identify clear performance indicators (including amount of CO_2 leaked) and recommended they be developed in conjunction with thresholds linked to potentially affected environmental compartments. Others have described a percentage of the total volume injected, for example 0.01%-0.001% per year (1% over 100 years up to 1% over 1000 years) (IPCC, 2005, Stenhouse et al., 2009). In an attempt to assess the probability that leakage and leakage rate to atmosphere would surpass a regulated threshold, Gerstenberger et al. (2015) proposed an assessment structure to calculate rate, volume, and concentration level of CO_2 that would be compared to local health, safety, or environment standards.

Safety in the elicitation was defined as percentage of facilities not failing and the expert elicitation panel understood that a generic storage site would be properly selected, characterized, and designed. The median response indicated that for greater than 95% of storage, these would remain safe for almost 13,000 years, albeit with wide 90% confidence bounds. Both the median number of years and uncertainty increased as the percent of safe facilities decreased (TQ43R-45R, Table 5.1).

Markusson et al. (2012a, p. 912) suggested "there is uncertainty as to whether geological storage of CO_2 will prove safe over long time periods, as well as if and how the associated risks can be reliably assessed and managed". In another application, safety criteria have been determined for Yucca Mountain, the potential geologic repository to store and dispose of high-level radioactive waste. The 2008 Environmental Protection Agency standard set a radiation dose limit to protect public health for the first 10,000 years after disposal, with a higher acceptable limit between 10,000 and 1 million years (US Environmental Protection Agency, 2016). Watson et al. (2014) also used the management of radioactive waste in the UK as an analogue case study regarding safe storage uncertainties that could inform CCS.

Given the long project lifespans, sometimes referred to as "permanent sequestration" spanning centuries, Bachu (2008) discussed the assumption of long-term operational and financial liability for both monitoring and remediation in case of CO_2 leakage. In addition to the injection and storage project costs should be mandated by regulatory agencies for both environment and human health protection, proponents could make a further financial commitment to be reasonably secure against gross negligence claims in any post-failure litigation. The experts' median estimate was approximately 11% of the injection and storage operational budget, double the suggested regulated amount. While the lower limit was equal for costs mandated and invested, the upper limit was more variable (TQ57-58, Table 5.1). Wilson et al. (2009) assessed the liability regime for CCS in the US and suggested risk management tools that could provide financial security to investors. While not limited to environmental or health impacts of leakage scenarios outside of normal operating conditions at CCUS projects, Pollak et al. (2013) proposed a leakage impact valuation (LIV) method to estimate the financial implications for wide ranging stakeholders (for both low and high cost storylines): leakage only, interference with each of subsurface activity and groundwater, and migration to the surface. A cost category was included for legal expenses that may be incurred by the geologic storage site operator to defend against lawsuits in the United States.

Should data be made available, further research into budgeting for existing and proposed CCS projects could begin to clarify and quantify proponents' perspectives and effort in environmental and human health risk management.

4.2 Low probability high impact events

Dedicated risk management of LPHI is necessary for continued public and public sector support of this new technology. A poor outcome could not only affect containment risk, but public perception, and public acceptance overall.

The elicitation considered risk management of LPHI events in two ways. Relative risk of four distinct causes of local health or environmental hazards was assessed using pairwise preference semi-quantitative ranking, as discussed in the companion article (Larkin et al., *submitted-e*). In this question, experts ranked caprock integrity loss due to hydraulic fracturing as a lower relative hazard, but did not agree on the rank order of the other three hazards: brine, HCO_3, or elevated gas-phase CO_2 migration into the shallow subsurface and near-surface environment; a seismic event of magnitude $M \geq 5$ on the Richter scale; or explosive re-release of CO_2 to the surface.

These hazards were closely reiterated in the Likert-scale rating of risk management options for LPHI events (Table 5.3). Such hazards were also assessed as accidents, malfunctions and unintended events (AMUE) under the *Canadian Environmental Assessment Act* review of the Shell Quest project (Shell Canada Limited, 2010). Note that risk management in the present elicitation was focused on injection and storage and therefore excluded capture infrastructure included by Shell.

Table 5.3: Selection of low probability high impact (LPHI) events in carbon capture and storage

RM of five LPHI Events (Figure 5.3)	Relative risk - distinct causes of local environmental and human health hazards (companion article)	Shell Quest Accidents, Malfunctions and Unintended Events (Shell Canada Limited, 2010)
Large migration out of pore space	Brine/gas CO_2 migration into shallow subsurface, near surface	Release of CO_2, BCS brine or CO_2 saturated brine from the storage complex or injection wells
Induced seismic M>4 quake[1]	Seismic event M>5[1]	
Caprock fracture	Caprock integrity loss due to hydraulic fracturing	
Massive release of CO_2 resulting in human fatalities	Explosive re-release of CO_2 to the surface	CO_2 pipeline rupture or injection well head failure
Catastrophic wellhead failure		
		Process upsets in CO_2 capture infrastructure

[1] Slightly different cutoff in each question.

An interesting finding of the elicitation is the dichotomy of risk management approaches deemed effective for three LPHI leakage georisks compared with events more directly related to human health and safety (Figure 5.3). Only site selection and monitoring were considered “very” effective risk management options for large migration out of pore space, caprock fracture, and induced seismic event M > 4. However, with the exception of site selection, the other five risk management options – well integrity studies, emergency response plan, monitoring, automatic emergency shut down system, and training – were considered “very” or “extremely” effective in managing the potential massive release of CO_2 and catastrophic wellhead failure. The expert panel collectively identified order preferences for most risk management options for most scenarios (Supplementary Material). The one scenario for which there was no clear consensus on effective measures is ‘massive release of CO_2 resulting in human fatalities’, where the heat matrix indicates high effectiveness for all options except site selection.

Wilson et al. (2008) discussed the special attention that could apply to injection in CCS sequestration projects, given projected high volumes and inherent buoyancy in the supercritical state. Both individual and societal risk estimates could be calculated. In the Weyburn-Midale EOR project geosphere risk assessment, it was assumed that the public safety (societal) risk would be unacceptable if it exceeded a probability of 1×10^{-3} per year of one or more fatalities (the Australian National Committee tolerability for Large Dams (ANCOLD) guideline limit); and that it would be marginally acceptable if it was between this tolerability limit and a lesser probability level of 1×10^{-4} per year (Bowden et al., 2013b). Pawar et al. (2015) found that one sequestration project application, FutureGen in the United States, estimated the frequency of an eruptive event to be remote (probability of $<10^{-6}$ per 5,000 years). Jenkins et al. (2015) found that analyses have not assessed significant adverse effects on the environment or other resources very well and that contingency planning for an adverse event has not been well developed.

Indeed, Larkin et al. (*submitted-a*), identified few RA/RM frameworks in the regulatory context that include a requirement for contingency plans for large incidents, being limited to the *United Nations Framework Convention on Climate Change modalities and procedures for CCS as a clean development mechanism* (2011), Australia's *Offshore Petroleum and Greenhouse Gas (Environment) Regulation* (Australian Government, 2014), and the US State of Kansas enabling legislation (Kansas State Corporation Commission, 2010). As a non-regulatory guidance document, *DNV* CO_2*RiskMan* (2013) provides extensive hazard risk management guidance to consider the large quantity, concentrated, and pressurized nature of the CO_2 stream within the capture, transport and injection chain activities (Det Norske Veritas, 2013, Holt et al., 2012). However, impacts to groundwater quality from CO_2 or brine, as well as the storage chain, are excluded from the guidance document. Pawar et al. (2015) concluded that research has reduced uncertainty for some major risk issues, such as leakage pathways and induced seismicity, but that more limited efforts have been made to quantify other low probability events of high consequence such as well blowout or catastrophic caprock failure.

An area of further research could consider why site selection was not judged more effective to manage human health risks considering that this phase in project development could underpin safety overall. It is possible the expert panel considered proper site selection having already been completed and so site selection could do nothing more to limit LPHI events.

4.3 Emphasis on monitoring

Monitoring options for CCS help to manage performance, containment, and public perception risk issues in leakage and safety. In considering a suitable monitoring period, the experts' median estimate is 92 years, i.e. about a century in duration (TQ55, Table 5.1). However, responses included uncertainty of three orders of magnitude, with a credible upper limit of almost 1,000-year monitoring period. A monitoring plan during the operations phase of CCS sequestration projects is a mandatory or voluntary activity in a wide variety of elaborated risk assessment and risk management frameworks developed in the regulatory and non-regulatory context (Larkin et al., *submitted-a*).

Dixon et al. (2015) noted that monitoring is based on site specific risk assessments, and that review articles to share good practice and learnings are forthcoming. One of the most detailed existing documents is the US National Energy Technology Laboratory guidance on monitoring, verification, and accounting of CO_2 stored in deep geologic formations (2012). (This general topic is usually referred to as MMV – monitoring, measurement and verification – but in the US it is also called MVA – monitoring, verification, and accounting). In 2012 the NETL best practices was that projects demonstrate 99% retention of CO_2 through GS [geological sequestration], up from 95% in 2008. These retention levels were defined by the ability of a sequestration site to detect CO_2 leakage at levels of 5% and 1% of the stored amount of CO_2 into the atmosphere. Jenkins et al. (2015) reviewed advances in monitoring technologies. In Alberta, the Quantification Protocol for CO_2 Capture and Permanent Storage in Deep Saline Aquifers (Government of Alberta, 2015c) requires MMV of containment, as described in the Alberta Energy Regulator directives for MMV activities under the *Mines and Minerals Act.* Project developers must attempt "to ensure there are no emissions from the subsurface to the atmosphere" (Government of Alberta, 2015c, p. 56). Bourne et al. (2014) describe the MMV plan for the Quest project operating in that province.

Project leaders and regulators continuously improve understanding of injectivity and storage parameters such as flow and pressures, ultimately seeking to demonstrate that a storage site is operating safely and reliably as planned. With respect to LPHI, Jenkins et al. (2015, p. 343) suggested that "explicit consideration of significant adverse events would be helpful in designing monitoring strategies and clarifying requirements". This review acknowledged the need for a number of techniques, also suggesting monitoring could nevertheless miss significant adverse events, notwithstanding the evidence from the past decade that has demonstrated these risks to be small, and indeed less than risks posed by climate change.

With the emphasis on monitoring as one of the preferred RM options, effective mitigation responses are also required should an adverse circumstance be identified. Guénan et al. (2011) created a database of mitigation measures for risk events and Manceau et al. (2014) provide a review of mitigation and remediation technologies and practices for the case of undesired CO_2 migration in a storage unit. Farhat and Benson (2015) proposed a methodological framework that aims to link risk assessment to corrective measures, using a collaborative and transparent contingency planning process; this could have potential application to LPHI events. On the other hand, Pawar et al. (2015) suggested that an assessment of mitigation options themselves is not well advanced.

5 Conclusion

In an effort to assess and address potential hazards associated with an activity or innovation, risk assessment and management has been undertaken conjointly and are fundamentally matters of judgement in probability and uncertainty (National Research Council, 1983). Within this context, efforts attempt to determine acceptable societal risk and risk control options.

In this paper, findings from a structured expert elicitation provide insights into target questions focused on CCS issues in risk management. A companion article provides the expert panel's judgements on a series of risk assessment target questions that provide a backdrop to the risk management options discussed here (Larkin et al., *submitted-e*). Findings include pairwise rankings of risks between technology, environment, and health in each domain of capture, transport, injection, and storage; experts' best estimate and uncertainty bounds for likelihood of leakage in each of capture, transport, injection, and storage (the latter over three time periods);

judgements for the likelihood and severity of well leakage, injection, intrinsic storage, and induced storage hazards that could cause leakage or seepage; and judgements on the likelihoods of major CO_2 storage leakage that would require an intervention to mitigate negative environmental impacts or adverse public health impacts over three time periods: 0-50 years, 51-499 years, and 500+ years. This article also provides comments on the elicitation process.

In conjunction with findings for risk assessment, we have increased understandings of relative risk and quantified collective uncertainty judgements for a variety of difficult decision challenges for CCS. Some responses to quantitative target questions conveyed larger judged uncertainties than others. For example, the percentage of facilities achieving safe storage lifetimes as a function of time ranged over five orders of magnitude. In almost all cases the performance weight uncertainty was less than equal weight. CCS is a multidisciplinary approach to climate change mitigation requiring a diversity of expertise for safe and secure CO_2 injection and sequestration in the long term. It is hoped that outcomes reported here might stimulate further scientific deliberations towards achieving objective judgements on CCS risk issues.

Risk management of low probability high impact (LPHI) events is particularly important because effects could unfold at both the local and global scales, both within the project’s designated area of influence or emergency planning zone, and more broadly with respect to public acceptability of the CCS technology worldwide. A LPHI event has the potential to seriously affect the future implementation of CCS – whether a major accident resulting in morbidity or mortality, unintended large migration of CO_2 out of the pore space, caprock fracture, or an induced significant seismic event. Site selection and monitoring were deemed very effective georisk management options; and five options of well integrity studies, emergency response plan, monitoring, automatic emergency shut down system, and training considered “very” or “extremely” effective in managing the potential massive release of CO_2 resulting in human fatalities or catastrophic wellhead failure.

The emphasis on monitoring as a risk management option leads to the question of how long this should continue and potential mitigation of an adverse event. Our experts’ pooled median response was a period of almost 100 years, although reservations, arising from uncertainty, could plausibly extend this to almost 1000 years. The development of robust protocols for credible monitoring and verification, and the testing of these protocols in public engagement processes, could be viewed as essential for risk acceptability of CCS. Public understanding for the proposed response(s) to an adverse measurement is likely of equal importance.

The findings and insights from the expert elicitation of scientific judgements reported here illustrate risk management options that could be considered during the review and approval of potentially thousands of deep geological saline aquifer sequestration projects worldwide. Indeed, public stakeholders could be unforgiving if hazard assessment and risk management in CCS is considered insufficient, thus affecting future implementation of this climate change mitigation technology. On the other hand, comprehensive risk assessments and rational risk management could impact public perception for CCS positively, in turn instilling confidence, public acceptance, and ongoing support.

Chapter 5 References

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Chapter 6: An Integrated Risk Assessment and Management Framework for Carbon Capture and Storage in the Canadian Context

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Abstract

Risk assessment and management (RA/RM) frameworks focused on health and environmental effects of carbon capture and storage (CCS) have been published worldwide. Non-binding guidance is emphasized, possibly because governments may require RA/RM in general terms within established legislation or regulations. Storage site selection and characterization is often identified as the most effective approach to reduce risk; an iterative approach is recommended to monitor and re-assess risk; accessible and transparent processes are gaining momentum; and comprehensive risk estimation is not yet promoted. An integrated risk management framework for CCS in the Canadian context is proposed with reference to steps demonstrated in CCS projects to date. Findings from an expert elicitation of relative risk and uncertainty in injection and storage illustrate a number of difficult decision challenges that will exist during future approval processes. Components of the next generation in risk-based decision making are described and applied to the IRMF for CCS.

Key words

Carbon capture and storage, risk assessment, risk management, framework, health, environment, injection, storage, expert elicitation

1 Introduction

Beginning with *Risk Assessment in the Federal Government: Managing the Process,* also known as the "Red Book" (National Research Council, 1983), the process of risk assessment and risk management is fundamentally a matter of judgement in probability and uncertainty. The graphical representation of risk assessment and risk management processes related to technologies and technological change has evolved significantly over the past thirty years, with enhancements to the defined steps that address health and environmental risks (Krewski et al., 2007, Leiss et al., 2010). Jardine et al. (2003) found that risk management processes should meet the decision making needs of the specific application. There has also been an increased requirement to communicate the technical analyses in risk assessment and management to much broader audiences in order to try to improve the level of public confidence in the ultimate decisions based on them (Leiss et al., 2010). Another issue is the recognition that many of the most complex risk issues are shared by a mix of nations around the world (sometimes all of them, for example with climate change), and that effective international coordination of risk management decision making – in an age of increasing global economic integration – is both desirable and necessary.

This paper first provides an overview and comparative analysis of comprehensive risk assessment and risk management (RA/RM) frameworks for carbon capture and storage (CCS) that have developed in both the regulatory and non-regulatory context since the *Special Report on Carbon Capture and Storage* was published by the Intergovernmental Panel on Climate Change (IPCC, 2005). Major frameworks contain, at a minimum, a list of considerations for health or environmental RA/RM during project planning and implementation; more elaborated frameworks contain detailed methodological considerations or requirements. Collectively, these frameworks offer valuable guidance on how to move forward with this technology in a safe and effective manner.

As an outstanding issue for CCS, Koornneef et al. (2012) suggested that ongoing uncertainty in injection and storage components of integrated projects has the potential to become a bottleneck for wide-scale implementation of CCS, if not properly addressed. An overview and preliminary findings from a recent structured expert elicitation on uncertainties and potential risks in injection and storage, and risk management of low probability high impact events, are provided in Section 3.

The elements of the comprehensive frameworks and elicitation results are incorporated into the proposed integrated risk management framework (IRMF) for carbon capture and storage in the Canadian context, Section 4. Attributes and practical dynamics of the IRMF are described, as well as risk-based decision making and risk management for CCS within the next generation of risk science (Krewski et al., 2014). This includes important considerations for CCS project proposals that could underpin identifying, evaluating, selecting, and implementing acceptable risk control options. Based on the REACT framework for risk management and population health (Krewski et al., 2007, Krewski et al., 2014), wide-ranging options for CCS risk management interventions are identified.

2 Overview of Comprehensive Frameworks

Selected RA/RM regulations, guidelines and best practice manuals were reviewed by Forbes et al. (2009), Stenhouse et al. (2009), Condor et al. (2011a), and Larkin et al. (*submitted-c*). Dixon et al. (2015) also provided details on the historical development and provisions within significant CCS regulations. All elaborated RA/RM frameworks are included here for completeness.

2.1 Elaborated RA/RM frameworks in a regulatory context

2.1.1. *International Maritime Organisation, London Convention and Protocol*

The *Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures* (*RAMF*) (International Maritime Organization, 2006) was adopted by Contracting Parties under the London Convention in association with the amendment to Annex 1 of the London Protocol. The framework is for guidance only, to be applied on a site-specific basis to enable the collection of all necessary information to address uncertainties and any residual risks. The six stages include problem formulation; site selection and characterization; exposure assessment; effects assessment; risk characterization; and risk management. Parties to the London Protocol also adopted the *Specific Guidelines on Assessment of CO_2 Streams for Disposal into Sub-Seabed Geological Formations* (International Maritime Organization, 2012). These guidelines advise on stream characterization and acceptability, site selection and characterisation, effects (risk) assessment, monitoring, and risk management.

2.1.2. *OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic*

The OSPAR *Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations* discuss the elements of a risk assessment framework applicable to both onshore and offshore geological CO_2 storage projects (OSPAR Commission, 2007). They are mandatory and are in force, although their application includes some flexibility (Dixon et al., 2015). An iterative process for continual improvement during CCS project life cycle is described in Annex 1 to the guidelines, the *Framework for Risk Assessment and Management*

(FRAM), including the following steps that built upon the London Protocol RAMF: problem formulation; site selection and characterisation; exposure assessment; effects assessment; risk characterisation; and risk management. "A decision to grant a permit or approval shall only be made if the process is completed to the satisfaction of the competent authority and that the storage will not lead to significant adverse consequences for the marine environment, human health, and other legitimate uses of the maritime area" (OSPAR Commission, 2007, p. 4).

2.1.3. *European Union Directive on the Geological Storage of Carbon Dioxide (CCS Directive)*

The EU CCS Directive (European Union, 2009) sets criteria for assessing the safety of a storage site, including potential risks associated with leakage or other significant environmental or health impacts. Risk assessment is mandatory and framed in a similar way to the RAMF of the London Protocol and the FRAM of the OSPAR Convention. This assessment requires: hazard characterisation; exposure assessment; effects assessment; and risk characterisation, including geological characteristics and use of computerised storage simulations. It requires an assessment of sources of uncertainty and evaluation of ways to reduce uncertainty. Guidelines for site monitoring are contained in an Annex, including provisions for a Monitoring Plan, Corrective Measures Plan, Update to the Monitoring Plan, and Post-closure Plan.

In support of the CCS Directive, four non-binding guidance documents were published. For example, guidance on the *Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures* (European Commission, 2011b) elaborates on these titled issues, as well as exposure and effects assessment, including risk ranking. It also describes processes to be used by competent authorities to interact with operators at various stages in the

CCS value chain, particularly with regard to risk management. Other EU Directives that apply to CCS RA/RM include the Environmental Assessment Directive (European Union, 1985).

2.1.4. *UN Framework Convention on Climate Change, Clean Development Mechanism*

The *Modalities and procedures for carbon dioxide capture and storage in geological formations* as a Clean Development Mechanism (United Nations Framework Convention on Climate Change, 2011) enables industrialized countries to earn certified emission reduction credits for CCS projects undertaken in developing countries. There are mandatory requirements for the selection and characterization of the geological storage site, risk and safety assessment for human health and ecosystems, and monitoring. Site characterization shall consider dynamic behaviour, sensitivity characterization, and RA, using numerical dynamic modelling. The risk and safety assessment is to include hazard identification, exposure assessment, effects assessment, risk characterization, and contingency planning for large incidents, for the full chain of CO_2 capture, transport and storage, including surrounding environments. Methodologies are intended to address emissions from injection points, above ground and underground installations, seepage, lateral flows, migrating plumes, catastrophic release of stored CO_2, and impacts on human health, ecosystems, and the climate. RA shall also be used to inform the site development and management plan, approaches for enhanced monitoring activities, and the basis for remedial measures and response plans. RA shall include a communication plan and shall be used to inform environmental and socio-economic impact assessments.

2.1.5. *Australia Commonwealth*

The focus of RA/RM under the *Offshore Petroleum and Greenhouse Gas Storage Act* [OPGGS], *2006* (Australian Government, 2011c), and the *Offshore Petroleum and Greenhouse Gas Storage (Greenhouse Gas Injection and Storage) Regulations 2011* (Australian Government, 2011a) is to minimize seepage and migration impacts on other petroleum resources. A proposed site plan must include the spatial extent and predictions of the behaviour of the greenhouse gas (GHG) substance to be stored; RA for plume migration, including engineering enhancements; and RA/RM containment control and remediation strategies. Monitoring must satisfy that any significant events, as well as variations from predicted behaviour, will be detected in a timely fashion. The regulation also outlines requirements for determining ‘significant risks of a significant adverse impact’ (with respect to costs of event); incident reporting for any variations from the behaviour predicted and any leakage from wells; a decommissioning plan and site closure certificates; and requirements to report on consultations with stakeholders such as other users of the sea.

Following the Montara Well Blowout incident in 2009 and subsequent inquiry (Barrett, 2015), the objectives of the OPGGS were extended from economic optimisation of field operations for petroleum recovery to a greater emphasis on safety. The *Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulation 2011* (Australian Government, 2011b) requires a well operations management plan (WOMP) to include, among other provisions, a description of:

- the risk management process used to identify and assess risks to the integrity of the well

- lifecycle risk reduction and risk control measures, including performance standards and measurement, for the integrity of the well to as low as reasonably practicable
- the monitoring, audit, and well integrity assurance processes

The WOMP is the “sole permissioning” provision (Barrett, 2015) and guidance on its development considers content and detail required for a complete submission under the regulation (National Offshore Petroleum Safety and Environmental Management Authority, 2016). Potential risk assessment inclusions are listed. The following considerations in the 2011 interim guideline (no longer posted) were removed in the final guidance document:

- that it clearly describe interaction with the Environment Plan and the Safety Case to avoid overlaps or duplications or gaps of risk assessment related information in various plans;
- that a Public Interest Test be completed, which considers impacts on the environment and some social determinants of health; and
- that community consultation activities are described and provided (including provision to provide comments) as a method of assuring the public that the project will not pose any significant health, safety, or environmental risks.

2.1.6. *United States*

At the Federal level, the US Environmental Protection Agency’s (USEPA) Underground Injection Control (UIC) Program is aimed at protecting underground sources of drinking water (USDW). US states may apply for primacy in implementation. In 2011, the UIC Class VI Well Program was approved, having more comprehensive operating requirements, mechanical integrity testing, and monitoring and emergency and remedial response criteria than for Class II wells which permit CO_2 injection for enhanced oil or gas recovery (US Environmental Protection Agency, 2011). Modifications were deemed necessary in order to address the relative buoyancy of CO_2, its mobility in the subsurface, its corrosivity in the presence of water, and the large injection volumes anticipated at CCS projects.

The Class VI rule does not include a mandatory requirement for RA/RM. However, detailed voluntary guidance describes the recommended approach to meet regulatory requirements in the following areas:

- *Project Plan Development* (US Environmental Protection Agency, 2012b), describing required elements for Area of Review and Corrective Action Plan, Testing and Monitoring Plan, Injection Well Plugging Plan, Post-Injection Site Care (PISC), Site Closure Plan, and Emergency and Remedial Response Plan. Predicted risk to USDW will inform the monitoring program.

- *Well Site Characterization* (US Environmental Protection Agency, 2013c), including hydrological, geomechanical, geochemical and geophysical information used to determine storage capacity and demonstrate confining zone integrity. Characterization will inform the monitoring program.

- *Well Construction* (US Environmental Protection Agency, 2012a), including construction, testing and operating requirements.

- *Well Testing and Monitoring* (US Environmental Protection Agency, 2013d) for mechanical integrity testing; operational testing and monitoring during injection, including CO_2 stream composition, injection pressure, rate and volume, and corrosion; ground water quality and geochemical; plume and pressure front tracking; and surface air and soil gas.

- *Area of Review* (AoR) Evaluation and Corrective Action (US Environmental Protection Agency, 2013a), focused on storage area delineation and the identification, evaluation, and performance of corrective action should artificial penetrations exist with the AoR.

- *Draft UIC Program Guidance on Transitioning Class II Wells to Class VI Wells* (US Environmental Protection Agency, 2013b), addressing the EPA's concern for increased risk to USDWs where a well or group of wells is first used for CO_2 injection for enhanced oil recovery and then converted to maximize CO_2 volumes for permanent storage.

2.2 Elaborated RA/RM frameworks in non-regulatory context

2.2.1 *World Resources Institute, Guidelines for Carbon Dioxide Capture, Transport and Storage*

The World Resources Institute attempts to publish "timely, scholarly treatment of a subject of public concern" (World Resources Institute, 2008, p. 2). *Guidelines for Carbon Dioxide Capture Transport and Storage* were developed through a diverse multi-stakeholder consultative process involving business, non-governmental organizations, academia, and others.

The guidelines suggest a comprehensive RA for the capture chain would consider materials, procedures, and processes that are fit-for-purpose, including assessment of environmental impacts of any co-constituents, and the benefits of CO_2 emissions reductions. Non-CO_2 environmental impacts on air, water, and solid waste, would also be included. In transport, RA would address pipeline design and operations, safety and integrity, siting, and access and tariff regulation. RM practice would include meeting higher than regulated safety standards as a minimum best practice, along with options for increasing due diligence on placement, controls, and monitoring.

Storage is discussed in greater detail. The primary risk is identified as the potential adverse impacts of potential CO_2 leakage on human health and the environment. RA and Measurement, Monitoring and Verification (MMV) are discussed as cross-cutting issues, including an iterative and integrated RA/MMV program. Site characterization and an MMV implementation plan would assist an operator to effectively manage risk of unexpected leakage. The recommended stages of RA include hazard identification (confining zone or caprock failure, wells, faults and fractures, seismic events) and the evaluation of receptor impacts (effects assessment on humans and ecosystems, groundwater, and atmospheric release). The guidelines include a conceptual approach to selecting MMV tools, based on benefits and costs. Mitigation or remediation planning is also discussed.

2.2.2 *US Department of Energy, National Energy Technology Laboratory (NETL)*

2.2.2.1 *Risk Analysis and Simulation for Geologic Storage of CO_2*

This manual is not intended to be prescriptive, but rather shares the experiences and lessons drawn from the risk analysis and numerical simulation activities of the Regional Carbon Sequestration Partnership (RCSP) field projects (National Energy Technology Laboratory, 2013c). The integration and iterative applications of risk analysis, numerical simulation, site characterization, monitoring, and public outreach in CCS project implementation and accounting are described. The section on risk characterization is sub-divided into exposure and effects assessment, determination of risk probabilities, and impacts. A list of RA methods and tools, as published by a range of organizations and institutions, is included. The manual suggests that RA provide the basis for the RM program, and that mitigation and control plans rely on monitoring data. There is a description of Risk Source Assessment, particularly with reference to Quintessa's database of risk features, events, and processes (FEPs), described below.

2.2.2.2 *Best Practices for Carbon Storage Systems and Well Management Activities*

This manual shares lessons learned regarding site-specific management for CCS well systems (primarily with regard to the EPA UIC Class VI Well program), with a focus on planning, permitting, design, drilling, implementation, and decommissioning of wells for geologic storage projects (National Energy Technology Laboratory, 2013a). RA (risk analysis, in their terminology) is mentioned briefly, with regard to its usefulness in gauging the importance of data gaps; RA is positioned as an iterative process to characterise the site and project, and determine impacts on project budget. RM is directly linked to RA, where post-injection operations anomalies observed through MVA (monitoring) may need to be re-evaluated and corrective measures (mitigation plans) implemented. These may include remedial work and safety plans, but are not elaborated upon.

2.2.2.3 *Monitoring, Verification, and Accounting (MVA) of CO_2 Stored in Deep Geologic Formations*

This technical guide (National Energy Technology Laboratory, 2012) suggests that site characterization and associated RA focus on identifying and quantifying potential risks to humans and the environment prior to operations, and that these risks play a significant role in determining an appropriate CCS monitoring program. MVA in turn supports an interactive RA process. The stated goals of monitoring are to demonstrate that “99% of injected carbon dioxide (CO_2) remains in the injection zones” (up from 95% in the 2009 edition), retention figures that are based on the ability to detect 5% and 1% leakage rates.

2.2.2.4 *Public Outreach and Education for Carbon Storage Projects*

This manual outlines best practices derived from the experience of the RCSPs (National Energy Technology Laboratory, 2013b). The guidance notes that “any concerns that have been identified, including perceived risks, should be addressed in language and formats suited to the intended audiences” (National Energy Technology Laboratory, 2013b, p. 24). However, it also notes that “public outreach, even when done well, does not guarantee public acceptance of a given CO_2 storage project” (2013b, p. 13). Ten best practices for designing an outreach program are detailed, including the important RA/RM issue of transparency. Specifically, it is suggested that “pro-active engagement can contribute to a sense of project openness and transparency” (2013b, p. 27).

2.2.2.5 *Other guidance*

NETL published *Site Screening, Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations* (National Energy Technology Laboratory, 2013d), with a focus on factors that would support a go/no go project decision. Project risks include financial, public acceptance, political, liability, and uncertainty issues. The guidance lists key technical risks as faults and fractures, fate of CO_2, and issues with geomechanical/mechanical/flow models. Social context analysis is suggested as a way for project developers to understand potential perceived benefits and risks of the project for the community.

2.2.3 *DNV GL (formerly Det Norske Veritas)*

Det Norske Veritas (DNV GL) produced numerous detailed CCS RA/RM guidance documents, with a goal to create consensus among project developers and regulators on proper site selection and management. The company's approval process included feedback from representatives of national regulators, interest organizations, project developers, and external stakeholders.

2.2.3.1 *Qualification Procedures for CO_2 Capture Technology*

This document proposes qualification procedures for CO_2 capture technologies and covers the three main approaches of pre-combustion, post-combustion, and oxy-fuel combustion capture (Det Norske Veritas, 2010c). It suggests that a systematic set of activities (technology and threat assessment, development and execution of qualification plan, and performance assessment) will contribute to managing risk of implementation and will play an important role in increasing confidence in new and scaled-up CO_2 capture technologies.

2.2.3.2 *Project Specific Guideline for Safe, Reliable and Cost-Effective Transmission of CO_2 in Pipelines*

DNV's pipeline guideline supplements existing pipeline standards and is applicable to both onshore and offshore installations (Det Norske Veritas, 2010b). The document suggests there is significantly less industry experience for pipelines that carry CO_2 and related compositions than for hydrocarbons such as natural gas, and that these issues need to be understood and associated risks managed effectively.

The RA methodology includes threat identification to an area or to equipment; threat assessment in terms of incidence, likelihood, and consequences; risk reduction through mitigation; and measuring risk reduction results. Human impact is discussed explicitly with regard to CO_2 exposure limits for the public and workers. RM includes consideration of pipeline design, safety objectives, population density along the pipeline route, topography with reference to both gas dispersion and flow assurance, requirements for pipeline integrity conditions (monitoring, inspection and reporting), shut-down and re-start, and operation and upset inventory conditions.

2.2.3.3 *Recommended Practice - Geological Storage of Carbon Dioxide*

In 2012, this Recommended Practice (RP) (Det Norske Veritas, 2012) incorporated and combined previous guidance *CO_2QUALSTORE - Selection and Qualification of Sites and Projects for Geological Storage of CO_2* and *CO_2WELLS - Guideline for the risk management of existing wells at CO_2 geological storage sites*.

Based on DNV's seven identified project phases the RP provides detailed guidance on site screening and appraisal, as well as proposed inclusions for three permitting stages (exploration, storage, transfer of responsibility); well qualification (appraisal through close phases); and risk management throughout all phases of a CCS project. Transparency and traceability are emphasized.

Risk performance that targets all significant risks is included for the permitting stages, including considerations to arrive at acceptable risk in a qualitative, case-by-case basis. Suggested health and environmental issues include occupational health and safety, environmental receptors, timescales, and threshold values. Risk treatment and monitoring targets are to be determined. In risk evaluation, three risk categories are suggested: broadly acceptable or negligible, with no need for detailed effort to demonstrate "as low as reasonably practicable" (ALARP); tolerable or ALARP, described as tolerable only if risk reduction is impracticable or if the cost is grossly disproportionate to the improvement gained; and unacceptable, where risks cannot be justified except in extraordinary circumstances.

2.2.3.4 *CO_2RISKMAN Guidance on CCS CO_2 Safety and Environment, Major Accident Hazard Risk Management (Levels 1, 2, 3, 4)*

CO_2RISKMAN Guidance (Det Norske Veritas, 2013) is focused on major accident hazard management for the CO_2 stream that could affect human health or the environment. There is increasing detail from Level 1 (Executive Summary) through Level 4 (Specific CCS Chain Guidance (310pp)). Integration of risk management across the full CCS chain recognizes that a number of chain-specific stakeholders will be involved in a fully integrated project.

Hazard identification, risk assessment, risk reduction (including elimination, prevention, control, mitigation, and emergency response), and risk management measures are described for capture facilities, onshore pipelines, submarine pipelines, wells, offshore injection facilities, intermediate buffer storage, and carrier ships. The guidance does not consider potential longer term impacts to groundwater quality from CO_2 or displacement of other reservoir fluids such as brine.

The major CO_2 stream hazards are grouped as initial loss of containment (mechanical or corrosion damage; pressurization); immediate escalation hazards (explosion; crack propagation; pipe flailing); and post-event consequences (impairment from inhalation or contact with CO_2 vapour or solids; exposure to very cold ambient air conditions; lack of awareness or poor visibility of CO_2 plume, cloud or accumulation; incomplete competency with hazard management; topographic effects; release of toxics; stopping of internal combustion engine). Risk evaluation is described as the process to compare the level of risk found during the analysis process with risk criteria established when the context was defined; based on this comparison, the need for risk reduction can be considered.

Level 3 guidance includes hazard identification with a generic bow-tie diagram, listing possible event causes and consequences, event prevention, and recovery measures. The objective of the lifecycle plan is to deliver a high level of safety and environmental performance. Human health impacts from exposure to concentrated CO_2, as a result of loss of containment, are discussed. RM includes “suitable and sufficient RA; risk reduction to an acceptable level, including risk treatment hierarchy; optimal capital investment with a view to risk minimization; a practical strategy to manage each of the primary risk drivers; an effective and reliable combination of measures to implement the strategy; and that project and corporate goals are met for the whole lifetime of the facility" (Det Norske Veritas, 2013, pp. 4, Level 3).

2.2.4 *CSA Group, Standard Z741 - Geological Storage of Carbon Dioxide*

The CSA Standard (CSA Group, 2012) includes, but is not limited to, the safe design, construction, operation, maintenance, and closure of facilities (injection wells) and storage sites. The boundary periods (project phases) are: Site Screening; Site Characterization, Assessment and Selection; Design and Development; Operational; and Post Injection & Closure. The Standard does not apply to Post-Closure Period.

The elements of concern in RM are suggested to fall within categories of human health and safety, the environment, and system performance. RA would be completed with regard to the natural environment, regional natural resources, infrastructure, human culture, legal and regulatory environment, industry best practices, and project management considerations. Suggested RA of identified elements includes site screening, characterization, and selection, such that results would demonstrate that storage of the CO_2 stream at the candidate site(s) does not pose an unacceptable risk to other resources, to the environment and human health, or to project developers, owners, and operators. RA includes risk identification, risk analysis, and risk evaluation (the likelihood and severity of consequences for each risk scenario), including assessment of uncertainty. Standard Z741 refers to consideration of Features, Events and Processes, similar to that developed by Quintessa (see on-line resource, below). Risk ranking is discussed with respect to both site selection and injection.

2.2.5 *Online elaborated RA/RM tools and resources*

The World Resources Institute created a *CCS Regulatory Comparison Matrix 2.0* (World Resources Institute, 2012). The web-based tool allows users to compare 20 identified key issues for CCS regulations, standards, and best practice guidelines between four RA/RM frameworks: the *WRI CCS Guidelines* (Wilson et al., 2008), the International Energy Agency (IEA) *Model Regulatory Framework* (IEA, 2010a), the *US Class VI Well Program* (US Environmental Protection Agency, 2011), and the *EU CCS Directive* (European Union, 2009). RA/RM and project management topics are included. WRI identified social and environmental criteria and analyzed how the selected frameworks addressed the issues. The *Matrix 2.0* is designed to provide transparent, easy-to-access information regarding existing regulations and to allow users to assess language and approach. It is also a mechanism for stakeholders to provide input on how CCS regulations could be improved.

While not developed as a RA/RM framework, an extensive on-line resource is Quintessa's *CO_2 Features, Events and Processes* (FEP) database for CO_2 underground storage projects (Quintessa Ltd., 2013). There are eight categories of FEPs: Assessment Basis; External Factors; CO_2 Storage; CO_2 Properties, Interactions and Transport; Geosphere; Boreholes; Near-Surface Environment; and Impacts to humans, flora, fauna or the physical environment. This database can be used as part of systemic assessments of safety and performance.

The Global Carbon Capture and Storage Institute (GCCSI) created *openCCS* in 2011, an online handbook aimed at identifying key processes and steps required in the development and delivery of each component of an integrated CCS project (Global Carbon Capture Storage Institute, 2016). Separate webpages consider Power Capture, Transport, and Storage with suggested undertakings during a six-step project delivery (Identify, Evaluate, Define, Execute, Operate, and Closure) for each chain component. The most relevant topics for RA/RM include environmental management; health and safety; measuring, monitoring and verification; stakeholder and external relationship management; exploration risk assessment; and risk management. For each topic area within the project steps, the handbook suggests the objective and major deliverables, and provides a list of specific tasks.

Last, the United Kingdom CO_2 Storage Evaluation Database *CO_2 Stored* (The Crown Estate and British Geological Survey, 2016) began as a region-specific online subscription-based resource and is now available free of charge. The database contains derived geological data, storage estimates, risk data, and economics for nearly 600 potential CO_2 storage units located offshore of the UK. Gammer et al. (2011) describe the methodology used to assess the storage potential for both saline aquifers and depleted hydrocarbon fields. Units can be searched based on formation, permeability, porosity, and CO_2 theoretical capacity. Geological risk for each storage unit considers parameters for containment risks such as seals, faults, lateral migration, wells, formation damage, and connectivity. Criteria defining the high-, medium- and low-likelihood of failure are provided. A risk profile (severity and likelihood of impact) is also shown for both costs and capacity of the sites, including descriptions for containment and operational elements of risk. The data include economics analysis based on injection rates per year, and undiscounted lifetime costs of chain activities. A Monte Carlo simulation summary is also provided.

2.3 Commonalities and differences among RA/RM frameworks worldwide

Guidance documents include four to six identified project phases from project development through closure. Table 6.1 presents the terminology/phases identified by several RA/RM frameworks described here. Where the number of phases is the same, the label can vary; and the use of the same term may include discrete activities between frameworks. Also see Appendix E (Supplementary Material, Chapter 6).

2.3.1. Risk Assessment

Elaborated frameworks mostly focus on specific value chain components of CCS activities. In both the regulatory and non-regulatory context, a greater number of frameworks has addressed storage phase risks, fewer focus on RA/RM guidance for capture, transport, and injection chain activities. The United Nations Framework Convention on Climate Change (2011), WRI CCS Guidelines (2008), DNV CO_2RISKMAN (2013), and openCCS (Global Carbon Capture Storage Institute, 2016) are the most inclusive RA/RM frameworks available worldwide.

Required risk assessment activities in the regulatory context vary across jurisdictions. For example, the 2011 UNFCCC Modalities and Procedures for CCS as a Clean Development Mechanism (United Nations Framework Convention on Climate Change, 2011) includes mandatory and comprehensive RA/RM requirements for capture, transport, storage, and post-injection, with few notable gaps. The US EPA UIC Class VI Well Program, approved the same year, did not include any mandatory requirements for RA/RM, although voluntary guidance is

Table 6.1: CCS Project phases identified in selected elaborated risk assessment and risk management frameworks

RA/RM Framework	Project Phases								
NETL MVA	Pre-operation				Operation	Post-operation	Closure		
IMO London Convention	Planning			Construction	Operation		Site closure	Post-closure	
US EPA UIC Class VI Rule	Siting and Evaluation			Well Construction	CO_2 Injection and Monitoring	Post-injection Site Care		Post-closure	
EC CCS Directive Guidance Document 1	Assessment of storage capacity	Characterisation/assessment of storage complex		Development	Operations			Post-closure pre-transfer	Post-transfer
DNV Geological Storage	Screen	Assess and Select		Design, Construct	Operate		Close		
GCCSI openCCS	Identify	Evaluate	Define	Execute	Operate		Closure		
CSA Z741	Site Screening	Site Characterization	Assessment and Selection	Design and Development	Operational	Post-injection & Closure			

extensive (US Environmental Protection Agency, 2012a, US Environmental Protection Agency, 2012b, US Environmental Protection Agency, 2013a, US Environmental Protection Agency, 2013b, US Environmental Protection Agency, 2013c, US Environmental Protection Agency, 2013d).

In the regulatory and non-regulatory context, RA is almost always suggested for storage site selection and characterization, with the view that this is the best way to reduce risk of leakage. In terms of specified steps, European Commission (EC) sourced directives and guidance (European Commission, 2011a, European Commission, 2011b, European Commission, 2011c, European Union, 2009), the UNFCCC (2011), and several non-government contributions (Det Norske Veritas, 2012, National Energy Technology Laboratory, 2013c, World Resources Institute, 2008) list a 4-step RA process – hazard identification, exposure assessment, effects assessment, risk characterization – but the descriptions of these steps are not consistent in depth or breadth, with the least guidance provided for exposure assessment and risk characterization. More recently, non-regulatory guidance is modifying RA terminology, notably moving to a 3-step sequence for hazard identification, risk analysis, and risk evaluation activities (CSA Group, 2012, Det Norske Veritas, 2013). This may reflect variance between human health risk assessment frameworks and those developed from an engineered systems safety assessment perspective (International Energy Agency Greenhouse Gas R & D Programme, 2009). While the core structure may be very similar, some assessment components are complimentary: human health RA is focused on hazard assessment, effects assessment and the consequences, while engineered systems' focus is on "establishing the context and vulnerability of potential receptors and the risk management steps, particularly the treatment of risk, monitoring and review" (International Energy Agency Greenhouse Gas R & D Programme, 2009, p. 23).

As a separate step, several non-government guidance documents discuss the need for risk ranking, primarily with regard to site selection (CSA Group, 2012, Det Norske Veritas, 2012, World Resources Institute, 2008) and risk management (Det Norske Veritas, 2013). Recent frameworks suggest risk ranking be completed through an expert facilitated workshop/brainstorming session and that such discussions be documented. Several elicitations have been reported: Illinois Basin-Decatur Project, USA (Hnottavange-Telleen et al., 2011); CASSEM Project, Scotland (Polson et al., 2012); and IEAGHG Weyburn-Midale CO_2 Monitoring Project, Saskatchewan, Canada (Bowden et al., 2013a, Bowden et al., 2013b).

Gaps in these frameworks include a lack of guidance on risk estimation which provides a quantitative characterisation of the risks associated with CCS. Furthermore, few regulatory and non-regulatory frameworks link with an assessment of emissions, waste or water use in CCS; and only a few discuss CO_2 stream assessment which could have an effect on injectivity, well integrity and physical aspects of storage (Talman, 2015). DNV's CO_2RISKMAN (2013) addressed the CO_2 stream in detail for capture, transport and injection, but not for storage. Few documents discuss RA or consequences of mitigation measures, as also found by Pawar et al. (2015).

2.3.2. Risk Management

Risk management decision making is commonly based on the risk assessment process. Monitoring is identified as the key RM activity during operations, principally to demonstrate containment in the short term and conformance in the longer term (Jenkins et al., 2015). It is also recognized as required for the closure phase of CCS projects; however, elaboration of monitoring and mitigation at closure is limited in regulatory and non-regulatory documents reviewed here.

An iterative process to monitor injection and storage, including use of results to calibrate and update modelling and monitoring activities, is recommended (CSA Group, 2012, Det Norske Veritas, 2012, European Commission, 2011a, European Commission, 2011b, National Energy Technology Laboratory, 2012, National Energy Technology Laboratory, 2013c, National Energy Technology Laboratory, 2013d, United Nations Framework Convention on Climate Change, 2011, Wilson et al., 2008). Relatively few documents discuss or require CO_2 stream monitoring through the CCS Chain, except for DNV's CO_2RISKMAN as described above. There is also little guidance on monitoring of surrounding (shallow) domains. Jenkins et al. (2015) describe progress in monitoring and verification as a risk management tool in the ten years since the *CCS Special Report* (IPCC, 2005), particularly with respect to research and approach for groundwater, soils, vegetation, and atmospheric issues.

Contingency monitoring and planning is included within RM planning by WRI (Wilson et al., 2008), NETL MMV (2012), DNV Geological Storage (2012), DNV Pipeline (2010b), and Canadian Standard Z741 (CSA Group, 2012). Contingency planning for large incidents is only mandatory in the regulatory context by the UNFCCC-CDM (United Nations Framework Convention on Climate Change, 2011) and Australia's *Offshore Petroleum and Greenhouse Gas (Environment) Regulation* (Australian Government, 2014). CO_2RISKMAN (Det Norske Veritas, 2013) also suggests numerous techniques for major accident hazard risk management using a lifecycle RM approach. Recovery measures are suggested for capture, transport, wells, and intermediate storage. The guidance does not consider potential longer term impacts to groundwater quality from CO_2 or displacement of other reservoir fluids such as brine.

Jenkins et al. (2015) suggested that assessment and planning for potential significant adverse effects on the environment or other resources are not yet well developed.

2.3.3. Other risk-based considerations

Common project-based considerations such as uncertainty assessment, stakeholder communication and consultation, and the goal of transparency in risk assessment and management, are discussed frequently in non-regulatory documents, but only sparsely in those enacted in a regulatory context. Non-regulatory publications include best practices for public outreach and education (National Energy Technology Laboratory, 2013b) and World Resources Institute Guidelines for Community Engagement (Forbes et al., 2010). Ashworth et al. (2015) found, in part, that public awareness for CCS remains low, except where a local controversy may have developed. Stakeholder communication and consultation, and the goal of transparency, are addressed in this Special Issue by Leiss and Larkin (*submitted*), *Risk Communication and Public Engagement in CCS Projects: The Foundations of Public Acceptability*.

2.4 Summary of comprehensive RA/RM frameworks

With increasingly comprehensive understanding of the many different dimensions of risk associated with CCS, suggested practice described in elaborated RA/RM frameworks has evolved across CCS value chain and risk issue domains. Leading stakeholders are also publishing and updating both print-based and web-based guidance regularly. Documents often refer to and build upon previously existing documentation from within an organization or as developed by others.

At least one series of best practice manuals has been updated: NETL reviewed and revised its guidance in light of the National Academies Press Report on the potential for induced seismicity in energy technologies (National Research Council, 2013). Going forward, the International Standards Organization is developing ISO/TC 265 Carbon dioxide capture, transportation, and geological storage (ISO) based in large part on CSA Z741 (CSA Group, 2012). As well, non-government entities are creating on-line (real time) resources where continuous improvement is anticipated through contributions from CCS practitioners (Global Carbon Capture Storage Institute, 2016).

There is, however, evidence of terminological variations in RA/RM activities as sourced from different parts of the world – with a four-step RA prevalent in the European/International regulatory context (hazard identification, exposure assessment, effects assessment, risk characterization) more recently being reduced to three-step RA in non-regulatory frameworks (hazard identification, risk analysis, risk evaluation). Risk assessment criteria and risk ranking are discussed in increasing detail in the non-regulatory context, including the use of expert judgement, but comprehensive project risk estimation has not been listed as a step in RA/RM frameworks to date.

3 Risks and attendant uncertainties in CCS

3.1. Expert elicitation

A panel of twelve international experts, representing academia and government research centres, participated in a structured expert elicitation focused on relative risk and uncertainty judgements with respect to injection and storage and risk management of low probability high impact (LPHI) events. While the insights are not applicable to a specific project's risk assessment, the findings assist in better understanding of a number of difficult decision challenges that exist. The findings provide motivation for further scientific deliberations to achieve objective judgements on CCS risk issues. Full findings are reported in this Special Issue by Larkin et al. (*submitted-d*, *submitted-e*).

As an approach to address a knowledge gap, structured expert elicitation has been shown to be of value where information is scarce, knowledge is limited, uncertainties are great, and risks are theoretically very low (Aspinall, 2010). The Classical Model formal expert weighting procedure was used to analyse opinions for CCS risk issues. The theoretical basis and principles of the Classical Model are detailed in Cooke (1991), and Cooke and Goossens (2008) provides case histories using the method. Distinct weights were given to eleven experts in order to pool opinions in an optimal way on questions primarily related to injection and storage activities and risk management options. This calibration was based statistically on their ability to judge uncertainties, as derived from control questions. EXCALIBUR software is used to analyze the opinions (Aspinall, 2008). Relative risk of selected issues were obtained using probabilistic inversion of the importance ordering choices made by the experts using a paired comparison approach; these were analysed with the UNIBALANCE software (Macutkiewicz and Cooke, 2006). Experts also assessed the likelihood and severity of hazards associated with injection and storage (leakage from wells, injection, intrinsic and induced storage circumstances) using Likert scale ratings. Experts' judgements regarding the effectiveness of risk management options for five LPHI events were also elicited.

3.2 Selected elicitation findings

Experts' indicated increasing uncertainty for the likelihood of minor, major, and catastrophic CO_2 leakage in capture, transport, and injection during the operating period (0-50 yrs), with virtual certainty of some minor leakage in capture at the lower limit of the credible range (5th percentile). In storage, the performance weight (PW) median response for the likelihood of leakage in three time periods (0-50 yrs, 51-499 yrs, and over 500 yrs) was very similar for each of minor, major and catastrophic event types (>1 in 30; ~1 in 1,000; ~1 in 11,300, respectively). Median likelihood of major CO_2 leakage that would result in measurable environmental or public health impact was the same over three time periods, approximately 1 in 1,050. Experts' judgements find very long safe storage lifetimes – with 95% of facilities not failing for almost 13,000 years.

The median response for the percent of CO_2 that can be expected to be retained for 1,000 years was virtually the same for both saline aquifer sequestration and enhanced oil recovery (EOR) operations (99.8%). However, there was greater uncertainty for EOR.

Experts’ ranking of technical, environmental, and health risk in capture, transport, injection, and storage was elicited using pairwise comparison. In all cases, the rank scores did not separate strongly and systematically; however the rank order for health risk had a clear preference, with the highest risk in capture.

The likelihood and severity of hazards associated with well leakage, injection, intrinsic storage, and induced storage circumstances were elicited based on a five-point Likert scale previously used by Polson et al. (2012). Where risk was calculated as Likelihood × Severity of the mean responses, leakage from unknown and unlocatable wells was the only hazard to score high risk based on the risk ranking cutoffs.

Experts also assessed the effectiveness of six risk management options (site selection, well integrity studies, emergency response plan, monitoring, automatic shut down system, and training) for three georisks and two human health LPHI events: large migration out of pore space; caprock fracture; induced seismic event M>4; massive fatal release of CO_2 resulting in human fatalities; and catastrophic injection wellhead failure. Regarding georisks, site selection and monitoring both clearly separated as the preferred risk management options and were considered “very” effective measures. With the exception of site selection, all options were considered “very” or “extremely” effective for both massive fatal release and catastrophic wellhead failure.

Several Classical Model questions also considered risk management. For injection and storage activities, experts' quantitative judgement suggested that approximately 12% of risk management should be focused on mitigating environmental impacts as opposed to human health impacts. Expert responses suggested storage site monitoring should continue for 92 years, with the 90% credible interval being 8 through almost 1000 years. Regarding the proportion of capital and operating costs that regulatory agencies could mandate for environmental and human health protection during injection operations and the storage period, experts' suggested approximately 5.5%, with 1-17% credible range. This median is approximately half of the experts' judgement for budget allocation such that project leaders be reasonably secure against gross negligence claims in post-failure litigation (11%).

4 Integrated Risk Management Framework for Carbon Capture and Storage

4.1. Previous attempts at integration

Previous attempts at integration in risk assessment and risk management have been made at the conceptual and project level. Bowden and Rigg (2004) published the first major overview of risk assessment for CO_2 projects, testing a conceptual approach in the context of four sites in Australia. The proposed approach was to build on the familiar FEP (feature, event, process) analysis, which is focused first on the understanding of complex failure modes, then on scenario analysis, process modelling (the behaviour of injected CO_2 under various physical conditions), and finally consequences analysis for health, safety, and environmental parameters. In addition, transparency in the risk assessment process was enhanced, so as to "provide an interface with the wider community and allow stakeholders to assess whether the process is safe, measurable, and verifiable, and whether a selected alternative site would deliver cost-effective greenhouse benefits" (Bowden and Rigg, 2004, p. 678). An independent and objective expert panel would carry out quantitative estimates of likelihood and consequences for selected risk scenarios and report their findings to the public and key stakeholders, following the risk identification and strategy using quantitative evaluation (RISQUE).

Risk assessment of CO_2 capture, transport and storage is considered within an Environmental Impact Assessment (EIA) context in a major study by Koornneef et al. (2012). Among other reasons, they argue that this larger context is important because CO_2 capture at power plants entails "cross-media impacts" which, for example, change the profile of other key atmospheric emissions (such as NO_x and NH_3) and produce an increase in water consumption and the creation of new waste by-products. In other words, risk assessments that focus exclusively on the transport, injection, and underground storage of CO_2 itself normally do not capture any associated cross-media impacts and thus may underestimate the overall magnitude of the environmental consequences of a CCS project. Table 10 in Koornneef et al. (2012, p. 82) provides a summary of the key issues in the assessment of environmental interventions regarding CO_2 capture, transport, and storage. Given these additional complexities in the risk assessment of CCS projects, the authors recommend the utilization of a "transparent process that demonstrates [to] the general public how risks and uncertainties are managed" (Koornneef et al., 2012, p. 82).

Gerstenberger et al. (2013) presented an overview of methods and tools that are available for 'integrated risk assessment for CCS'. Both qualitative tools – including brainstorming, a risk register, structured expert elicitation, and bow-tie diagrams – as well as probabilistic or quantitative tools are reviewed, with an indication how different tools may be phased-in during stages of a complex decision process. The authors strongly recommend in particular the use of an expert elicitation process in order to respond to the inevitable uncertainties and limited data available at the time decisions are made. Gerstenberger et al. (2013, p. 2782) conclude on a note that is fundamental to the overall process: "A key component of an effective risk assessment is communication. The assessment should effectively communicate to varied stakeholders the current state of knowledge with respect to risk within the system".

Multicriteria Decision Analysis (MCDA) is one of the most familiar and well-tested methods for taking a structured approach to the evaluation of risk, particularly for evaluating and ranking alternative solutions. Choptiany and Pelot (2014) and Choptiany et al. (2015) apply the MCDA approach to CCS problems, such as choosing among competing CO_2 storage sites and optimizing mitigation measures for risk reduction. The articles develop this approach for hypothetical coal-fired power plants involving post-combustion CO_2 capture, pipeline transport, and storage in depleted oil reservoirs. The decision model development has the standard MCDA features, including hierarchy of objectives, elicitation of utility functions, criteria weighting, scoring, and sensitivity analysis. In Choptiany and Pelot (2014), the authors argue that this method enables an interactive engagement process with stakeholders who can participate as decision-makers in study process and can provide a "transparent assessment method by which to choose among competing projects". In Choptiany et al. (2015) results further indicated functionality and positive responses from experts in government, environmental non-government organisations, research, and industry who participated in the case study.

The most comprehensive risk assessment project level documentation on a group of proposed CCS sites, the *Final Risk Assessment Report for the FutureGen Project Environmental Impact Statement*, was issued in 2007 by the U. S. Department of Energy (National Energy Technology Laboratory, 2007). The project included a coal-fired generation plant upgrade with an oxy-combustion technology, capture of 1.1 million tons of CO_2 (more than 90% of carbon emissions), criteria air quality contaminant emissions reductions to near-zero levels, and pipeline transportation of the sequestered gases to an underground storage site. The risk assessments for four proposed sites, two in Illinois and two in Texas, evaluated both human-health and environmental adverse effects; human-health effects were considered separately for workers and the public. The release scenarios encompassed two categories, pre-sequestration releases from pipelines and wellheads as well as post-sequestration releases through caprock, faults, and wellbores. More than a dozen separate failure modes were considered in the release scenarios, and the probabilities of at least one failure were estimated quantitatively for each one. Thousands of pages of text and illustrations, including methodologies, were made available on a publicly-accessible website. Subsequently the site in Meredosia, Illinois was chosen for the project. However, the federal funding for the project was cancelled in 2015.

For the Illinois Basin - Decatur Project (IBDP), Hnottavange-Telleen et al. (2011) noted that a risk management program for geological sequestration sites should aim to maximize the chance of project success "by assessing, monitoring, minimizing all risks in a consistent framework" (p. 4044). An FEP-based expert elicitation methodology was used to rank risks and scenarios were identified that would provide the "tangible and temporal malignant chains of events against which interventions – risk reductions – can be designed" (p. 4051). The authors' stressed that risks as perceived by a variety of interested parties and stakeholders are no less important than those identified by experts, and that adequately addressing all risks is indispensable for project success.

Bowden, Pershke, and Chalaturnyk (2013a, 2013b) reported two related studies dealing with the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project in Saskatchewan, Canada. The first was labelled a "geosphere risk assessment" and the second, a "biosphere risk assessment." The biosphere is defined as "the air, soils, rivers, lakes and groundwater, and everything contained therein, that lie above the base of the Cretaceous-Tertiary aquifers". The base of the biosphere occurs at a general depth of 150 m in the Weyburn–Midale Project area and the geosphere as everything below that depth. The geosphere assessment used the RISQUE method (Bowden and Rigg, 2004) to identify in quantitative terms the "containment risk" – possible leakage of CO_2 from underground storage – as well as further research needs and risk reduction opportunities. The containment target was set at 99% of stored CO_2 over the first 1000 years, at a confidence level of 80%. An expert panel concluded that this target would be met; however, it also identified well pathways as the greatest risk to containment, and recommended a review of well abandonment practices to address this risk. The biosphere study used "the outputs (pathways, likelihoods, and CO_2 mass) from geosphere risk assessment to identify the general physical and chemical effects on the fundamental biosphere components (groundwater, surface water, soil, air) and the consequential impacts on organisms, habitat, amenity, and public safety" (Bowden et al., 2013a, p. S291). These effects were reported in a semi-quantitative form and were put in the context of environmental impact assessment methods. The thorough public engagement strategy adopted the view that stakeholder perceptions are an important factor in project success and sought direct stakeholder inputs (including values) on a wide range of specific issues associated with the biosphere risk assessment process. It also used a “socially acceptable risk” concept holding that “if risks are low enough, the community will accept them.”

The project application, review, and approval of the Shell Quest saline sequestration project in Alberta, Canada, included the identification and assessment of environmental and human health risks for each of capture, transport, injection, and storage. Qualitative, semi-quantitative, and quantitative methodologies were undertaken and the storage scheme was assessed by an Independent Panel Review. The 20-month process generated approximately 4000 pages within 400 documents; however, transparency, in terms of ease of access and the fullest possible disclosure, was problematic. The subsequent regulatory decision by Alberta’s Energy Resources Conservation Board (now the Alberta Energy Regulator) illustrates the risk management decision-making process (Energy Resources Conservation Board, 2012). This project is included in the detailed analysis of regulatory practice reported in this Special Issue by Larkin et al. (*submitted-b*).

What is still lacking in a Canadian context is a response to the challenge posed in the articles by Gerstenberger et al. (2013) and Pawar et al. (2015), for effective communication with a broader range of stakeholders on the risk assessment and risk management of CCS projects which would help to foster further acceptance of this technology. Leiss and Larkin, in this Issue, further consider *Risk Communication and Public Engagement in CCS Projects: The foundations of public acceptability*, suggesting a chain of social interactions begins with public perception of the risks and benefits of CCS generally; continues with effective communication of these at the project level; then involves robust and credible mechanisms for public engagement; and results in transparent decision making processes. The 2012 CSA Group Standard for CCS also stipulates that risk communication and consultation should specifically address the thoroughness, accuracy, transparency, traceability, and consistency of the risk assessments, and the nature and degree of understanding of known or perceived risk scenarios (CSA Group, 2012).

Furthermore, in assessing the continuing evolution of RM frameworks over the past thirty years, Leiss et al. (2010) noted three issues that had not yet been well addressed. Frameworks have not included a mechanism to break down the distribution of authority for human health and environmental risk factors within the 'silos' of line departments at all levels of government. As well, particularly for global risk issues, mechanisms need to be developed that provide opportunities for international collaboration in risk management. And third, some risk issues are now known to span long timeframes whereby the capacity of agencies to manage risk at critical junctures needs to be supported (Leiss et al., 2010). Each of these issues is relevant to CCS given the complexity of integrated projects, including wide ranging human health and environmental hazards spread over four value chain components; the place of CCS within the global issue of climate change mitigation; and the timeline of project implementation spread over decades, with the goal for permanent storage giving rise to intergenerational considerations.

4.2 Attributes and dynamics of IRMF in practice

The proposed integrated risk management framework (IRMF) for CCS in the Canadian context includes both a systematic transparent ten-step process for project proponents and regulators to follow, and integrates government and nongovernment partners throughout the life of a project

(Figure 6.1). The terms partner and stakeholder are used interchangeably. While illustrative, instances where partners were included in Canadian decision-making processes, particularly for the Shell Quest Carbon Capture and Storage Project and the Alberta Carbon Trunk Line (ACTL) are also indicated.

The central panel (Figure 6.1) indicates core federal and provincial government agencies that have been responsible for project review and approvals. Greater detail is provided for Alberta and Saskatchewan because the four approved large scale integrated projects are located in these provinces (with Quest being the only aquifer sequestration project type). For a specific project proposal, the lead proponent would also be identified. Other government and non-government partners (left- and right-hand panels, respectively) are also shown to have a role to play. On the three left-hand panels potential government partners within Canada, among foreign governments, and among international agencies are listed. The three right-hand panels categorize the non-governmental partners, including directly impacted industry sectors, other external stakeholders (research communities, environmental non-governmental organizations), and various publics. While nineteen government and quasi-government organizations have been identified to date, the non-governmental partner list is substantially longer.

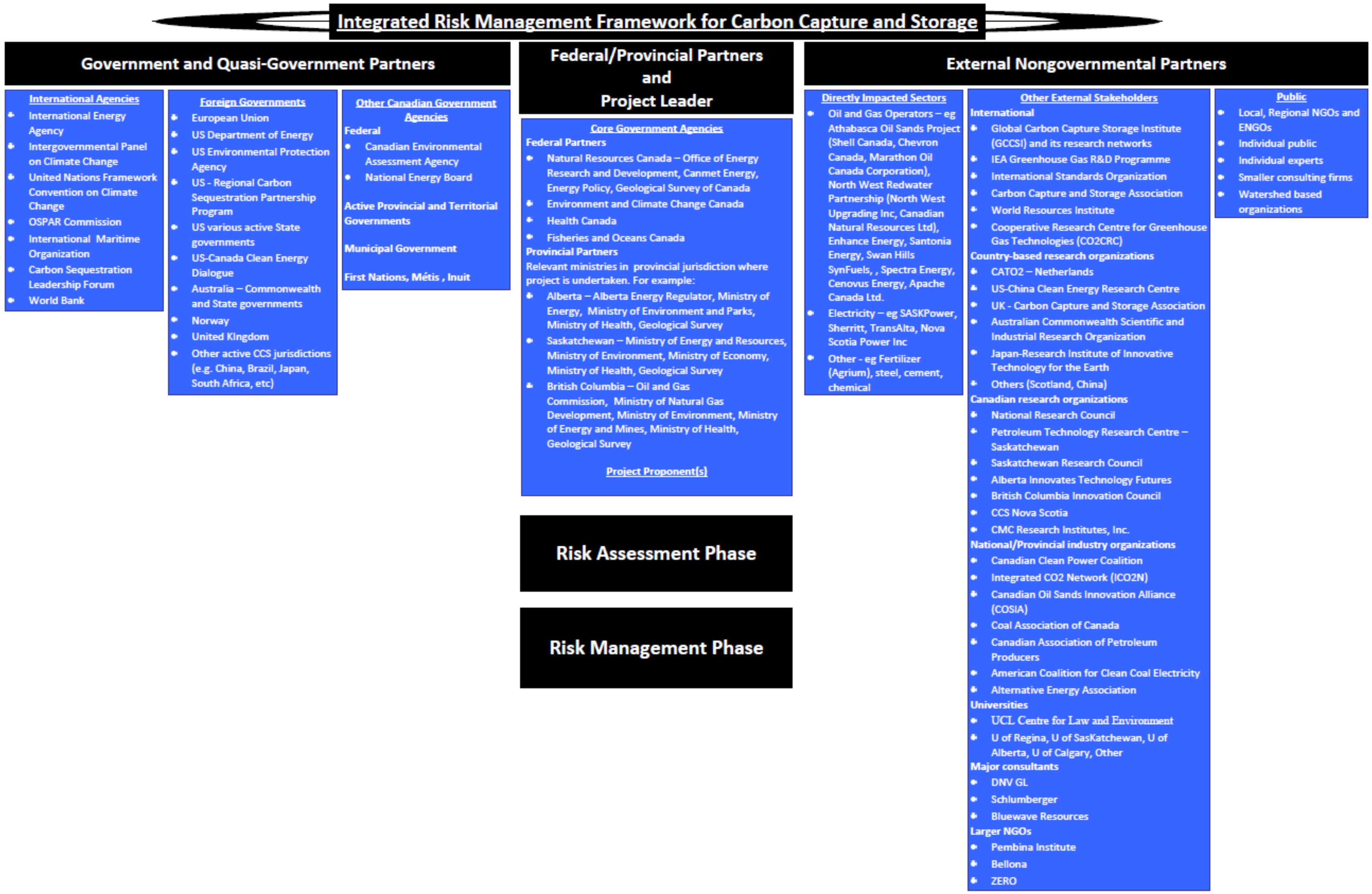


Figure 6.1: Overview of Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context

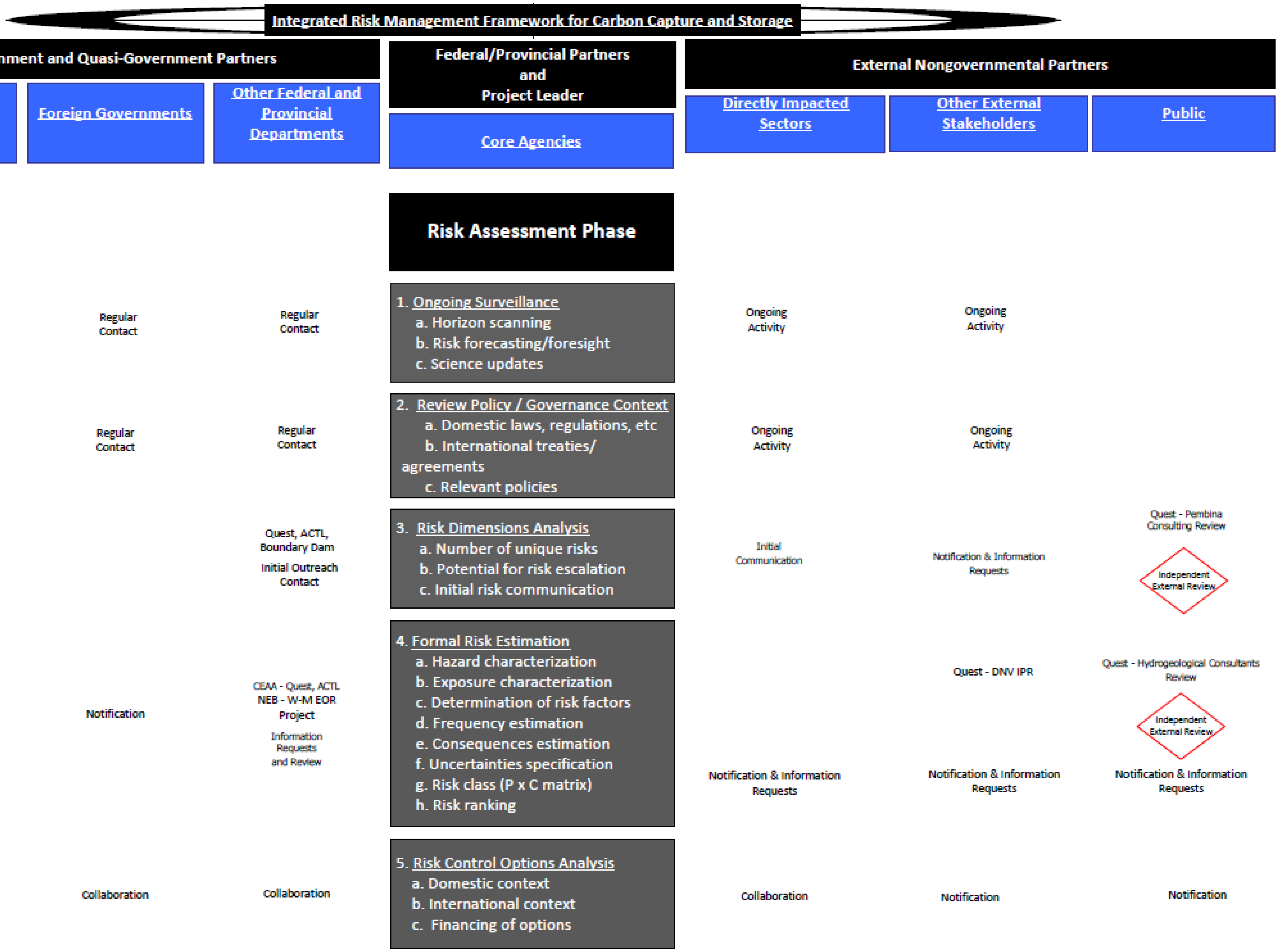
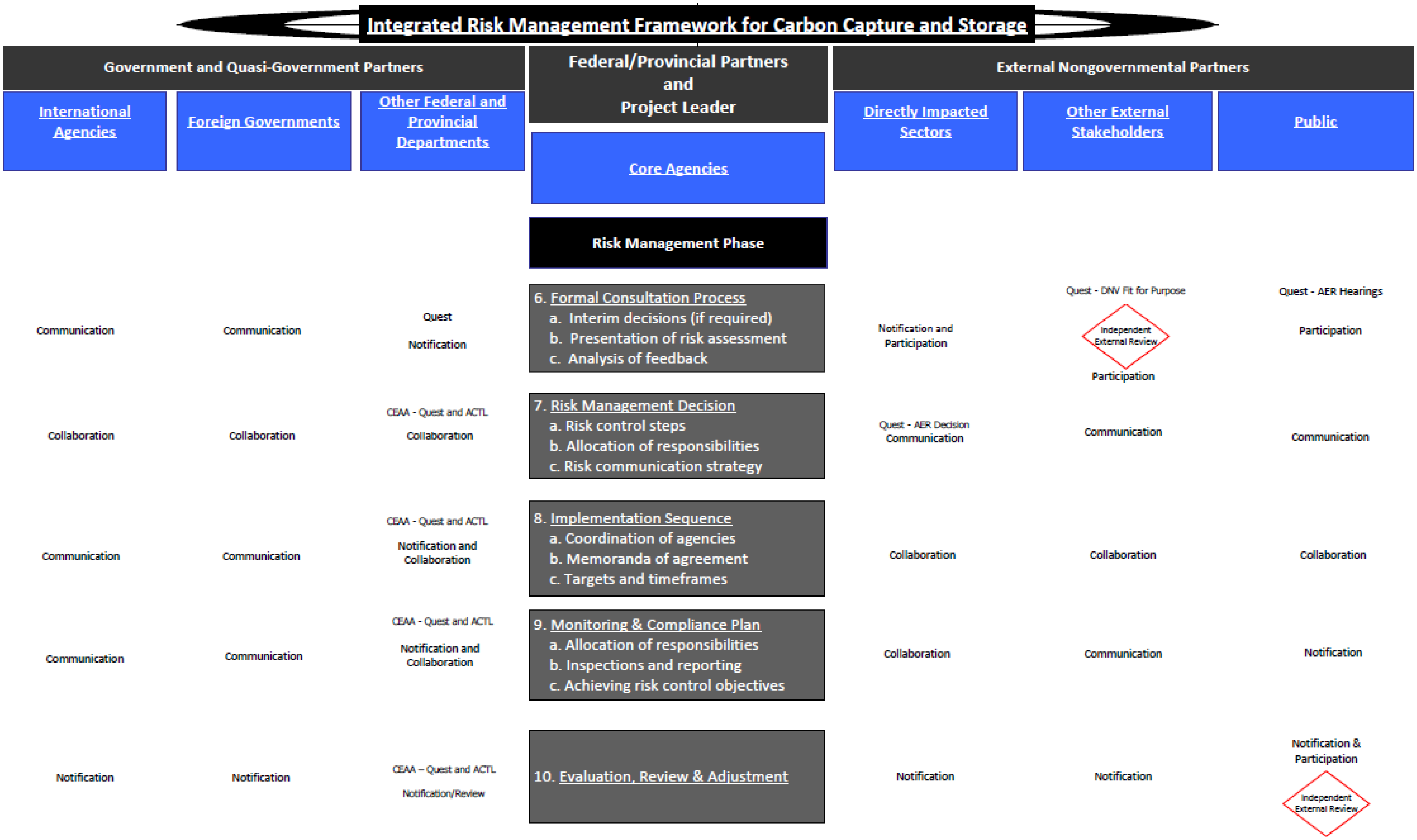


Figure 6.1 (Con't): Risk Assessment Phase of Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context



Integrated Risk Management Framework for Carbon Capture and Storage

Government and Quasi-Government Partners			Federal/Provincial Partners and Project Leader	External Nongovernmental Partners		
International Agencies	Foreign Governments	Other Federal and Provincial Departments	Core Agencies	Directly Impacted Sectors	Other External Stakeholders	Public
			Risk Management Phase			
Communication	Communication	Quest Notification	6. Formal Consultation Process a. Interim decisions (if required) b. Presentation of risk assessment c. Analysis of feedback	Notification and Participation	Quest - DNV Fit for Purpose Independent External Review Participation	Quest - AER Hearings Participation
Collaboration	Collaboration	CEAA - Quest and ACTL Collaboration	7. Risk Management Decision a. Risk control steps b. Allocation of responsibilities c. Risk communication strategy	Quest - AER Decision Communication	Communication	Communication
Communication	Communication	CEAA - Quest and ACTL Notification and Collaboration	8. Implementation Sequence a. Coordination of agencies b. Memoranda of agreement c. Targets and timeframes	Collaboration	Collaboration	Collaboration
Communication	Communication	CEAA - Quest and ACTL Notification and Collaboration	9. Monitoring & Compliance Plan a. Allocation of responsibilities b. Inspections and reporting c. Achieving risk control objectives	Collaboration	Communication	Notification
Notification	Notification	CEAA – Quest and ACTL Notification/Review	10. Evaluation, Review & Adjustment	Notification	Notification	Notification & Participation Independent External Review

Figure 6.1 (Con't): Risk Management Phase of Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context

The RA phase includes Issue Awareness, Review of the Policy and Governance Context, Risk Dimension Analysis, Formal Risk Estimation, and Risk Control Options Analysis. The RM phase continues with Formal Consultation Process, Risk Management Decision, Implementation Sequence, Monitoring and Compliance Plan, and Evaluation, Review and Adjustment. The extensive and ongoing opportunities to integrate input from partners are depicted by the vertical panels adjacent to the indicated steps for both RA/RM phases. Discussion would include not only hazard and risk issues, but costs and benefits of a project proposal.

Integrated partner engagement throughout these phases will provide risk managers with a detailed picture of the risk management context. This framework allows flexibility to accommodate the local context and would support the outcomes of the risk decision-making process; that is, to identify acceptable risk control options for a specific CCS site. Pawar et al. (2015, p. 307) found that "while the GCS [geologic CO_2 storage] field projects executed to date have taken into account the public perception risk (acceptance of the project), no documented GCS risk assessment application exists where the public perception risk has been explicitly addressed as part of a structured risk assessment approach". As suggested by Leiss et al. (2010), a continuum of partner interaction and engagement is possible and desirable such that input provides clarity as to what is important, what is acceptable, and what risk control options could be applied. These could include activities such as notification, communication, participation or collaboration, depending on the step in the process and the partner in question.

In their review of RA/RM developments in the decade since publication of the IPCC *Special Report on CCS* (IPCC, 2005), Pawar et al. (2015, p. 307) reiterated how "an effective communication approach needs to demonstrate how the risk assessment approach has effectively taken into account various stakeholder concerns during the assessment process, how the uncertainties have been handled, what impact uncertainties have on risks, and how risk is managed via monitoring and mitigation actions". Findings from the expert elicitation (Section 3.2, Larkin et al. (*submitted-d, submitted-e*)), provide new understandings of the difficult decision challenges related to hazard and risk issue uncertainties that are expected during an integrated risk assessment and risk management process. The IRMF is of value to government, industry, and non-government organizations, and the general public by providing ongoing opportunity to identify and address issues for focused discussion and acceptance -- as the risk assessment process unfolds and risk control options are analysed, implemented, monitored, and evaluated.

The IRMF could be used as a process checklist, where the responsibility to conduct various interactions with other agencies and affected parties are recorded as having been completed. It could also record the completion of proactive consultations with interested stakeholders. Results could thereby form the basis of a published document once the regulatory approval process is concluded. Moreover, applying an IRMF to CCS would create opportunities for meaningful discussion on both the safety and contribution of CCS to mitigate climate change, thus also having a role to play in public acceptance to support broad application.

Figure 6.1 provides examples of where some key components of the IRMF have already been implemented by project leaders and regulators (project name is shown above engagement type for selected RA/RM steps). For example, for Shell Quest and Alberta Carbon Trunk Line

(ACTL), the Canadian Environmental Assessment Agency was engaged in the formal risk estimation, risk management decision, implementation sequence, monitoring and compliance plan, and with an ongoing role in evaluation, review and adjustment. Because of the international pipeline, the National Energy Board only had a role to review and approve the risk estimation for the Weyburn-Midale EOR project (Chapter 3).

With respect to non-government engagement, Shell Quest engaged an independent review of their consultation process and risk estimation for the storage component and a member of the public engaged an independent review of the hydrological risk estimation. An independent review also certified the project as fit-for-purpose. The ERCB project review and decision for Quest was a public hearing process. In Alberta, all energy-related project applications are posted and updated on the regulators' website.

4.3 Risk-based decision making

Risk-based decision making and risk management of technologies and technological change should be based on four broad issue areas: well-established principles of risk management, economic analysis, sociopolitical considerations, and risk perception (Krewski et al., 2014). These are important features of the context of a CCS project proposal and should underpin the IRMF's risk management activities to select and implement acceptable risk control options.

The ten decision-making principles of risk management were first proposed by Jardine et al. (2003): a) beneficence and non-maleficence (do more good than harm); b) natural justice (a fair process of decision making); c) equity (ensure an equitable distribution of risk); d) utility (seek optimal use of limited risk management resources); e) honesty (be clear on what can and cannot be done to reduce risk); f) acceptability of risk (do not impose risks that are unacceptable to society); g) precaution (be cautious in the face of uncertainty); h) autonomy (foster informed risk decision making for all stakeholders); i) flexibility (continually adapt to new knowledge and understanding); j) practicality (the complete elimination of risk is not possible).

Krewski et al. (2014) suggested that the importance of each of these principles could vary for each decision-making context and that their consideration may not lead to the same risk management conclusion. Integrated engagement from the outset, as depicted in the IRMF, might therefore be of benefit because stakeholders will have an opportunity to discuss the ten principles that could affect the decision making at three levels: first, the "approach principles", namely beneficence/non-maleficence and/or precaution; the "process principles", potentially choosing the emphasis between natural justice, equity, honesty, acceptability, and autonomy; and the "operational principles", including utility, flexibility, and practicality of risk management options.

These principles of risk management and the broad issue of risk perception are closely linked for CCS at the project level and on an individual risk basis. Stakeholder engagement in the determination of the three levels of approach, process, and operational risk management principles of greatest effect would help to build trust and a consensus could develop for the IRMF's decision-making process. Indeed, the importance of trust and fairness was found to have a bearing on public understanding and acceptability in risk management, as discussed by Leiss and Larkin (*submitted*) in this Special Issue.

Economic analysis as a broad area contributing to risk-based decision making is relevant at three scales. In the first instance, this would be completed in advance of a proponent's final investment decision on whether or not to proceed with a CCS project. Second, once a decision to proceed is made, the risk management principle to seek utility through the optimal use of RM resources would manifest in economic analysis on an individual risk basis. Economic interest lies in "the extent to which a quantitative statement of monitorable project goals can reduce cost and improve stakeholder confidence" (Jenkins et al., 2015, p. 343). Lastly, at the global level, Heyes and Urban (*submitted*) in this Special Issue considered more generally the *Economic Evaluation of the Benefits and Costs of Carbon Capture and Storage* as a mitigation strategy for climate change. The conclusion was that the valuation of the social cost of carbon, as a policy input adopted by Canada and the United States, indicate lower benefits than costs from large scale CCS implementation, but sometimes by a small margin. The opportunities for varied stakeholder input throughout the IRMF process would improve understanding and develop support for the economic analysis that underpins the choice to proceed with the project and the choices for risk management options.

Sociopolitical considerations that underpin risk management options for CCS are also considered in this Special Issue. Leiss and Krewski discuss wide ranging risk management challenges for CCS in the paper *Environmental Scan and Issue Awareness: Risk Management Challenges for CCS*. Two identified categories are relevant to this contextual component: 1) government and industry factors, including competent regulatory oversight, an adequate RA/RM framework as described here, and supportive public policy architecture; and, 2) socio-economic factors, including information provision, effective communication, stakeholder engagement, and social and public acceptability through decision support mechanisms. Within the IRMF, socio-political considerations in risk-based decision making can be more easily identified and addressed from the outset through ongoing integrated partner engagement with the wide-ranging government, quasi-government, external non-government, and public stakeholders. Aspects of the sociopolitical landscape are provided in this Issue by Larkin et al. (*submitted-b*), *Regulating the Risks of Carbon Capture and Storage: A Global Perspective* and Bankes (*submitted*), *Alberta's Approach to the Transfer of Liability for Carbon Capture and Storage Projects.*

Full understanding of these four broad issue areas, that is, to consider well-established principles of risk management, economic analysis, sociopolitical considerations, and risk perception, underpin the complex risk management decision making context for CCS. The most important RM principles, the economic analysis, sociopolitical considerations, and risk perceptions will be different at each of three scales, namely the individual value chain component risk, the project risk, and the societal/policy (global) domain, as well as from a myriad of stakeholders' points of view. With respect to project risk, Arvai and Arvai (*submitted*) in *Improving Decision-making processes for Carbon Management Initiatives* in this Special Issue, reviewed behavioural and perceptual obstacles, as well as those associated with the complexity of carbon management problems themselves. Leiss and Larkin (*submitted*) also note that "the perception of benefits – or the failure to appreciate the benefits of CCS – may be more important than perception of the associated risks (where the normal case is the exact opposite)". With respect to the global domain, L'Orange Seigo et al. (2014) suggested that the public is not overly frightened about potential risks of CCS, instead exhibiting greater uncertainty about the role of CCS in climate change mitigation. Once again, the opportunities for varied partner engagement throughout the IRMF process will assist with creating the conditions for a positive outcome for the local and global community in CCS risk based decision making.

4.4. Risk management options for CCS

An illustrative but incomplete hazard taxonomy for integrated CCS projects is provided each of which could require a variety of environmental and health risk management options (Table 6.2).

Table 6.2: Illustrative environmental and human health hazard taxonomy and risks for integrated CCS Projects

<table>
<tr><th colspan="4">CCS Value Chain Activity</th></tr>
<tr><th>Capture</th><th>Transport</th><th>Injection</th><th>Storage</th></tr>
<tr><td colspan="4">Physical Hazards</td></tr>
<tr><td colspan="4">CO_2 stream impurities</td></tr>
<tr><td>CO_2/amine/criteria contaminant air emissions</td><td>Pipeline failure</td><td>Injection wellhead or well casing failure</td><td>Unexpected plume migration</td></tr>
<tr><td>Amine/criteria contaminant land/water deposition</td><td>Associated systems failure</td><td>Caprock fracture</td><td>CO_2, brine or CO_2 saturated brine migration through caprock</td></tr>
<tr><td></td><td></td><td colspan="2">Induced seismicity</td></tr>
<tr><td></td><td></td><td colspan="2">Direct surface leakage – well leakage or far field</td></tr>
<tr><td colspan="4">Accidents, Malfunctions, Unplanned Events (Process Upsets)</td></tr>
<tr><td colspan="4">Human Health and Environmental Hazards</td></tr>
<tr><td colspan="4">CO_2 inhalation - occupational and/or public and/or wildlife morbidity/mortality</td></tr>
<tr><td colspan="4">Drinking water, soil, air contamination from amines, criteria contaminants, CO_2, or brine</td></tr>
<tr><td></td><td></td><td colspan="2">Surface uplift or earthquake</td></tr>
<tr><td colspan="4">Unanticipated CO_2 leakage rate to atmosphere contributing to climate change</td></tr>
</table>

Developed as the REACT framework for risk management and population health (Krewski et al., 2007, Krewski et al., 2014), risk management options include these potential actions:

- Regulatory: Government policies, legislation, guidelines, permits, or approvals for required action (three categories of statutes include products, emissions, and natural environmental protection)
- Economic: Insurance, levies and other cost structures, designed as incentives to take action
- Advisory: Programs developed to encourage action, including communications, education and awareness
- Community-based: Public inception, support, and commitment to take action, often volunteer-based
- Technological: Action through improved advances in technological abatement.

Integrated partner engagement, as depicted in the IRMF, through notification, communication, and consultation, as appropriate, could lead to discussions and decisions within these five categories of risk management interventions for CCS.

Wilson et al. (2003), Keith et al. (2005), and Wilson et al. (2008) were among the first to examine the kind of regulatory regimes that might provide a credible basis for risk-based decision making for CCS (see also Leiss, 2009). Site evaluation and monitoring, and especially the latter, have been identified as key to confirming the robustness of the assumptions built into the risk estimation (National Energy Technology Laboratory, 2012, Smith et al., 2011).

With focus on regulatory oversight, Wilson et al. (2008) suggested that CCS needs to be done right, because a “single major accident, resulting from inadequate regulatory oversight, anywhere in the world, could seriously endanger the future viability of GS [geological storage]" (p. 2782). Additionally, "any regulatory framework to manage GS should therefore be adaptive, without compromising the basic objectives of safety and climate policy".

Similarly, Pawar et al. (2015, p. 307) suggested no CO_2 storage site "should be permitted without significant characterization and regulatory scrutiny" and that where a site has a small chance of CO_2 leakage, "permitting would be unlikely, that monitoring will always be required, and that approved injection parameters will minimize residual risk". Jenkins et al. (2015) further discussed the regulatory linkage between monitoring and verification.

Potential risk management options within each of the five REACT categories are indicated in the Supplementary Material. These options were identified from the variety of RA/RM frameworks discussed here, analysis by Larkin et al. presented in this Special Issue (*submitted-b, submitted-c*), findings from the expert elicitation (Larkin et al., *submitted-d,* Larkin et al., *submitted-e*), and research reported in Gale et al. (2015). Key risk management options include: baseline measurements, operations, emissions, monitoring and reporting regulations; penalties, fines, and liability funds; notification processes; community-based siting and emergency response planning; training and operations strategies; and monitoring technologies, alarms and shut down procedures. Given the wide ranging possibilities for stakeholder engagement, the IRMF would support clarity and development of acceptable risk control options.

It is arguable whether an individual risk management option should be established by regulation rather than as an advisory or community-based approach. The Supplementary Material illustrates wide-ranging approaches to be discussed and accepted within the risk management context in which the project is proposed. Minimum documentation requirements could also be identified. As suggested by this IRMF, Det Norske Veritas (2012), and the Independent Project Review of Shell's Quest Project (Det Norske Veritas, 2010a), a risk register would record all hazards, how each was considered, and the chosen risk management option in order to instill completeness and transparency. Jenkins et al. (2015) also suggested a need to consider significant adverse events explicitly from evaluation through monitorable outcomes.

5 Summary and Conclusions

Comprehensive risk assessment and risk management frameworks for CCS have been developed in both the regulatory and non-regulatory context since the publication of the *Special Report on Carbon Capture and Storage* by the Intergovernmental Panel on Climate Change (IPCC, 2005). Mandatory requirements in leading jurisdictions include the European Union *Directive on the Geological Storage of Carbon Dioxide* (European Union, 2009) and United Nations Framework Convention on Climate Change, *Modalities and procedures for carbon dioxide capture and storage in geological formations as a Clean Development Mechanism* (United Nations Framework Convention on Climate Change, 2011). Elaborated non-regulatory guidance has been published by the US National Energy Technology Laboratory (National Energy Technology Laboratory, 2012, National Energy Technology Laboratory, 2013a, National Energy Technology Laboratory, 2013b, National Energy Technology Laboratory, 2013c, National Energy Technology Laboratory, 2013d) and DNV GL (Det Norske Veritas, 2010b, Det Norske Veritas, 2010c, Det Norske Veritas, 2012, Det Norske Veritas, 2013), as well as through web-based resources maintained by the Global Carbon Capture and Storage Institute (Global Carbon

Capture Storage Institute, 2016). At a minimum, health and environmental protection considerations are listed, with more elaborated frameworks detailing methodological approaches.

Preliminary results of an expert elicitation of scientific judgements, reported in detail in this Issue, assist understanding of relative risk and quantify collective uncertainty judgements for CCS hazard and risk issues. While the insights are not applicable to a specific project's risk assessment, given the newness and complexity of this technology such empirical data could stimulate further scientific deliberations towards reducing uncertainty on CCS risk issues. Difficult decision challenges are expected throughout risk assessment and risk management processes, particularly with respect to injection and storage risks of CCS and risk management of low probability high impact events. The Cooke Classical method identified the performance weights and equal weights uncertainty distribution ranges for questions focused on the likelihood of leakage in injection and storage (the latter with respect to three time periods); what should be the monitoring period; how long could the operations remain safe; and budget allocations for health and environment protection.

In terms of risk management, the expert elicitation identified monitoring as one of the most effective options to reduce risk of low probability high impact events. However, the credible judgement for the monitoring period ranged up to 1000 years. Jenkins et al. (2015, p. 343) suggested that "explicit consideration of significant adverse events would be helpful in designing monitoring strategies and clarifying requirements that these need to be systematically linked to clearly monitorable outcomes; as well as a need to demonstrate that the monitoring system can detect these events". Jenkins et al. (2015) also suggest that planning for an adverse event is just beginning; and that experience in adverse event detection and remediation will improve confidence in monitoring and verification overall.

Previous attempts at integration in RA/RM of CCS were identified. Pawar et al. (2015, p. 308) suggested that “significant progress has been made to effectively integrate communication strategies with risk management approaches to increase stakeholder confidence in effectiveness of deployed risk management approaches to manage risks”. To advance this further, the integrated risk management framework presented here, for use by project proponents and regulators, is based on the systematic ten-step process that has evolved for thirty years (Krewski et al., 2007, Leiss et al., 2010). Enhancement includes deliberate and transparent integration of government and non-government partners for the duration of the project application and approval, operations, monitoring, and evaluation periods.

The application of the integrated risk management framework could therefore anticipate and prevent local harms from this technology that may be avoidable. The IRMF would underpin a documented process of improved risk-based decision inputs and risk management outcomes that would contribute to acceptance of this mitigation technology. Proponents, regulators, and stakeholders have wide ranging opportunities for engagement with government and non-government partners worldwide. In following the process, improved understanding and consensus of all stakeholders for the principles of risk management, economic analysis, sociopolitical considerations, and risk perception issue areas could be developed. In avoiding conflict through four phases of a project (Permitting, Injection, Post-closure and Stewardship), Wilson et al. (2008, p. 2719) suggested that if large-scale [geological storage] GS is to proceed, “the competing needs and interests of the public, project developers, financial and insurance institutions, government regulatory agencies, nongovernmental organizations, and national and international agencies managing CO_2 trading must be appropriately balanced”. Consensus developed through the IRMF process could underpin risk control options that result in an acceptable CCS project. This would therefore also begin to address issues identified by Pawar et al. (2015) in their assessment of what needs to be done to improve overall risk management and to remove barriers associated with large-scale deployment. Essentials include stakeholder confidence in quantitative risk assessment approaches; testing the effectiveness of integrating risk assessment with monitoring and mitigation in risk management; and further development of outreach and effective communication strategies in order to minimize risks and boost acceptance of wide-scale deployment of GCS [storage] technology (Pawar et al., 2015).

The application of the IRMF for CCS could provide a context in which to discuss potential for re-release of injected CO_2 during operations or the post-injection period. In a survey conducted by Johnsson et al.(2010) (cited in Heyes and Urban, this issue), leakage from reservoirs was ranked the number one risk of CCS by individuals working at stakeholder companies that shape CCS policy, including oil and gas companies, electric utilities, CO_2-intensive industries and NGOs. Wilson et al. (2003) and IPCC (2005) suggested the effects of re-release are time-dependent, with less serious effects if anticipated leakage occurs in the long term. Nevertheless, re-release of unanticipated volumes of CO_2 could affect both local population and environmental health and the role of CCS in emissions reductions, thereby exacerbating public acceptance and anticipated global population health benefits of CCS as a mitigation option. The application of an IRMF could provide a process in which to address this concern.

This research also suggests risk management options for CCS under five action categories: regulatory, economic, advisory, community-based, and technology based approaches. Key risk management options include: regulations for baseline measurements, injection and storage operations, contaminant emissions and leakage rates, monitoring requirements, and public reporting; penalties, fines, and liability funds; notification processes; community-based siting and emergency response planning; training and operations strategies; monitoring technologies, alarms, and shut down procedures. Multiple acceptable risk management options are considered best practice in a decision-making context from a population health perspective; that is, to take coordinated action at multiple levels and multiple scales to protect or improve human health and the natural environment upon which we depend.

Chapter 6 References

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Chapter 7 Thesis Summary and Future Directions

Climate change is a global risk issue. Human health and environmental impacts are anticipated from fluctuations in temperature and precipitation regimes, increasing average temperatures, and incidences of climate extremes. These are expected to increase the frequency and severity of natural hazards such as storms and flooding, extreme heat, drought, and wildfires; reduce food availability, water quality, and water quantity; reduce air quality; extend the geographic range of infectious diseases; and increase exposure to ultra-violet radiation. A major contributing factor to climate change is anthropogenic CO_2 emissions to the atmosphere from fossil fuel based energy production and industrial processes.

This Chapter provides a summary of this research project to develop an *Integrated Risk Management Framework (IRMF) for Carbon Capture and Storage (CCS) in the Canadian Context.* Human health and environmental protection are key goals for this technological process that can mitigate climate change. Consideration is also given to two additional barriers to widespread CCS implementation: project costs and public concerns. The chapter concludes with future risk management policy scenarios for both the local and global contexts.

1 Summary of thesis

Chapter 1, the Introduction, describes the potential for CCS mitigation technology to be part of the solution to reduce point source CO_2 emissions that contribute to climate change. Currently, several project types are in various stages of development worldwide; however, this research project focused specifically on the development of an integrated risk management framework for geological sequestration of CO_2 in saline aquifers. It has been estimated that up to 3,000 large scale integrated sequestration projects (LSIPs) are required globally by 2050 if CCS is to contribute a projected 13% cumulative CO_2 emission reductions proposed by international agencies (GCCSI, 2014a, IEA, 2015a). By 2050, up to 8 $GtCO_2$/year could be sequestered compared with business as usual. Chapter 1 also describes the supportive Canadian policy context for CCS. We have 3 LSIPs operational and another coming on stream in 2016. However, three of these projects were developed for enhanced oil recovery (EOR) purposes and not dedicated saline aquifer sequestration.

The introduction also provides a summary of the physical hazards within the capture, transport, injection, and storage value-chain of CCS integrated projects and a summary of associated human health and environmental hazard and risk issues. These can include: CO_2 inhalation, causing occupational and/or public morbidity or mortality; drinking water, soil, or air contamination from amines, criteria contaminants, CO_2, or brine; surface uplift or earthquakes; and an unanticipated CO_2 leakage rate to the atmosphere potentially contributing to climate change sometime in the future.

Chapter 1 includes a description of the population health model of the research problem. The linkages between CO_2 emissions and population health and wellbeing are depicted for both global and local risk issues. The place and execution of an IRMF is an intervention that could reduce hazards and associated risks in terms of likelihood and consequence, as well as identify acceptable risk management options, thereby leading to broad acceptance of CCS as a climate change mitigation technology. This would therefore also have an important part to play in protecting global population health and wellbeing in the long term.

Chapter 2, *Regulating the Risks of Carbon Capture and Storage: A global perspective*, provides the current international regulatory context for CCS, with a focus on requirements for risk assessment and risk management (RA/RM). Frameworks to assess hazards and manage risks have advanced in both the regulatory and non-regulatory context concurrent with project implementation. There is wide variation between jurisdictions in Canada and internationally (particularly in the European Union, as well as Australia and the United States) in mandatory and voluntary provisions applied to CCS; mandatory requirements are not often elaborated; and the use of guidance documents is discretionary. Canadian provincial oil and gas related legislation, regulations, and directives apply to both saline sequestration and enhanced oil recovery (EOR) projects. Under certain circumstances, projects are also subject to the *Canadian Environmental Assessment Act*, legislation that is currently under review. Under CEAA2012 (Government of Canada, 2012) there are substitution provisions of the federal for a provincial environmental assessment process. In British Columbia and Alberta, implementation of recommendations that resulted from comprehensive regulatory review processes could strengthen RA/RM in the future.

Chapter 3, *The Evolution of Regulatory Practice for CCS Projects in Canada*, considered the approval process for the four Canadian LSIPs: the Weyburn-Midale Enhanced Oil Recovery Operations and Boundary Dam Integrated CCS Demonstration Project in Saskatchewan; and the Alberta Carbon Trunk Line and Quest Carbon Capture and Storage Project in Alberta. At the time of writing, Quest is one of three operational saline sequestration projects worldwide (with two others in the execution stage). Regulatory oversight of these projects was value chain specific, with notable advances in technical risk assessment that supported project approvals. A growing number of human health and environmental risks were assessed in the fifteen year study period using referenced approaches, however global risk estimation was not completed. Moreover, analysis found that project assessment was more comprehensive, with better access to documentation, when reviewed under the *Canadian Environmental Assessment Act* compared with provincial oil and gas legislation and regulations. (Projects were reviewed under an earlier version of CEAA, prior to CEAA2012). The primary risk management option for CCS is ongoing monitoring. With respect to risk communication, mechanisms to ensure transparency are not well developed and this could affect the potential for broad public acceptance of CCS in the long term.

Turning to risk assessment, Chapter 4 details findings from a structured elicitation of experts into hazard and risk issues that underlie difficult decision challenges that can be expected during future CCS project assessments. Structured expert elicitation has been used successfully to produce a ‘rational consensus’, that is, a weighted opinion of uncertainty, for many risk issues (Aspinall, 2010). Although some have questioned the utility of this approach, uncertainty spreads are generally narrower than found with other elicitation methods dependent on expert discussion of opinion, but wider than would be quantified by an individual. Because of the complexity of CCS, the technique required that participating international authorities from academia and public research institutes represent diverse backgrounds in injection and storage. The use of interviews or focus groups aimed at reaching consensus might not have reflected the heterogeneity of the group. Experts were permitted to decline to answer elicitation questions which they considered outside of their range of expertise. A significant amount of information was collected in a short period (two half-days), with experts participating remotely from Canada, United States, Europe, Australia, and Saudi Arabia.

With a common understanding of the CCS scenario not related to a specific project proposal, experts focused on injection and storage, contributing objective judgements on relative risk; uncertainties in injectivity and storage performance; and the likelihood and consequence of CO_2 leakage in short and long term scenarios. Experts also rated likelihood and severity of potential hazards in well leakage, injectivity, and intrinsic and induced storage circumstances. The expert panel suggested the likelihood of three leakage scenarios was almost equal for each of three time periods (operational for 0-50 years and storage for 51-499 years and over 500 years), with a significant decrease in likelihood from minor to major to catastrophic leakage scenario (approximately >1 in 30; 1 in 10^3; 1 in 10^4, respectively). The likelihood of major leakage with measurable human health or environmental impacts was essentially equivalent (1 in 10^3) in the three time periods. Similar to other research, only leakage from unknown or unlocatable wells ranked as a high risk.

Chapter 5 reports on findings from the expert elicitation with respect to understanding and beliefs about risks and attendant uncertainties in human health and environmental risk management, particularly with respect to low probability high impact events (LPHI). Participating experts were authorities in the technical risks related to the LPHI, whereby the overarching goal for CCS is to ensure safe and effective implementation in the subsurface, thus preventing health or environmental impacts in the long term. Experts' opinions are therefore useful points of reference for policy makers. Here, results suggest similarities and differences in expert opinion for selected risk management options, an outcome that may reflect both the level of experience and the complexity of this technological process. The expert panel suggested a median approaching 100% of injected CO_2 would be retained over 1,000 years for both saline sequestration and EOR project types. The associated uncertainty band was wider for EOR. The median judgement for a suitable monitoring period was 92 years (almost a century); however, uncertainty spanned three orders of magnitude, with a credible upper limit judgement (1 in 20) of almost 1,000 years. Site selection and monitoring were considered "very" effective risk management options for elicited CCS georisks, including large migration out of pore space, caprock fracture, and induced seismic event >M4. Five risk management options – well integrity studies, emergency response plan, automatic emergency shut down system, training, and monitoring – were considered "very" or "extremely" effective in managing two risks with a more direct effect on human health: a potential massive release of CO_2 and catastrophic wellhead failure. The findings illustrate options for LPHI risk reduction that could be considered by all stakeholders during future project development, approval, and implementation.

The overarching objective of this research project, the *Integrated Risk Management Framework for Carbon Capture and Storage in the Canadian Context*, is presented in Chapter 6. Wide ranging elaborated frameworks are described, providing an update, overview, and comparative analysis of elaborated risk assessment and risk management approaches in both the regulatory and non-regulatory context. Attempts at integration in the CCS context are discussed, followed by the attributes and dynamics of the IRMF. Key government and non-government stakeholders in the Canadian context are identified. It becomes clear that integrated engagement with wide-ranging organizations and the public throughout the ten steps identified in the IRMF would provide risk managers with unprecedented understanding for the context in which a CCS project is proposed and approved, both at the local and global scales. Organizations and members of the public would be engaged in a variety of ways throughout project approvals, thus playing a role in the development of acceptable risk control options. Increased opportunities for meaningful discussion on the safety and effectiveness of CCS in climate change mitigation could also play a role in developing support for broad application.

With additional effort to identify country-based stakeholders in other parts of the world, the IRMF could also be used as a risk management framework to assess saline sequestration CCS projects outside Canada. Chapter 6 is completed with a discussion of the application of the IRMF within the next generation of risk-based decision making for CCS; multiple risk management options for each value-chain activity are identified within regulatory, economic, advisory, community-based, and technological domains.

2 Other barriers for CCS

Risk assessment and risk management are not the only critical issues for widespread CCS project development. Technological progress and challenges are indeed well documented (see, for example, Boot-Handford et al. (2014), Gale et al. (2015), Gibbins and Chalmers (2008), Nykvist (2013)). Pawar et al. (2015) also identified two additional risk issue areas (aspects of which are discussed next).

- "Public perception risks: risks to public acceptance of field projects.
- Market failure risks: financial risks to deployment or execution of field projects with feedback from site performance, containment, and public perception risks" (p. 293).

2.1 Public perception and communication

As depicted in the conceptual framework for the research project (Chapter 1), two scales of activities are needed to address risk perception and to support credible risk communication activities that would lead to public acceptance: at the project level, where the hazards and associated risks and uncertainties exist in the capture, transport, injection, or storage value chain activities; and at the regional, national or international level where CCS technology is included as a CO_2 emissions mitigation option. In this thesis, Chapter 3 includes discussion of transparency and communication in Canadian project assessments and Chapter 6 considered how risk communication is included in elaborated risk assessment and risk management frameworks, as well as how risk perception is one aspect of the risk-based decision making backdrop in determining risk management options for CCS. Issues in project risk perception, risk communication, and public engagement are discussed further in an overview of risk management challenges for CCS (Leiss and Krewski, *submitted*), and *Risk Communication and Public Engagement in CCS Projects: The Foundations of Public Acceptability* (Leiss and Larkin, *submitted*).

As with other risk topics, outstanding challenges at the local project scale surround the use of language; for instance, who is “community”; the source of the message (trust); the receiver’s background and attributes, and the message interplay between the two; the place of government both as proponent, in terms of supporting CCS (Chapter 1) and regulator (Chapters 2 and 3); and uncertainty. With respect to public concerns and options for feasible and achievable risk reduction in a cost-effective manner, risk assessment and management that is done well would, importantly, develop trust in the review process with concomitant linkages to risk acceptability (Leiss and Larkin, *submitted*). The steps and engagement within an integrated risk management process could ultimately support regulators in making the argument that a project has achieved an acceptable level of risk (i.e., a level of risk that is likely to be perceived by the public as being acceptable).

Furthermore, adherence to the proposed steps and stakeholder engagement presented in the IRMF (Chapter 6) could greatly assist the objectives of regulators in identifying the full suite of CCS issues and concerns. As suggested by Leiss and Larkin (*submitted*), an effort to identify and discuss the benefits of CCS may be equally important, if not moreso, to the effort and discussion regarding project risks, where the case is normally the opposite. Benefits of a project could include employment, as with the Quest and Boundary Dam capture facilities, and all pipeline development. Proponents also point to employment in maintaining raw material production, such as the coal for Boundary Dam and oil production in both Alberta and Saskatchewan. Project implementation may also have less quantifiable benefits for a community or corporation, namely in their demonstrated effort in climate change mitigation, with an underlying inspiration for others that reducing point source emissions can be done. At the regional or national scale, Arvai and Arvai (*submitted*) suggested that “benefit perceptions might be susceptible to the national context where CCS is deployed … [possibly] due to differences in the national energy mix and energy policy.” Another set of benefits associated with CCS is the myriad of avenues for work in science or policy research and public sector policy development. There may also be benefits accrued in Canada through knowledge transfer, for instance at Saskatchewan’s Petroleum Technology

Research Centre now under collaborative research agreements with various agencies in Canada and other parts of the world.

On the other hand, with respect to CCS more generally, social science studies about the development and future of this technological process have found an uneasy coalition of supportive actors (Markusson et al., 2012b), and debate continues as to the interpretation of this technology as a climate protective strategy (Wassermann et al., 2011). This is because CCS is sometimes viewed as an end-of-pipe solution to CO_2 emissions, thus enabling ongoing fossil fuel extraction (as also suggested as a benefit, above). Currently, the approval process for large energy-related projects on the Canadian landscape is under significant public scrutiny; resistance to several fossil fuel pipeline proposals could spillover to the CCS transport (by pipeline) and storage activities. Furthermore, intergenerational challenges add a dimension of social justice in creating a responsibility for storage and storage monitoring over the very long term. Hammond and Shackley (2010) summarized arguments against CCS as reflecting "doubts over efficacy to combat climate change, especially when compared to: other sustainable energy options; responsibility for long term liability; decreased plant efficiency, implying higher costs and more fossil fuel extraction and combustion; perpetuation of the fossil fuel industry" (p. 30). More deeply, some opponents state that "the only option for climate protection can be seen in the transformation of the energy system, which means to overcome the dependence on fossil energies" (Wassermann et al., 2011, p. 6357). The current emphasis on CCS-EOR (81% of global capture rate, Chapter 1, and discussed further in Section 3.1), as interim demonstration projects of this technological process, could begin to collapse the actor network coalition because CCS supporters may not perceive adequate progress towards permanent geological sequestration.

In a ten-year review of social science with respect to CCS, Ashworth et al. (2015) completed an assessment on the awareness of the general public and key stakeholders; communication style and content; and experiences from specific projects. Overall, findings suggested the pre-conditions for CCS described in the IPCC *Special Report on Carbon Capture and Storage* (2005) have not materialized: recognition that anthropogenic global climate change is a serious problem and that there is a need for large CO_2 emission reductions. Perhaps this has now been addressed – with 195 country approval of the 2015 Paris Agreement, although targets are not binding. As well, Ashworth et al. (2015) found that public awareness of CCS remains low except where there has been controversy in the local context. In Canada, L'Orange Seigo et al. (2014, p. 30) found low knowledge about CCS and concluded: "It is certainly necessary to educate the public about CO_2 and CCS, because knowledge is a prerequisite for making informed decisions, and knowledge was generally low in our sample".

2.2 Cost of CCS

Barriers to CCS engendered by negative public perception and cost are closely related. Saline aquifer sequestration is costly, with such projects potentially adding to the overall consumer expense for fossil fuel power generation and industrial products. While researchers have had difficulty in acquiring accurate CCS data as input to economic studies (Choptiany and Pelot, 2014), Markusson et al. (2012) (cited in Choptiany et al. (2014)) suggested wide ranging cost estimates (and CO_2 markets), in conjunction with uncertainties in other issue areas, is putting a risk premium for CCS and limiting development.

A majority of project costs, upwards of 70%, is attributed to the capture technology (IEA, 2013a). However this cost is expected to decrease as new LSIPs are brought on stream. With respect to power plant projects, for instance, the Australian Energy Technology Assessment (AETA) provides periodic updates on projected cost curves for a variety of power sources. Estimates show that the 'levelized cost of electricity' (LCOE) for CCS technologies is expected to decrease from 2025 to 2050 (Australian Government, 2013). Similarly, the operators of Boundary Dam and Shell Quest suggested costs could be reduced 20-30% in subsequent projects (Massachusetts Institute for Technology, 2016), in the latter case, in part, because intellectual property is open source (Natural Resources Canada, 2017).

While the cost of storage is much lower than the cost of capture, projects show that many years and often several hundred million dollars of at-risk funds must be made available for the exploration and development of a storage site. Experience indicates that it typically takes five to ten years from the initial site identification to the qualification of a new saline formation, and in some cases even longer. For projects using depleted oil and gas reservoirs or EOR, this lead time may be shorter, but the storage capacities are usually more limited (Carbon Sequestration Leadership Forum, 2013). Interestingly, the cost of storage does not put a value on the use of the storage reservoir itself, although regulations sometimes address the potential and remedy if the CO_2 stream or saline water interfere with other oil and gas operations (Chapter 2). In terms of public perception, one might question what the difference is between free CO_2 emissions to the atmosphere, which governments are now trying to address, and free CO_2 injection into deep geological formations, a relatively new frontier.

The IEA (2013c) reported cumulative spending on CCS demonstration projects between 2007 and 2012. US and Canadian government grants totalled almost US$2.4B of the US$10.2B spent on CCS-equipped power generation with a capacity greater than 100 MW and all scales of industrial applications. The balance came from the private sector, although this total includes significant spending on CO_2 capture for EOR. Another US$12.1B of public funds was made available to demonstration, research, and development projects worldwide (IEA, 2013c).

As examples, Table 7.1 provides figures for capital and operating expenditures, public funding, sequestration potential, and net GHG reduction for operating and executing saline sequestration projects. Based on available data, public funding per $MtCO_2$ stored ranges from US$9.6M/Mt (expansion of the Decatur Project into the Illinois Industrial CCS Project) to CAN$71.25M/Mt for the development and first 10 year operations of the Shell Quest project, Alberta, Canada.

The US Department of Energy has suggested that current CCS technology requires a US$70-$90/t price on CO_2 emissions if projects are to be developed without government subsidies (21st Century Tech, 2015). As noted in Chapter 1, several Canadian provinces have already established a price on carbon and the Pan-Canadian Framework on Clean Growth and Climate Change (PCF) (2016d) will see a price on carbon implemented across the country (possibly with the exception of Saskatchewan, where leadership is opposed): $10 per tonne in 2018, rising to $50 per tonne in 2022.

Table 7.1: LSIP/saline sequestration project costs and GHG reductions (based on figures from Massachusetts Institute for Technology (2016))

Project	Estimated capex Cost/Mt	Public funding	CO_2 sequestration potential (per year and	CO_2 reduction

			lifetime)	
Operating projects				
Sleipner, Norway (1991) Natural gas production		Credit for injected CO_2 and reduced Norwegian CO_2 tax[1]	0.9Mt/yr	Reduces CO_2 content in produced natural gas from approximately 9% to 2.5%
Snohvit, Norway (2008) Natural gas production		Credit for injected CO_2 and reduced Norwegian CO_2 tax[1]	Up to 0.7 Mt/yr	Reduces CO_2 content in produced natural gas from approximately 9% to 2.5%
Quest, Alberta (2015) Oilsands upgrader facility	Est CAN$1.35B capital and 10 yr operating budget $112.5M/Mt 2015 revised down $1.22B $101.6M/Mt	CAN$745M Alberta CAN$110M Federal + Emissions credits + USDOE contribution 1st 10 years CAN$71.25M/Mt	1.2Mt/yr (~12 Mt in 10 yrs) ~27 Mt lifetime (est. 25 yrs)	~35% capture rate net 17% CO_2 reduction after energy penalty
Projects being executed				
Gorgon project, Australia Natural gas processing facility	Total US$55B Injection project US$2B	Australian Government US$60M	3.4-4.0 Mt/yr ~120 Mt lifetime (est. 30 yrs)	Reduce CO_2 content of natural gas from 14% to approx. 8.6% GHG reduction approx. 40% for natural gas project
Illinois Industrial Carbon Capture and Storage Project Scale-up of successful Decatur project Bio-energy production – ethanol plant	US$208M	USDOE US$141.5M (68%) + $99M (2010) US$9.6M/Mt	1 Mt/yr ~25Mt lifetime (est. 25 yrs)	CO_2 >99% pure stream 90% capture rate

[1] Insufficient information available to determine tax credit amounts

As background research associated with the PCF, the Canadian First Ministers' Working Group on Specific Mitigation Opportunities considered a broad list of policy options, at varied estimated cost per tonne, for the following sectors: large industrial emitters, transportation, built environment, electricity generation and transmission, agriculture, forestry, waste, government operations and leadership, individual actions, and internationally transferred mitigation outcomes (Specific Mitigation Opportunities Working Group, 2016). CCS applications, both 'accelerated coal phase-out' for electricity generation and 'abatement and sequestration' for large industry were priced at between $50-$100/t. Table 7.2 indicates alternative policy tools estimated at the same cost that may be implemented for these sectors. Additional options were identified at costs between $0/t and >$250/t (Appendix F) (Specific Mitigation Opportunities Working Group, 2016). Wide ranging policy options have therefore been identified for potential inclusion in the portfolio of mitigation approaches undertaken.

Table 7.2: Comparison of Canadian policy options at $50-$100/tCO$_2$ emissions reduction (Adapted from Specific Mitigation Opportunities Working Group (2016))

Policy Tool	Estimated Emissions Reductions in 2030	Total cost	% contribution to 2016-2030 Emissions Reduction Target (219 Mt)
Electricity Generation			
Emissions intensity performance standards	9-21 Mt $0-$50 or $50-$100/t		4 – 9.6 %
Accelerated coal phase-out, with flexibility for CCS	15 Mt $50-$100/t (Nova Scotia >$250/t)	$750M - $1.5B	Announced Nova Scotia – side agreement
Non-emitting portfolio standard	8-15 Mt $50-$100/t		Underway in Nova Scotia
Financial support for non-emitting generation	13-19 Mt $50-$100/t	$650M - $1.9B	5.9 – 8.7 %
Large industry			
Switch fuels with lower carbon alternatives	1-27 Mt $0-50 to $100-$250		
Abatement and sequestration	3-5 Mt $50-$100/t	$150M – $500M	1.3 – 2.2 %
Methane reductions for upstream oil and gas	18-20 Mt $0-$50	$900M - $1B Eg @$50	Announced

During the period of this research project, the projected cumulative global contribution of saline sequestration projects to global CO$_2$ emissions through 2050 has decreased from approximately 19% to 13% through 2050 (IEA, 2009, IEA, 2015a). The reasons for this are not clear. However, the IEA Technology Roadmaps for CCS also indicate an increasing potential share of CO$_2$

emission reductions for end-use fuel and electricity efficiency, rising from 36% to 42%. Further, alternative energy sources are expected to compete with fossil fuels without CCS even at a zero carbon price. The Australian LCOE cost estimates for some renewables such as solar photovoltaic and onshore wind decrease more significantly and become some of the cheapest energy options on the market (Australian Government, 2013).

In identifying and securing private, public, or partnership funding, CCS could be included in the measures to meet the 2DS climate change goal. However, climate policy options might ask how much government tax or private sector cost allocations should go to CCS as a mitigation strategy in the short to medium term compared with other mechanisms for carbon reduction. Although outside the scope of this research to complete a comparative analysis of technologies and approaches, CCS may nevertheless be the best (only?) option for large point source emissions during the transition to other sources of energy through 2050.

3 Risk management policy scenario

In this concluding section, consideration is given to the prevailing context for CCS implementation, underlining the potential usefulness of the IRMF in Canadian and global climate change mitigation efforts. A risk management policy scenario is also provided as a summary of options that would help to protect population health and wellbeing during the planning, execution, and monitoring of the CCS technological process worldwide.

3.1 Canadian and global context for CCS

Canada contributes a small percentage of global anthropogenic GHG emissions. Although projected to increase within our nation, emissions are anticipated to decrease as a percentage of global emissions, from approximately 1.8% in 2010 to 1.6% by 2020 (Environment Canada, 2013). In 2015, our 2020 and 2030 national emission projections were 768 $MtCO_2$equiv/yr and 815 $MtCO_2$equiv/yr respectively (Government of Canada, 2016b). In the PCF, the 2030 emissions projection is 742 $MtCO_2$equiv/yr; and our Paris Agreement 2030 target is 523 $MtCO_2$equiv/yr.

As an approach to climate change mitigation, Canada has been a leader in CCS. Federal and provincial governments have demonstrated a positive policy context for CCS, including financial incentives and developing regulatory frameworks (Chapters 1-2). Worldwide, we have one of few saline aquifer sequestration projects (Shell Quest, Alberta), with a second that has undergone feasibility studies (Spectra Energy's Fort Nelson CCS Project, British Columbia). We also have the first and only large scale power plant CCS-EOR project (Boundary Dam, Saskatchewan). Finally, the Alberta Carbon Trunk Line has a large built capacity (14.6$MtCO_2$/yr) for transport from additional, as yet unidentified, capture facilities to the established EOR injection site (Chapter 3).

For the 2020 and 2030 time horizons, estimated emissions from CCS-related sectors are provided in Table 7.3: the electricity sector is projected to decrease to approximately 7% of national total emissions; the oil and gas sector is projected to increase to approximately 27%; and the emission intensive trade exposed (EITE) sector (that includes steel, cement, fertilizer production) is also projected to increase, to about 13% of emissions. The CO_2 gas component is expected to remain approximately 79% overall but insufficient information is available to identify this particular percentage in each of these sectors (608 and 643 $MtCO_2$ gas is projected for 2020 and 2030 (Government of Canada, 2016b)).

Table 7.3: Potential CCS applications and related CO_2 emissions (based on data from Government of Canada (2016b))

Potential CCS application	Actual and Estimated GHG Emissions % of Canadian Total ($MtCO_2$equiv[1])			Approximate LSIP contribution to emissions reductions (rated capacity)
	2013	2020	2030	
Electricity sector - western provinces; Nova Scotia (Ontario and Quebec do not burn coal)	~12% (85)	~10% (74)	~7% (58)	1.35% 2020 1.72% 2030 (1 Mt) Boundary Dam
Oil and gas sector – western provinces (fossil energy used in oil and gas production and refining)	~25% (179)	~27% (210)	~29% (242)	2–2.3% 2020 1.8-2% 2030 (4.3-4.9 Mt) Quest, ACTL, Fort Nelson
Emission intensive trade exposed (EITE) industry – cement, steel (production across Canada, but with concentration in Ontario and Quebec[10]); fertilizer (west)	~10% (76)	~10% (76)	~13 (107)	0.8% 2020 0.5% 2030 (0.585 Mt) Agrium portion of ACTL

[1] Overall in Canada, an estimated 79% of GHG emissions is CO_2. There is insufficient information to calculate the CO_2 gas component of these projections.

At the moment, Canadian saline sequestration and CCS-EOR LSIPs are rated to capture approximately 6.4 $MtCO_2$equiv/yr (Table 7.3), roughly 3% of Canada's current national emissions reduction target of approximately 225 $MtCO_2$equiv/yr. If a large scale project captures and stores 1-2 $MtCO_2$/yr, Table 7.3 also indicates that Canada has a large potential for this technology. Indeed, the *North American Carbon Storage Atlas* (North American Carbon Atlas Partnership,

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[10] Location of cement facilities: http://www.cement.ca/en/Economic-Contribution.html;
Location of steel facilities: http://www.canadiansteel.ca/wp-content/uploads/2016/05/Steel_Facilities_Map.pdf

2012) lists 188 large stationary sources of CO_2 emissions in Canada: 71 electricity production sources and the remainder being industrial sites.

Including CCS in an attempt to reach our emission reduction goal for 2030 now requires a geographic match between point source power and industrial CO_2 emission sites and our potential geologic storage capacity (Bachu, 2003, North American Carbon Atlas Partnership, 2012). Table 7.3 indicates a western provincial bias with respect to CCS development in the electricity and oil and gas sectors. Indeed, Canadian projects have been located in the western provinces where there is a long history of oil and gas development and therefore familiarity with the premise of injection and storage that is CCS (Chapters 2 and 3). It is also a prime storage region given the large extent of the Western Canadian Sedimentary Basin (Bachu, 2003) (Chapter 1).

Based on future scenarios presented by Meadowcroft and Langhelle (2009), the Canadian geographical context is a microcosm of the global context: CCS could be a regionally significant technology, applied in fossil-fuel based western Canada. The favourable political economy landscape in Alberta was identified by Kern et al. (2016) as a critical feature for the success of Shell’s Quest project; British Columbia is also working to enable natural gas development within the provincial climate change strategy, which includes CCS sequestration storage option.

CCS sequestration projects may also be developed for emission intensive trade exposed industry (EITE) sites. In fact, the increase in emissions in this sector is approximately the same number of Mt between 2020 and 2030 (31 Mt) but the percentage increase is greater than for the oil and gas sector (41% increase compared with 15%) (Table 7.3). This would be analogous to the pathway suggested by Meadowcroft and Langhelle (2009), wherein CCS develops as a niche technology where industrial processes cannot be avoided. Similarly, Heyes and Urban (*submitted*) suggested that, “based on the existing knowledge about CCS, the economic and technological literature points to a potential niche role for CCS - applied in particular settings where the economics are favorable - but there is little evidence to suppose it is likely to play a central role in the shift to a lower carbon economy over the next two decades.” In large part, our EITE project locations would see CCS expand to more populated regions, such as Ontario and Quebec, if this emerging application is to also contribute to Canada’s emissions reductions. Although sedimentary basins exist (see Figure 1.3, Chapter 1), these regions have much less familiarity with pipelines and wells, and realising what are perceived to be acceptable risk control options may be more challenging. A review process that follows the suggested IRMF may be even more critical to future success outside western Canada.

Canadian policy signals with respect to concerted CCS development seem, however, mixed. Earlier in 2016, (now removed from the website) the federal government suggested (Government of Canada, 2016a):

> “Carbon capture, use and storage will help meet Canada’s 2030 emission reduction targets. This will particularly be the case in the oil and gas, and industrial sectors. R&D activities in this area will help reduce capture costs and improve efficiency to help deploy this technology more broadly ─ paving the way for significant emission reduction” (Government of Canada, 2016a).

As later agreed in the PCF, CCS as a decisive approach for point source emissions reductions is not mentioned specifically, except with respect to the Boundary Dam CCS-EOR as a demonstration project (Government of Canada, 2016d). However, as noted in Table 7.2 (and Chapter 1), the ‘accelerated coal phase-out, with flexibility for CCS’ policy option has been announced (Environment Canada, 2012, Government of Canada, 2016c).

Nevertheless, the projected CAN$50-$100/t (Table 7.2) or US$70-$90/t (21st Century Tech, 2015) cost for CCS-related policy options can be compared with the PCF price on carbon progression from $10/t in 2018 through $50/t in 2022 (Government of Canada, 2016d). At these prices, industry’s CCS implementation would remain unlikely without further government subsidy. Indeed, a spokesperson for Shell suggested that when the price of carbon approaches $100/t, CCS could be implemented without public financing (Jaremko, 2016). In the meantime, societal deliberations might consider how carbon tax revenues are allocated to competing social, economic, or environmental concerns.

Two scenarios come to mind: a lot could happen in implementing alternate climate change mitigation options in the interim period, then essentially leap-frogging CCS technology at varied costs and benefits; or, policy makers will recognize that CCS is the preferable and most cost effective option for point source emission reductions, as has been suggested by the IEA (2015a). A further corollary, therefore, is that if early projects have early upsets, taxpayers and government could abandon the approach in its infancy.

Therefore, regardless of region and jurisdiction, the common IRMF, presented effectively to the public, could make a convincing case that the significant investment by the private and public sectors is money well spent. Should policy makers decide to implement CCS as a climate change mitigation technology in suitable locations, the IRMF is designed to be a pathway for appropriate technological assessment, providing a coordinated, integrated, rational approach to risk management based on a step wise process with ongoing opportunities for wide ranging public engagement that can provide a forum for all viewpoints. Long-term reliability of storage sites needs to be comparable in order for the success of CCS for emissions reductions to be assessed. The process will provide a greater opportunity to reach consensus. Ongoing controversy such as being experienced with the Boundary Dam project (Chapter 3) could be avoided with a more robust process including greater public input and transparency at the community level.

The role of CCS-EOR must also be considered. In Canada and the US, these projects have been developed and promoted as proof of concept for commercial scale implementation. These projects have also received public financing (Massachusetts Institute for Technology, 2016), in addition to the oil and gas revenues that offset private sector costs. CCS-EOR accounts for 76% of projects and 81% of the global capture rate, with five of the next seven executing LSIPs EOR project types (Massachusetts Institute for Technology, 2016). While there is a current undertone that CCS-EOR projects are virtually synonymous with saline sequestration as demonstration sites, work to determine how these projects may account for storage credits is ongoing. EOR projects operate under regulatory regimes where monitoring and verification does not necessarily occur and results are not necessarily disclosed publicly. In Alberta and elsewhere, Jenkins et al. (2015) noted that these business operations are not required to and do not release information that demonstrates containment and performance. Indeed, measurement has not been regulated for EOR, leading Dixon et al. (2015) to suggest that amendments or new regulations may need to be approved in order to address storage-focused performance objectives. Research and discussion is underway regarding accounting of EOR within CCS for climate change mitigation (IEA, 2015b, Wong et al., 2013, Zakkour and Cook, *forthcoming*) as well as technical challenges for converting EOR to storage projects (Bachu et al., 2013).

As discussed in Section 2.1 with respect to risk perception, these developments may not support public acceptance of CCS overall. They are seen as an excuse to continue to rely on the traditional fossil fuel economy. In their assessment of relative risk, however, the expert elicitation panel did not suggest a difference in relative risk between the three storage options of saline aquifer sequestration, EOR, or coalbed methane (CBM) (Chapter 4). As well, the expert group suggested over 99% CO_2 retention in both saline aquifer and EOR project types over 1,000 years, although the credible uncertainty range was greater for EOR, particularly at the lower limit: the 1 in 20 judged likelihood is that 87% and 54% of injected CO_2 can be expected to retained in a saline aquifer and EOR projects, respectively. Such uncertainty is clearly an important outstanding issue. Perhaps ongoing and increased monitoring at CCS-EOR projects will support the contention that these projects are safe and reliable and positive contributions. However, the question of perpetuating the fossil economy is another matter.

In turning to the global context, the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) may create a new emphasis on collaboration to advance CCS worldwide. Here, CCS is identified as having a role in achieving the 2DS target in a least cost scenario.

However, as indicated in Chapter 1, "CCS is not on a trajectory to meet the 2DS target of 540 $MtCO_2$ being stored per year in 2025" (IEA, 2016b, p. 30). Indeed, the global capture rate is less than one-tenth of this (40 $MtCO_2$). Furthermore, fossil fuels will continue as a significant component of the global energy mix and CCS may be the only technological process to mitigate these emissions through 2050. As an example, the use of coal in Asia is expected to account for four of every five global tonnes of CO_2 emissions (IEA, 2015c).

At the moment, excluding Norway and Canada, only eight countries have named carbon capture and storage in their intended nationally determined contribution (INDC) under the Paris Agreement: Bahrain, China, Egypt, Iran, Malawi, Saudi Arabia, South Africa, and United Arab Emirates (PRIMAP-live, 2016). Furthermore, the GCCSI (2015) regulatory-readiness assessment indicator found that China, Egypt, Saudi Arabia, South Africa, and United Arab Emirates had "very few CCS-specific or existing laws that are applicable across parts of the CCS project cycle" (p. 3). Bahrain and Iran were not assessed. Overall, twenty-seven countries are somewhat prepared for CCS in the regulatory context; and twenty-three countries have made less progress in this regard (GCCSI, 2015).

Globally, the geographical emphasis for CCS is projected to transition from OECD to non-OECD countries (IEA, 2016b). The Clean Energy Ministerial identified barriers and suggested actions to address impediments to funding projects in non-OECD nations (GCCSI, 2012, GCCSI, 2013). In 2013, Canada was one of only six countries that made a funding contribution to CCS in developing countries (GCCSI, 2013). In 2015, the Government of Canada announced a US$2.65B commitment to the United Nations Green Climate Fund, intended to assist developing nations adapt and mitigate climate change (Green Climate Fund, 2016). Canadian project and regulatory experience, in conjunction with value-chain research in capture, transport, injection, and storage, could contribute expertise to project development in other parts of the world.

In contemplating projects in other countries, the IRMF for CCS clearly illustrates the ways in which wide ranging government and non-government organizations have an integral role to play in the assessment, approval, monitoring, and evaluation of proposals. Identifying key stakeholders in other jurisdictions would not be difficult and many internationally-based government, quasi-government, and non-government partners would remain the same as those listed in the Canadian context. Modification of the IRMF for application in another jurisdiction would include identifying core government agencies and other key government and non-government partners as depicted in Figure 6.1. This could assist with the recommendation of the Commission on Social Determinants of Health (2008), that mitigation and adaptation responses to climate change not unnecessarily and unfairly negatively impact populations, nor exacerbate health equity.

3.2 Risk management policy scenario

In addition to the development of the integrated risk management framework for CCS, the findings from this research project also provide direction for risk management policy scenarios for population health and environmental protection (Table 7.4). Priorities are listed within the categories of the REACT framework for risk management and population health (Krewski et al., 2007, Krewski et al., 2014). As described in Chapter 6, these include:

- Regulatory: Government policies, legislation, guidelines, permits, or approvals for required action (three categories of statutes include products, emissions, and natural environmental protection)
- Economic: Insurance, levies and other cost structures, designed as incentives to take action
- Advisory: Programs developed to encourage action, including communications, education, and awareness
- Community-based: Public inception, support, and commitment to take action, often volunteer-based
- Technological: Action through improved advances in technological abatement.

Table 7.4 presents risk management issues and options scenario that are currently implemented or available in Canada as well as suggestions that would create a more robust regime during the 2017-2030 period worldwide. Action needs to occur at multi-levels and multi-scales. In the case of CCS, these would occur variably for each value-chain component of an integrated project. Responsibility for each approach, however, whether undertaken individually or in partnership by the proponents, regulators, non-government organizations, and/or the public, is not identified specifically. In Canada, for example, some options fall more clearly within federal or provincial jurisdictions. Actions undertaken by international bodies are also indicated.

Table 7.4: Local and global CCS risk management issues and options scenario (acronyms detailed below[1])

Local Project Includes current Canadian approach	2016-2030 Acceptance	
	OECD With Canadian examples	Non-OECD
Regulatory/Policy Options		
Permitted design and operations specifications MMV Plan Renewable permitting Reporting CEPA coal regulations	Role of CCS within PCF CEPA oil and gas regulations Industrial mitigation targets	UNFCCC INDCs and 5 year review UNFCCC Modalities and Procedures for CCS as a clean development mechanism
	Public engagement and transparency Characterization of baseline conditions Design, operations, closure, and post-closure specifications Emergency Response Plan specifications Training/Certifications MMV period; MMV for CCS-EOR Health and environmental protection cost allocation Regulated leakage likelihood threshold	
Economic Options		
Incentives Carbon levy and credits	Public funding	UN Green Climate Fund
	Penalties and fines Contingency/liability funds Health and environmental protection cost allocation Storage formations as national assets Community compensation Price on carbon	
Advisory Options		
Public consultation Notification processes Emergency Response Plan development Safety procedures	Role of CCS within PCF Shared expertise and training	International collaboration Shared expertise and training
	Public engagement and transparency Proponent's health and environmental protection cost commitment Value chain specifications and performance requirements Value chain 3rd party review of technological parameters clearly defined, quantified, and documented	
Community-based Options		
Transport - Route selection	Site characterization and selection – capture, transport, injection, storage Development and implementation of Emergency Response Plan Shared expertise and training MMV Plan, including 3rd Party monitoring	
Technological Options		
Site characterisation and selection criteria Amine emission mitigation Well integrity studies Automatic emergency shut down system MMV program	New capture technologies Geological capacity and performance Acknowledge and address LPHI Responsive geosphere and biosphere MMV program Leakage measurement capacity MMV for CCS-EOR Closure/Post closure MMV program	

[1] OECD (Organization for Economic Cooperation and Development); CEPA (Canadian Environmental Protection Act); EOR (enhanced oil recovery); INDC (Intended Nationally Determined Contributions); MMV (Measurement,

Monitoring and Verification); PCF (Pan-Canadian Framework for Clean Growth and Climate Change); UNFCCC (United Nations Framework Convention on Climate Change)

A national or regional regulatory framework would include provisions for risk management in each category, with some interdependence. As an example, risk reduction based in regulation would only be successful insofar as there are technological options to support safe operations and monitoring. Furthermore, some options are repeated in more than one category, also indicating the interconnectedness of these approaches.

Important risk management options that fall within more than one category may be deemed crucial for widespread implementation of CCS in the years ahead. As evident in Table 7.4, these include:

- implementation options for Pan Canadian Framework for Clean Growth and Climate Change;
- site characterisation and selection criteria;
- value-chain performance and containment criteria;
- human health and environmental protection cost allocation;
- emergency response plan development and specifications;
- training;
- agreement on MMV period and specifications of MMV for CCS-EOR; and
- public engagement and transparency.

It is of note, in closing, that each of these activities falls within a risk assessment and risk management decision making process that could be made possible through the use of the integrated risk management framework for CCS. As suggested in Chapter 6, at the project level, implementation would be made within the context of risk management principles, socio-economics, risk perception, and economic analysis, each of which will vary in the local community, reflecting stakeholders and timeframes.

It is early days for carbon capture and storage. If this technological process is implemented to its full potential, wide ranging credible risk management options could underpin public acceptance as being reliable and effective in mitigating CO_2 emissions in OECD and non-OECD countries alike. This would help protect population and environmental health for those in the vicinity of local projects, as well as contribute to the global challenge of reducing greenhouse gas emissions responsible for climate change.

Chapter 7 References

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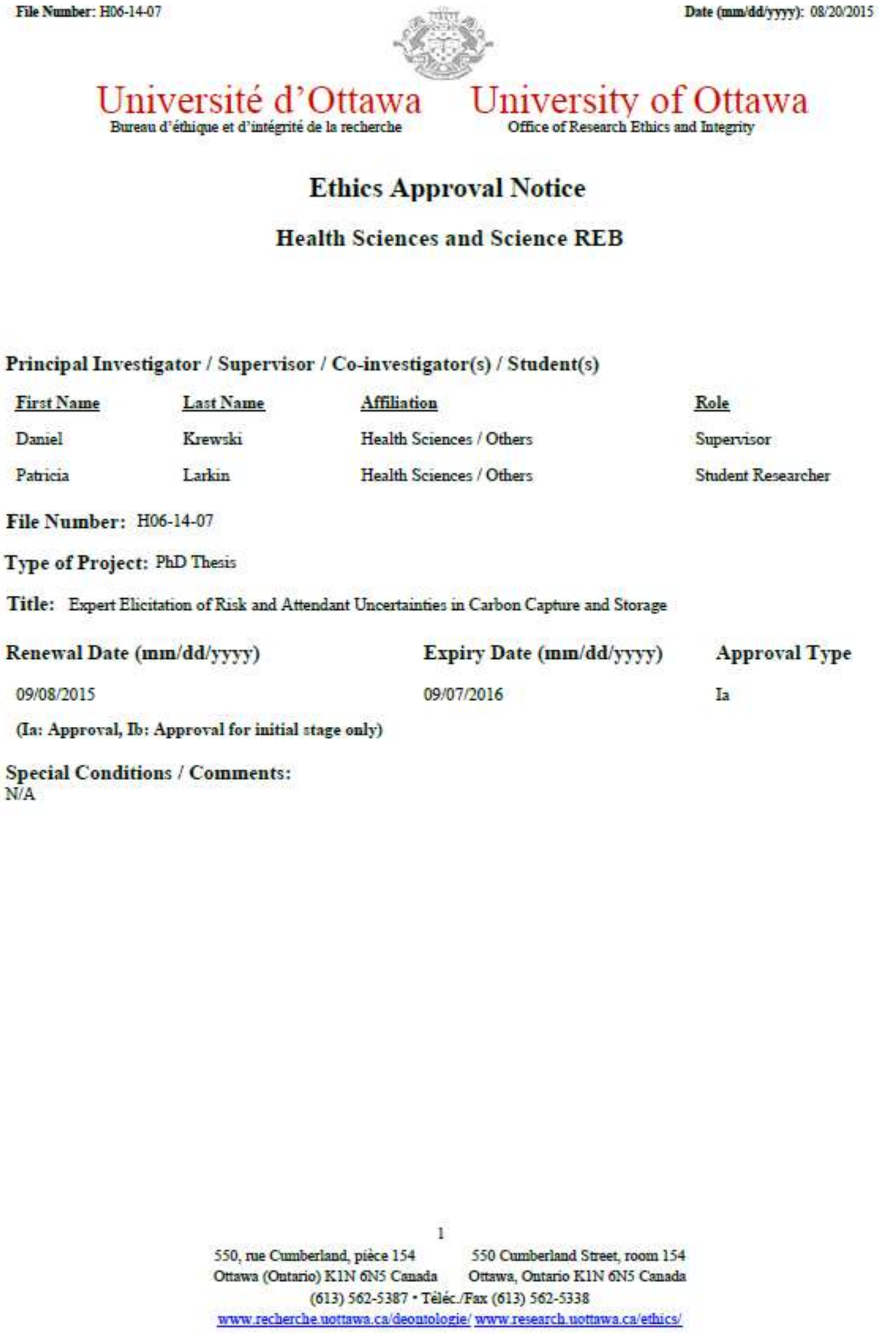
Appendix A: Expert Elicitation Materials

Ethics Approval



File Number: H06-14-07

Date (mm/dd/yyyy): 08/20/2015

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Daniel	Krewski	Health Sciences / Others	Supervisor
Patricia	Larkin	Health Sciences / Others	Student Researcher

File Number: H06-14-07

Type of Project: PhD Thesis

Title: Expert Elicitation of Risk and Attendant Uncertainties in Carbon Capture and Storage

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
09/08/2015	09/07/2016	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A

1

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Consent to Participate in Research

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Expert Elicitation of Risk and Attendant Uncertainties in Carbon Capture and Storage (CCS)

You are asked to participate in a research study conducted by Dr. Daniel Krewski from the McLaughlin Centre for Population Health Risk Assessment at the University of Ottawa. Your participation in this study is entirely voluntary. Please read the information below and ask questions about anything you do not understand, before deciding whether or not to participate.

You have been asked to participate in this study because you are internationally recognized as an authority in the field of carbon capture and storage.

PURPOSE OF THE STUDY

To complete an expert elicitation of scientific judgements, with emphasis on likelihood and severity of impact of risks related to injection and storage phases of CCS, as well as risk management of high impact low probability (catastrophic) risk events.

The research team would like to investigate these questions before completing an Integrated Risk Management Framework for CCS.

PROCEDURES

If you volunteer to participate in this study, you will be asked to do the following things:

- All Experts are expected to participate simultaneously in the Elicitation.
- Dr. Daniel Krewski will lead the process.
- There will be time to familiarize yourself with the nature of expert elicitation process; to review the sections of the instrument; to discuss the questions and make revisions where necessary prior to beginning the questions.
- The Elicitation is expected to last 1.5 days, scheduled for ____________ and ________________, 2015.
- The Elicitation will be recorded in order to review the oral discussion post hoc if required.

POTENTIAL RISKS AND DISCOMFORTS

No risks or discomforts are expected during the Expert Elicitation process.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

In the first instance, the elicitation will provide an opportunity for leading experts in the field of CCS to meet. Following the elicitation process, results will be disseminated and participants will benefit from a better understanding of risks and uncertainty in carbon capture injection and storage chain components of CCS, as well as for risk management options.

This research will benefit society by addressing identified data gaps in risks and attendant uncertainties in two chain components of CCS integrated systems, as well as with risk management of high impact low probability events. Addressing these outstanding questions is important to the development of an Integrated Risk Management Framework (IRMF) for Carbon Capture and Storage in the Canadian Context. The results will strengthen the final IRMF, which in turn will provide a blueprint for safe and effective implementation of a new technology to mitigate climate change, a technology that has the potential to provide a significant reduction of greenhouse gas emissions to the atmosphere. Given projected fossil fuel dependence while the world transitions to other energy sources through 2050, this work has important benefits for societal economic, health, and environmental wellbeing, both in Canada and abroad.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential to the researchers and will be disclosed only with your permission. For analysis purposes, experts' responses will be anonymized and identified only by number, not by name. However, given the nature of the panel (group) discussion, confidentiality cannot be guaranteed.

Dr. Krewski and the Research Assistant will have access to the completed elicitation instrument and the audio-recording. Results will be stored in locked cabinet at the McLaughlin Centre for Population Health Risk Assessment and will be destroyed after 5 years.

PARTICIPATION AND WITHDRAWAL

You can choose whether or not to be in this study. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind or loss of benefits to which you are otherwise entitled. You may also refuse to answer any questions you do not want to answer. There is no penalty if you withdraw from the study and you will not lose any benefits to which you are otherwise entitled.

IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about this research, please contact
Dr. Daniel Krewski, Principal Investigator,
Faculty of Medicine
McLaughlin Centre for Population Health Risk Assessment.
University of Ottawa
Ottawa, Ontario, Canada K1G 3Z7
cphra@uottawa.ca

RIGHTS OF RESEARCH PARTICIPANTS
The University of Ottawa Office of Research Ethics and Integrity has reviewed the request to conduct this project.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Printed Name of Participant

____________________________________ ______________________
Signature of Participant Date

____________________________________ ______________________
Signature of Principal Investigator Date

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EXPERT ELICITATION INSTRUMENT

RISKS AND ATTENDANT UNCERTAINTIES
IN CARBON CAPTURE AND STORAGE

MCLAUGHLIN CENTRE FOR POPULATION HEALTH RISK ASSESSMENT

UNIVERSITY OF OTTAWA

MARCH 25, 2015

EXPERT ELICITATION INSTRUMENT

Risks and Attendant Uncertainties of Carbon Capture and Storage

Contact information
Principal investigator: Dr. Daniel Krewski, Director, McLaughlin Centre for Population Health Risk Assessment, University of Ottawa
Research assistant: Patricia Larkin, PhD Candidate, Population Health, University of Ottawa

Background and Goal

Carbon Capture and Storage (CCS) has been identified as a mitigation strategy to decrease industry-based anthropogenic sources of greenhouse gas emissions. The four broad phases of project implementation are CO_2 capture, transport, injection, and storage, each of which includes potential risks to the environment and human health.

Expert elicitation has been shown to be of value where information is scarce, knowledge is limited, uncertainties are great, and risks are theoretically very low. The purpose of this expert elicitation of scientific judgements is to consider experts' understanding and beliefs about risks of CCS, with an emphasis on injection and storage phases of project implementation and risk management of high impact low probability events. Your responses will assist in understanding relative risk and to quantify the collective uncertainty judgements. This is an important component of a reasoned and planned integrated risk management framework that can be applied to CCS projects in Canada and possibly abroad.

Answers to this elicitation instrument will be analyzed using the Cooke Classical Model within the EXCALIBUR software package. The UNIBALANCE software package is used for the paired comparison approach.

Thank you, in advance, for your participation.

Arriving at Understanding

Prior to beginning the elicitation questions, you are invited to arrive at a common understanding of CCS failure scenarios. You will also have opportunities to clarify questions and seek revisions during the elicitation process.

- Throughout this elicitation instrument, unless otherwise specified, "risk" refers to combined probability and consequence of an adverse effect

- The term "CO_2 leakage" represents both leakage and seepage scenarios:
    - Leakage - refers to movement of fluids (including injected CO_2) outside the storage formation. This can involve movement through the upper and lower bounding seals or through wellbore pathways. Monitoring for leakage is focused on processes that may lead to CO_2 movement towards and possibly into the biosphere
    - Seepage - refers to movement of fluids (including injected CO_2) from the geosphere to the biosphere. Monitoring for seepage is focused on limiting any health, safety or environmental issues

- Questions do not differentiate between point source leakage or diffuse leakage over a large area

- Some questions distinguish between three CO_2 leakage scenarios:
    - Minor leakage (light and slow, escaping repository);
    - Major leakage (requires intervention to mitigate effects); or
    - Catastrophic leakage (significant infrastructure damage or evacuation)

  The amount of leakage can be considered as any of:

    - Percentage of mass injection rate of CO_2
    - Percentage of total injected CO_2 mass
    - Total mass of leaked CO_2 per year

- Some questions indicate timeframes for leakage scenarios

- CCS projects are expected to be developed in low to medium population density areas, remote from major urban centres

- Note that the elicitation does not attempt to assess your judgement on what is "acceptable" risk.

Part 1: Seed Questions

1. How many major sedimentary basins exist in the world?

Lower limit ______ (5th percentile)	Central value _______ (median)	Upper limit _______ (95th percentile)

2. What is the minimum depth for the top of the CO_2 storage aquifer in the Western Canadian Sedimentary Basin, as was recommended by van der Meer (1993)?

Lower limit depth ______ (m) (5th percentile)	Central value depth _____(m) (median)	Upper limit depth____(m) (95th percentile)

3. What minimum temperature is required for CO_2 to remain in a supercritical state at $P > 7.38$ MPa (kg/m^3T) (^{o} C)?

Lower limit ______ (^{o} C) (5th percentile)	Central value _______ (^{o} C) (median)	Upper limit ______ (^{o} C) (95th percentile)

4. In a modeled brine saturated sandstone storage site, what is the maximum porosity for the greatest bulk volume residual sequestration in a nonwetting phase (%)?

Lower limit ______ (%) (5th percentile)	Central value _______ (unit) (median)	Upper limit _______ (unit) (95th percentile)

5. What percentage of the fracture extension pressure is permitted in the Shell Quest sequestration project?

Lower limit ______ (m) (5th percentile)	Central value _______ (m) (median)	Upper limit _______ (m) (95th percentile)

6. Due to the limited availability and proprietary nature of industry CCS data, it is not feasible to obtain detailed data on industry CCS CO_2 leakages. A literature review to identify records of CO_2 surface leakages worldwide was undertaken by Augustin (2014), and data were obtained from databases maintained by the United States Geologic Survey, the United States Environmental Protection Agency, and the Italian Googas Database. These data covered 288 unique sites.

   How many surface leaks were recorded between 1986 and 2012?

Lower limit ________ (5th percentile)	Central value ________ (median)	Upper limit _______ (95th percentile)

7. From the same study (Augustin, 2014), what was the largest recorded CO_2 leak, in (US) metric tons?

Lower limit ______ (US Mt) (5th percentile)	Central value ______(US Mt) (median)	Upper limit _____ (US Mt) (95th percentile)

8. From 1990 through 2012, what was the total number of Alberta pipeline incidents (hits, leaks, ruptures) reported to the regulator for all pipeline types?

Lower limit __________ (5th percentile)
Central value _________ (median)
Upper limit _______ (95th percentile)

9. A pipeline leak is defined as a situation where a pipeline may be losing product but continuing to operate. A rupture is a situation where the pipeline has been compromised to the point where it cannot continue to operate, and can cause serious damage and injury. From 1990 through 2012, what percentage of Alberta pipeline incidents for all pipeline types were ruptures?

Lower limit ______ (%) (5th percentile)
Central value _______ (%) (median)
Upper limit _______ (%) (95th percentile)

10. From 1990 through 2012, what percentage of all pipeline failures reported to the Alberta regulator was caused by internal corrosion (%)?

Lower limit ______ (%) (5th percentile)
Central value _______ (%) (median)
Upper limit _______ (%) (95th percentile)

11. Based on the Chart at right, assuming total use of the pore volume, what is the maximum mass of pure CO2/m^3 in rock with 20% porosity at 90 ^{o}C and 15 MPa?

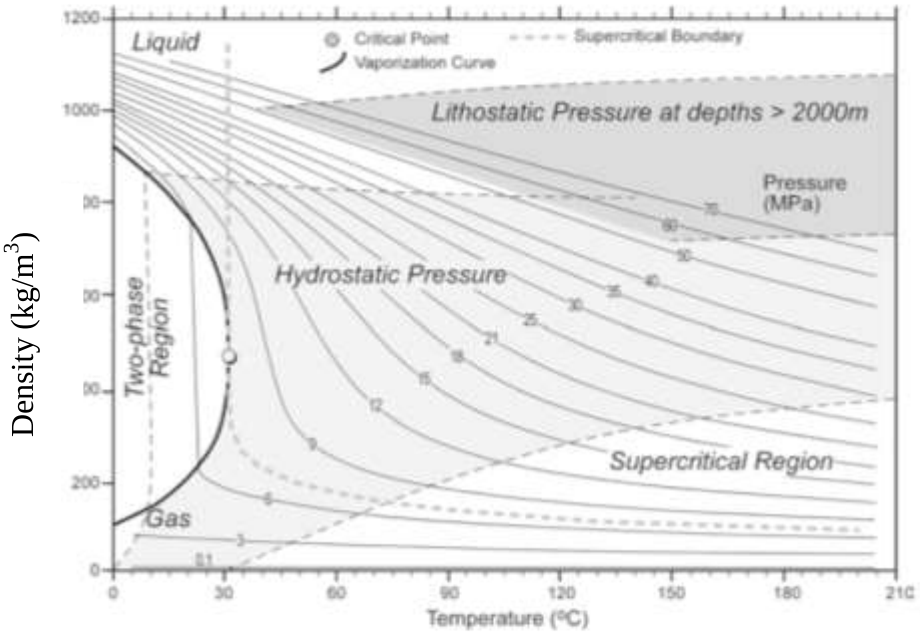

Fig. 4
Variation of CO_2 density as a function of temperature and pressure, showing the range of density that would be encountered in sedimentary basins around the world for various surface temperatures and geothermal gradients, assuming hydrostatic and lithostatic pressure conditions

Lower limit ______ (kg) (5th percentile)
Central value _______ (kg) (median)
Upper limit _______ (kg) (95th percentile)

12. As reported by Alberta's Energy Resources Conservation Board (the regulator) in 1990, what was the injection well failure frequency for sour gas wells in Alberta (number per 1,000 wellheads over a period of 10 years)?

Lower limit (5th percentile) _______ (per 1,000 wellheads in 10 years)
Central value (median) _______ (per 1,000 wellheads in 10 years)
Upper limit (95th percentile) _______ (per 1,000 wellheads in10 years)

13. Empirical observations in the early 20th Century on viscous flow instabilities in porous oil-bearing rocks led to the recognition of 'viscous fingering'. In a recent study, Al-Housseiny and colleagues investigated experimentally in the lab a variant of the classical viscous fingering problem by introducing a small depth gradient in a Hele–Shaw cell (see figure). Their experimental set-up involved non-wetting air displacing a wetting mineral oil, with fingering triggered by instability evolution at a critical capillary number (found to be: Cac = 5.4×10−3).

What is the corresponding flow speed V of the air at this critical point (mm/s)?

Lower limit ______ (mm/sec) Central value _______ (mm/sec) Upper limit _______ (mm/sec)
(5th percentile) (median) (95th percentile)

14. In taking a moderate sorption capacity of 0.5 mmol CO2/g rock (22 kg/t), a caprock thickness of 100 m, with a bulk density of 2.4 g/cm^3, what theoretical total sorption quantity (t per unit area) (not including CO_2 dissolution in water) was calculated by Busch et al. (2009)?

Lower limit ______ (unit) Central value _______ Upper limit _______
(5th percentile) (median) (95th percentile)

15. As found by Raistrick et al. (2006) following 40 months of injection at Saskatchewan's IEA Weyburn Greenhouse Gas Monitoring and Storage Project, what percentage of HCO_3^- was calculated to have formed from dissolved injected CO_2 (%)?

Lower limit ______ (%) Central value _______ (%) Upper limit _______ (%)
(5th percentile) (median) (95th percentile)

16. What minimum pressure is required for CO_2 to remain in a supercritical state at T > 31.1 °C?

Lower limit ______ (kg/m^3) Central value ______ (kg/m^3) Upper limit _____ (kg/m^3)
(5th percentile) (median) (95th percentile)

17. What is the solubility of H_2O in CO_2 (Henry Constant per atmosphere)?

Lower limit ______ (%) Central value _______ (%) Upper limit _______ (%)
(5th percentile) (median) (95th percentile)

18. What radius from the injection well will be affected by salt precipitation, as determined by simulations conducted by Shell for the Quest Project (m)?

Lower limit ______ (m) Central value _______ (m) Upper limit _______ (m)
(5th percentile) (median) (95th percentile)

Part 2: Overview Questions

Instructions for Paired Comparison questions 1-3
In the tables for Questions 1-3, we need you to indicate which you consider to present the greater risk. Please complete the upper triangle of each preference matrix.

- If the row phase is more risky than the column phase, insert a greater than sign (>),
- If the row phase is less risky than the column phase, insert a less than sign (<).
- If the row and column phases are of equal risk, insert equal sign (=).

Example Q1:

- If capture is a greater risk than transport, then insert > as shown below

	Transport
Capture	>

- If capture is a less risk than transport, then insert < as shown below

	Transport
Capture	<

- If capture and transport are of equal risk, then insert = as shown below

	Transport
Capture	=

Please note, because of the way UNIBALANCE seeks numerically to synthesize experts' ranking preferences under probabilistic inversion, it is highly desirable to use the equality (=) condition as little as possible, and only if you are absolutely certain there is no way to distinguish between the two options. Effectively, an equality does not provide information and an excessive number (either within an individual expert's responses or across the panel as a whole) can prevent the inversion algorithm from converging to a meaningful outcome.

PC1-PC3: In order to rank the relative risk of four chain activities of integrated carbon capture and storage projects (capture, transport, injection, and storage), we need you to indicate which you consider to present the greater risk. Technical, environmental, and health risk is to be considered separately.

Technical Risk Matrix

	Capture	Transport	Injection	Storage
Capture				
Transport				
Injection				
Storage				

Environmental Risk Matrix

	Capture	Transport	Injection	Storage
Capture				
Transport				
Injection				
Storage				

Health Risk Matrix

	Capture	Transport	Injection	Storage
Capture				
Transport				
Injection				
Storage				

PC4. In order to rank the overall relative risk of the three main types of storage options (saline aquifer; coal bed methane seams; enhanced oil recovery), we need you to indicate which you consider to present the greater risk over the long term (>100 years)?

	Saline aquifer	Coal bed methane	Enhanced oil recovery
Saline aquifer			
Coal bed methane			
Enhanced oil recovery			

PC5. In order to rank the relative risks of distinct causes of local health and environmental hazards in a low to moderately populated area, we need you to indicate which you consider to present the greater risk

- Brine, HCO_3, or elevated gas-phase CO_2 migration into the shallow subsurface and near-surface environment
- A seismic event of magnitude $M > 5$ on the Richter scale
- Explosive re-release of CO_2 to the surface
- Cap rock integrity loss due to hydraulic fracturing caused by CCS project

	Brine, HCO_3, or elevated gas-phase CO_2 migration into the shallow subsurface and near-surface environment	A seismic event of magnitude $M > 5$ on the Richter scale	Explosive re-release of CO_2 to the surface	Cap rock integrity loss due to hydraulic fracturing
Brine, HCO_3, or elevated gas-phase CO_2 migration into the shallow subsurface and near-surface environment				
A seismic event of magnitude $M > 5$ on the Richter scale				
Explosive re- release of CO_2 to the surface				
Cap rock integrity loss due to hydraulic fracturing				

Paired comparison instructions for paired comparison questions 6 and 7
In the tables for Questions 6 and 7, we need you to indicate the relative reactivity of five naturally occurring minerals with CO_2 in the pure supercritical state (PC6) and CO_2 in the dissolved state (PC7):

$KAlSi_3O_8$ – $NaAlSi_3O_8$ – potassium or sodium Feldspar;
$CaCO_3$ – Calcite;
$CaSO_4$ – Anhydrite;
Hydrated clay minerals in a ductile shale;
SiO_2 - Quartz

Please complete the upper triangle of each preference matrix:

- If the row mineral is more reactive with CO_2 than the column mineral, insert a greater than sign (>)
- If the row mineral is less reactive with CO_2 than the column mineral, insert a less than sign (<)
- If the row and column minerals are of equal reactivity with CO_2, insert equal sign (=)

Please note, because of the way UNIBALANCE seeks numerically to synthesize experts' ranking preferences under probabilistic inversion, it is highly desirable to use the equality (=) condition as little as possible, and only if you are absolutely certain there is no way to distinguish between the two options. Effectively, an equality does not provide information and an excessive number (either within an individual expert's responses or across the panel as a whole) can prevent the inversion algorithm from converging to a meaningful outcome.

PC6: Reactivity of minerals with pure supercritical CO_2

	$KAlSi_3O_8$ – $NaAlSi_3O_8$ potassium or sodium Feldspar	$CaCO_3$ Calcite	$CaSO_4$ Anhydrite	Hydrated clay minerals in a ductile shale	SiO_2 - Quartz
$KAlSi_3O_8$ – $NaAlSi_3O_8$ potassium or sodium Feldspar					
$CaCO_3$ Calcite					
$CaSO_4$ Anhydrite					
Hydrated clay minerals in a ductile shale					
SiO_2 – Quartz					

PC7: Reactivity of minerals in CO_2-saturated saline water

	$KAlSi_3O_8$ – $NaAlSi_3O_8$ potassium or sodium Feldspar	$CaCO_3$ Calcite	$CaSO_4$ Anhydrite	Hydrated clay minerals in a ductile shale	SiO_2 - Quartz
$KAlSi_3O_8$ – $NaAlSi_3O_8$ potassium or sodium Feldspar					
$CaCO_3$ Calcite					
$CaSO_4$ Anhydrite					
Hydrated clay minerals in a ductile shale					
SiO_2 – Quartz					

Note: We are now moving from paired comparison to quantitative questions.

Recall: Some questions distinguish between three CO_2 leakage scenarios:

- Minor leakage (light and slow, escaping repository);
- Major leakage (requires intervention to mitigate effects); or
- Catastrophic leakage (significant infrastructure damage or evacuation)

The amount of leakage can be considered as any of:

- Percentage of mass injection rate of CO_2
- Percentage of total injected CO_2 mass
- Total mass of leaked CO_2 per year

Q19-36
In each of the four chain components of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of

d) minor leakage; b) major leakage; and c) catastrophic leakage
(1 in X, where X≥1)
For example, a risk of one in a million would be written as 1 in 1,000,000 or 1 in 10^6

A. Capture			
Assessment criteria	Lower limit (5th percentile)	Central value (median)	Upper limit (95th percentile)
Minor emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products			
0-50 years	(1 in X)	(1 in X)	(1 in X)
Major emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products			
0-50 years	(1 in X)	(1 in X)	(1 in X)
Catastrophic emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products			
0-50 years	(1 in X)	(1 in X)	(1 in X)

B. Transport			
Assessment criteria	Lower limit (5th percentile)	Central value (median)	Upper limit (95th percentile)
Minor CO_2 stream leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
Major CO_2 stream leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
Catastrophic CO_2 stream leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)

C. Injection			
Assessment criteria	Lower limit (5th percentile)	Central value (median)	Upper limit (95th percentile)
Minor CO_2 leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
Major CO_2 leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
Catastrophic CO_2 leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)

D. Storage			
Assessment criteria	Lower limit (5th percentile)	Central value (median)	Upper limit (95th percentile)
Minor CO_2 leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
51-499 years	(1 in X)	(1 in X)	(1 in X)
500+ years	(1 in X)	(1 in X)	(1 in X)
Major CO_2 leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
51-499 years	(1 in X)	(1 in X)	(1 in X)
500+ years	(1 in X)	(1 in X)	(1 in X)
Catastrophic CO_2 leakage			
0-50 years	(1 in X)	(1 in X)	(1 in X)
51-499 years	(1 in X)	(1 in X)	(1 in X)
500+ years	(1 in X)	(1 in X)	(1 in X)

37. From an engineering design perspective for CO_2 storage, what is the upper limit on the likelihood of minor (light and slow) CO_2 leakage
(1 in X, where X≥1)?

Lower limit _______ (%) (5th percentile)
Central value _______ (%) (median)
Upper limit _______ (%) (95th percentile)

38. From an engineering design perspective for CO_2 storage, what is the upper limit on the likelihood of a major CO_2 leakage (1 in X, where X≥1)?

Lower limit _______ (%) (5th percentile)
Central value _______ (%) (median)
Upper limit _______ (%) (95th percentile)

39. From an engineering design perspective for CO_2 storage, what is the upper limit on the likelihood of a catastrophic CO_2 leakage (1 in X, where X≥1)

Lower limit _______ (%) (5th percentile)
Central value _______ (%) (median)
Upper limit _______ (%) (95th percentile)

Q40-42 In a typical saline aquifer site, what is the likelihood of major CO_2 leakage that would result in significant effects on the local environment or human health in each of the time periods in the table below (1 in X, where X≥1)?

Time period (years)	Lower limit (5th percentile)	Central value (median)	Upper limit (95th percentile)
0-50	(1 in X)	(1 in X)	(1 in X)
51-499	(1 in X)	(1 in X)	(1 in X)
500+ years	(1 in X)	(1 in X)	(1 in X)

Preamble for questions 43,44, and 45:
Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO_2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).

How long will a typical saline aquifer storage site remain safe at the following confidence levels?

43. What is your judgement of the statistical 'low-end' safe storage lifetime – i.e. you think this duration will be exceeded in at least 95 facilities out of 100 (i.e. no more than five will fail in the same period)? Please give three duration values to express your uncertainty

Lower limit _______ (yrs) (5th percentile)
Central value _______ (yrs) (median)
Upper limit _______ (yrs) (95th percentile)

44. What is your judgement of the statistical median safe storage lifetime – i.e. you think it will be exceeded in at least 50 facilities out of 100? Please give three durations to express your uncertainty.

Lower limit _______ (yrs) (5th percentile)
Central value _______ (yrs) (median)
Upper limit _______ (yrs) (95th percentile)

45. What is your judgement of the statistical 'high-end' safe storage lifetime – i.e. you think it will be exceeded in only 5 facilities or fewer, out of 100? Please give three durations to express your uncertainty.

Lower limit _______ (yrs) (5th percentile)
Central value _______ (yrs) (median)
Upper limit _______ (yrs) (95th percentile)

46. In a typical large scale integrated *saline aquifer storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit _______ (%) (5th percentile)
Central value _______ (%) (median)
Upper limit _______ (%) (95th percentile)

47. In a typical large scale integrated *enhanced oil recovery storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit _______ (%)	Central value _______ (%)	Upper limit _______ (%)
(5th percentile)	(median)	(95th percentile)

48. What is the worldwide capacity for geological CO_2 sequestration in saline aquifers ($GtCO_2$)?

Lower limit ______ ($GtCO_2$)	Central value _____ ($GtCO_2$)	Upper limit _______ ($GtCO_2$)
(5th percentile)	(median)	(95th percentile)

49. What is the ultimate CO_2 sequestration capacity in solution as a percent (%) of a deep saline aquifer?

Lower limit ______ (%)	Central value _______ (%)	Upper limit _______ (%)
(5th percentile)	(median)	(95th percentile)

50. What percentage of a theoretical repository capacity for a reasonable quality saline aquifer would you generally expect could be accessed by carbon dioxide placement using horizontal wells (%)?

Lower limit ______ (%)	Central value _______ (%)	Upper limit _______ (%)
(5th percentile)	(median)	(95th percentile)

51. In a CO_2 injection scheme in deep saline aquifer (~1 $MtCO_2$/year), what is the modal distance from the injection well that is likely to be affected by salt precipitation (metres)?

Lower limit ______ (m)	Central value _______ (m)	Upper limit _______ (m)
(5th percentile)	(median)	(95th percentile)

52. What is the maximum magnitude of an earthquake that could be caused by increased pore pressure from CO_2 injection (induced seismicity caused by fluid injection itself) (Richter magnitude M)?

Lower limit ______ (M)	Central value _______ (M)	Upper limit _______ (M)
(5th percentile)	(median)	(95th percentile)

53. What is the maximum magnitude of an earthquake that could be caused by increased pore pressure, whereby small stress changes precipitate failure on pre-existing, stressed faults, even at significant distances (Richter magnitude M)?

Lower limit ______ (M)	Central value _______ (M)	Upper limit _______ (M)
(5th percentile)	(median)	(95th percentile)

<u>Part 3 – Target Questions</u>

Instructions for completing Target Question 1 (Likelihood) and 2 (Severity) of risks associated only with injection and storage phases of CCS.

Format Question 1:

Please rate the likelihood of each of the risks associated with injection and storage phases of CCS using the following 5-point Likert scale:

Likelihood		**If there were 100 similar projects, frequency of this risk element would occur . . .**
Improbable	1	Probably not at all, never
Unlikely	2	Fewer than three times among the 100 projects
Possible	3	5–10 times among the 100 projects
Likely	4	In around half of the 100 projects
Probable	5	In most or nearly all of the projects

Please put “x” on the five-level rating scale to show your opinion of the risk.

Rating Risk	Improbable	Unlikely	Possible	Likely	Probable
	1	2	3	4	5
Type 1		x			
Type 2	x				
Type 3				x	

Format Question 2:

Please rate the severity of each of the risks to health and environment associated with injection and storage phases of CCS using the following 5-point Likert scale:

Severity of impacts		**Change in state**
Light	1	No modification to initial state
Serious	2	Modification to initial state within acceptable limits
Major	3	Modification to initial state above acceptable limits but without damage
Catastrophic	4	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	5	Considerable modifications to initial state which is not repairable with existing technologies

Please put “x” on the five-level rating scale to show your opinion of the risk

Rating Risk	Light	Serious	Major	Catastrophic	Multi-catastrophic
	1	2	3	4	5
Type 1	x				
Type 2				x	
Type 3		x			

Start

Please rate the likelihood of each of the risks associated with injection (50 years) and storage (indefinite) phases of CCS listed below using the following 5-point Likert scale:

Likelihood		**If there were 100 similar projects, frequency of this risk element would occur . . .**
Improbable	1	Probably not at all, never
Unlikely	2	Fewer than three times among the 100 projects
Possible	3	5–10 times among the 100 projects
Likely	4	In around half of the 100 projects
Probable	5	In most or nearly all of the projects

Please put “x” on the five-level rating scale to show your opinion of the risk

A. Injection					
Likelihood Risk	Improbable	Unlikely	Possible	Likely	Probable
	1	2	3	4	5
Leakage from Wells					
CCS Injection wells					
CCS Monitoring wells					
Known oil and gas operating wells					
Legacy wells - suspended					
Legacy wells – abandoned					
Legacy wells - unknown and unlocatable					
Injection					
Poor injectivity					
Loss of wellbore integrity					
Development of vertical hydraulic fractures					
Breach of caprock (other than hydraulic fracturing)					
Breach of multiple barriers					

Likelihood		**If there were 100 similar projects, frequency of this risk element would occur . . .**
Improbable	1	Probably not at all, never
Unlikely	2	Fewer than three times among the 100 projects
Possible	3	5–10 times among the 100 projects
Likely	4	In around half of the 100 projects
Probable	5	In most or nearly all of the projects

B1. Storage - Intrinsic risks of leakage (existing pre-injection risks)					
Likelihood Risk	Improbable	Unlikely	Possible	Likely	Probable
	1	2	3	4	5
Unexpected insufficient storage capacity					
Unexpected non-sealing faults					
Unexpected pressures, stresses or temperatures					
Reactions with ductile shale caprock					
Deterioration and breaching of capillary seals					
Dissolution of carbonate minerals by acidified water					
Unexpected intensely fractured zones in the seal					
Lack of integrity in the seal system due to unexpected geology					

Likelihood		**If there were 100 similar projects, frequency of this risk element would occur . . .**
Improbable	1	Probably not at all, never
Unlikely	2	Fewer than three times among the 100 projects
Possible	3	5–10 times among the 100 projects
Likely	4	In around half of the 100 projects
Probable	5	In most or nearly all of the projects

B2. Storage - Induced risks of leakage
(during and after-injection)

Likelihood	Improbable	Unlikely	Possible	Likely	Probable
Risk	1	2	3	4	5
Tensile well shearing					
Vertical fracturing of caprock					
Thermal fracturing of caprock					
Re-opening of existing fractures					
Creation of a new fault					
Reactivation of existing fault					
Induced seismic activity M > 4					
Reduced injectivity due to plume-oil interaction					
Reduced injectivity due to salt precipitation					
Pressure induced surface uplift					

Severity
Please rate the severity of impacts on health and environment from each of the risks associated with injection (50 years) and storage (indefinite) phases of CCS using the following 5-point Likert scale:

Severity of impacts		**Change in state**
Light	1	No modification to initial state
Serious	2	Modification to initial state within acceptable limits
Major	3	Modification to initial state above acceptable limits but without damage
Catastrophic	4	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	5	Considerable modifications to initial state which is not repairable with existing technologies

Please put "x" on the five-level rating scale to show your opinion of the risk

A. Injection					
Severity of impacts Risk	Light	Serious	Major	Catastrophic	Multi-catastrophic
	1	2	3	4	5
Leakage from Wells					
CCS Injection wells					
CCS Monitoring wells					
Known oil and gas operating wells					
Legacy wells - suspended					
Legacy wells – abandoned					
Legacy wells - unknown and unlocatable					
Injection					
Poor injectivity					
Loss of wellbore integrity					
Development of vertical hydraulic fractures					
Breach of caprock (other than hydraulic fracturing)					
Breach of multiple barriers					

Severity of impacts		**Change in state**
Light	1	No modification to initial state
Serious	2	Modification to initial state within acceptable limits
Major	3	Modification to initial state above acceptable limits but without damage
Catastrophic	4	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	5	Considerable modifications to initial state which is not repairable with existing technologies

B1. Storage - Intrinsic risks of leakage (existing pre-injection risks)					
Severity of impacts / Risk	Light	Serious	Major	Catastrophic	Multi-catastrophic
	1	2	3	4	5
Unexpected insufficient storage capacity					
Unexpected non-sealing faults					
Unexpected pressures, stresses or temperatures					
Reactions with ductile shale caprock					
Deterioration and breaching of capillary seals					
Dissolution of carbonate minerals by acidified water					
Unexpected intensely fractured zones in the seal					
Lack of integrity in the seal system due to unexpected geology					

Severity of impacts		**Change in state**
Light	1	No modification to initial state
Serious	2	Modification to initial state within acceptable limits
Major	3	Modification to initial state above acceptable limits but without damage
Catastrophic	4	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	5	Considerable modifications to initial state which is not repairable with existing technologies

<table>
<tr><th colspan="6">B2. Storage - Induced risks of leakage (during and after-injection)</th></tr>
<tr><td rowspan="2">Severity of impacts
Risk</td><td>Light</td><td>Serious</td><td>Major</td><td>Catastrophic</td><td>Multi-catastrophic</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>Tensile well shearing</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Vertical fracturing of caprock</td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>Pressure induced surface uplift</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Part 4: Risk Management

49. This question is focused on risk management of high impact low probability (HILP) (catastrophic) events. For questions related to leakage, please note that the nature of the leaked substance (eg CO_2, brine, or another contaminant) is not the focus of the question; rather, the question focuses on a leakage of any kind.

Please rate the effectiveness of each of the following methods to manage risk of high impact low probability (HILP) (catastrophic) events using the following 5-point Likert scale:

Not at all effective	1
Minimally effective	2
Moderately effective	3
Very effective	4
Extremely effective	5

CCS Risk Management						
RM Measure / HILP Event	Site Selection	Well Integrity Studies	Emergency Response Plan	Monitoring	Automatic Emergency Shut Down System	Training (operating procedures)
Catastrophic injection wellhead failure						
Caprock fracture						
Induced seismic event >M4						
Large migration out of pore space						
Massive release of CO2 resulting in human fatalities						

54. What should be the storage project monitoring period (years)?

Lower limit ________ (years) (5th percentile)	Central value ________ (years) (median)	Upper limit _______ (years) (95th percentile)

55. Considering potential negative impacts of CCS on either the environment or human health, what proportion of risk management should be focused on mitigating environmental impacts as opposed to human health impacts (0-100%)?

Lower limit _______ (%) (5th percentile)	Central value _______ (%) (median)	Upper limit _______ (%) (95th percentile)

56. On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)?

Lower limit _______ (%)	Central value _______ (%)	Upper limit _______ (%)
(5th percentile)	(median)	(95th percentile)

57. Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?

Lower limit _______ (%)	Central value _______ (%)	Upper limit _______ (%)
(5th percentile)	(median)	(95th percentile)

End

Candidate Re-Elicitation Questions with Rationale

The purpose of the elicitation is to inform the development of an integrated risk management framework for CCS. *Findings and insights will not be used for a specific project risk assessment, but will assist in understanding relative risk and could assist in stimulating further scientific deliberations towards achieving objective judgements on CCS risk issues.*

Definitions and contextual understandings for some questions were refined during the elicitation event. For other questions, preliminary findings combined with expert comments suggest further clarification would benefit the process and the outcomes. These questions are provided here, with a rationale for re-elicitation, revised wording, and response tables, for your consideration.
Classical Model Quantitative Questions

1. T28-T36 - These nine sets of uncertainty distributions concern likelihoods of minor, major or catastrophic leakage during storage over three timeframes: 0-50 yrs; 51-499 yrs; 500+ yrs.

    In terms of the likelihood uncertainty distributions there are suggestions that ‘two schools of thought’ exist – represented by a division between those who suggest higher and those who suggest lower likelihoods - especially for the short-term outlook, 0 – 50 yrs for original Questions T28, T31, and T34 (Draft Report, begin pg. 23).

The results also suggest increased likelihood of minor leakage with longer storage timeframes; and increased likelihood of major and catastrophic leakage with longer storage time frames but only at the lower limit (5th percentile) (Draft Report, pg. 60-62). If this is contrary to what was expected, then these questions might be candidates for re-elicitation.

Recall the understandings

- ‘Storage’ includes the integrity of the geologic repository away from the wellbore
- Definitions of minor, major and catastrophic leakage:
    - Minor leakage (light and slow, escaping repository);
    - Major leakage (requires intervention to mitigate effects);
    - Catastrophic leakage (significant infrastructure damage or evacuation)
- The amount of leakage can be considered as any of:
    - Percentage of mass injection rate of CO_2
    - Percentage of total injected CO_2 mass
    - Total mass of leaked CO_2 per year

With this common understanding, it may be worth re-eliciting these questions:

T28-30Rev: In the first 50 years of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage b) Major leakage c) Catastrophic leakage

T31-33Rev: From year 51-499 of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage b) Major leakage c) Catastrophic leakage

T34-36Rev: From year 500 onwards of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage b) Major leakage c) Catastrophic leakage

D. Storage Leakage Likelihood			
	Lower limit (5th percentile)	Central value (median)	Upper limit (95th percentile)
0-50 years			
[28R] Minor	(1 in X)	(1 in X)	(1 in X)
[29R] Major	(1 in X)	(1 in X)	(1 in X)
[30R] Catastrophic	(1 in X)	(1 in X)	(1 in X)
51-499 years			
[31R] Minor	(1 in X)	(1 in X)	(1 in X)
[32R] Major	(1 in X)	(1 in X)	(1 in X)
[33R] Catastrophic	(1 in X)	(1 in X)	(1 in X)
Over 500 years			
[34R] Minor	(1 in X)	(1 in X)	(1 in X)
[35R] Major	(1 in X)	(1 in X)	(1 in X)
[36R] Catastrophic	(1 in X)	(1 in X)	(1 in X)

2. <u>T37-T39-</u> From an engineering design perspective for CO_2 storage, this triplet of questions concerns the upper limit on the likelihood of minor, major, and catastrophic leakage.

From experts' comments, it appears that 'an upper limit likelihood from an engineering perspective' is not a well-defined or universally recognized concept.

Recall the understandings

- 'Storage' includes the integrity of the geologic repository away from the wellbore
  - Minor leakage (light and slow, escaping repository);
  - Major leakage (requires intervention to mitigate effects);
  - Catastrophic leakage (significant infrastructure damage or evacuation)

With this common understanding and revised wording, it may be worth re-eliciting these questions:

Preamble:

Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).

T37-39Rev. What should be the regulated threshold for the likelihood of minor, major or catastrophic storage leakage in a LSIP sequestration project (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

d) Minor leakage *b) Major leakage* *c) Catastrophic leakage*

Leakage	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[37R] Minor	(1 in X)	(1 in X)	(1 in X)
[38R] Major	(1 in X)	(1 in X)	(1 in X)
[39R] Catastrophic	(1 in X)	(1 in X)	(1 in X)

3. <u>T40-T42 -</u> This triplet of questions concerns the likelihood of major CO_2 leakage in a typical saline aquifer that would result in significant effects on the local environment or human health, in each of three time periods: 0-50 yrs; 51-499 yrs; and over 500 yrs.

> A clear pattern of Experts' views divided into higher- and lower likelihoods, especially for the two shorter timeframes, 0-50 yrs & 51-499 yrs (T40, T41, Draft Report, pg. 36-37).

The results also suggest increased likelihood of major leakage causing significant effects with longer timeframes at lower limit (5th percentile) (Draft Report, pg. 64). If this is contrary to what was expected, then these questions might be candidates for re-elicitations.

> Expert discussion depicted this question as ambiguous thereby resulting in differences of interpretation.
>
> Recall the definition and understandings:
> - Major leakage (requires intervention to mitigate effects)
> - Measurable - detectable

With this common understanding of the definition and revised wording, it may be worth re-eliciting these questions:

T40-42Rev: In a typical saline aquifer storage site, what is the likelihood of major CO_2 leakage that would result in measurable negative environmental impact or adverse public health impact in each of the time periods (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) 0-50 years b) 51-499 years c) 500+ years

Time period (years)	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[40R] 0-50 yrs	(1 in X)	(1 in X)	(1 in X)
[41R] 51-499 yrs	(1 in X)	(1 in X)	(1 in X)
[42R] 500+ yrs	(1 in X)	(1 in X)	(1 in X)

4. T43-T45 - This triplet of questions considers how long a typical saline aquifer storage site would remain safe at ‘low-end’, ‘median’ and ‘high-end’ safe storage periods.

Example T43: What is your judgement of the statistical ‘low-end’ safe storage lifetime – i.e. you think this duration will be exceeded in at least 95 facilities out of 100 (i.e. no more than five will fail in the same period)? Please give three duration values to express your uncertainty

The Classical Model outcomes for the responses are notable for the markedly different central tendencies (median) of the Equal weights and the Performance weights solutions. The median Equal weight value reflected individual views of a significant majority of the experts in all 3 questions. Expected (mean) safe lifetimes were more similar between Equal weights and Performance weights solutions in T44, T45.

Expert discussion indicated that this type of question could use further clarification.

It may be worth re-eliciting these revised questions:

Preamble:

Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).

Assuming no fundamental change in technology, what is the safe storage lifetime of a typical saline aquifer storage site at the following confidence levels? Please give three durations to express your uncertainty.

T43Rev: How long will a typical saline aquifer storage site remain safe, where safe means 95% or more facilities will not fail in the time periods you specify (years)?

T44Rev: How long will a typical saline aquifer storage site remain safe, where safe means 50% or more facilities will not fail in the time periods you specify (years)?

T45Rev: How long will a typical saline aquifer storage site remain safe, where safe means 5% or fewer facilities will not fail in the time periods you specify (years)?

Facilities that will not fail	Safe Storage Lifetime		
	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[43R] 95% or more facilities	(yrs)	(yrs)	(yrs)
[44R] 50% or more facilities	(yrs)	(yrs)	(yrs)
[45R] 5% or fewer facilities	(yrs)	(yrs)	(yrs)

Likelihood and Severity of Potential Hazards

Verbal clarification during the elicitation arrived at the following understanding for the Likert-scale severity rating of potential hazards:

Should a (geotechnical) hazard exist, please rate the severity of the circumstance using the following 5-point Likert scale:

Severity	**Level**	**Change in state**
Light	1	No modification to initial state
Serious	2	Modification to initial state within acceptable limits
Major	3	Modification to initial state above acceptable limits but without damage
Catastrophic	4	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	5	Considerable modifications to initial state which is not repairable with existing technologies

The research team would appreciate experts completing a supplementary question for each hazard group (well leakage; injection; intrinsic storage; induced storage) using the Classical Model question format. [This question had been intended to be included in the original elicitation, but was incorrectly formulated.]

Recall the understanding

- Measurable - detectable

Recall examples of hazards (from initial Likert scale questions on hazard likelihood and severity):

- Well leakage hazard in a variety of type of wells - CCS Injection wells, CCS Monitoring wells, Known oil and gas operating wells, Legacy wells - suspended, Legacy wells – abandoned, Legacy wells - unknown and unlocatable
- Injection hazards - Poor injectivity, Loss of wellbore integrity, Development of vertical hydraulic fractures, Breach of caprock (other than hydraulic fracturing), Breach of multiple barriers
- Intrinsic storage hazards - Unexpected insufficient storage capacity, Unexpected non-sealing faults, Unexpected pressures, stresses or temperatures, Reactions with ductile shale caprock, Deterioration and breaching of capillary seals, Dissolution of carbonate minerals by acidified water, Unexpected intensely fractured zones in the seal, Lack of integrity in the seal system due to unexpected geology
- Induced storage hazards - Well shearing, Vertical fracturing of caprock, Thermal fracturing of caprock, Re-opening of existing fractures, Creation of a new fault, Reactivation of existing fault, Induced seismic activity M > 4, Reduced injectivity due to plume-oil interaction, Reduced injectivity due to salt precipitation, Pressure induced surface uplift

T59-78New - Preamble

The change in state associated with 5 levels of geotechnical hazard severity:

Hazard Severity	**Change in state**
Light	No modification to initial state
Serious	Modification to initial state within acceptable limits
Major	Modification to initial state above acceptable limits but without damage
Catastrophic	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	Considerable modifications to initial state which is not repairable with existing technologies

In answering the following questions, please consider the occurrence of any type of geotechnical hazard that could result in the described 'change in state'.

T59-63: At each of the following levels of severity, what is the likelihood that geotechnical well leakage hazards could have a measurable negative environmental impact or adverse public health impact (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

Severity of well leakage hazard	Likelihood of measurable negative effect on environment or human health		
	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[59] Light	(1 in X)	(1 in X)	(1 in X)
[60] Serious	(1 in X)	(1 in X)	(1 in X)
[61] Major	(1 in X)	(1 in X)	(1 in X)
[62] Catastrophic	(1 in X)	(1 in X)	(1 in X)
[63] Multi-catastrophic	(1 in X)	(1 in X)	(1 in X)

T64-68: At each of the following levels of severity, what is the likelihood that geotechnical injection hazards could have a measurable negative environmental impact or adverse public human health impact (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

Severity of injection hazard	Likelihood of measurable negative effect on environment or human health		
	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[64] Light	(1 in X)	(1 in X)	(1 in X)
[65] Serious	(1 in X)	(1 in X)	(1 in X)
[66] Major	(1 in X)	(1 in X)	(1 in X)
[67] Catastrophic	(1 in X)	(1 in X)	(1 in X)
[68] Multi-catastrophic	(1 in X)	(1 in X)	(1 in X)

The change in state associated with 5 levels of geotechnical hazard severity:

Hazard Severity	**Change in state**
Light	No modification to initial state
Serious	Modification to initial state within acceptable limits
Major	Modification to initial state above acceptable limits but without damage
Catastrophic	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	Considerable modifications to initial state which is not repairable with existing technologies

T69-73: At each of the following levels of severity, what is the likelihood that intrinsic geotechnical storage hazards could have a measurable negative environmental impact or adverse public health impact (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

Severity of intrinsic storage hazard	Likelihood of measurable negative effect on environment or human health		
	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[69] Light	(1 in X)	(1 in X)	(1 in X)
[70] Serious	(1 in X)	(1 in X)	(1 in X)
[71] Major	(1 in X)	(1 in X)	(1 in X)
[72] Catastrophic	(1 in X)	(1 in X)	(1 in X)
[73] Multi-catastrophic	(1 in X)	(1 in X)	(1 in X)

T74-78: At each of the following levels of severity, what is the likelihood that induced geotechnical storage hazards could have a measurable negative environmental impact or adverse public health impact (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

Severity of induced storage hazard	Likelihood of measurable negative effect		
	Lower limit (5th percentile)	Central Value (median)	Upper limit (95th percentile)
[74] Light	(1 in X)	(1 in X)	(1 in X)
[75] Serious	(1 in X)	(1 in X)	(1 in X)
[76] Major	(1 in X)	(1 in X)	(1 in X)
[77] Catastrophic	(1 in X)	(1 in X)	(1 in X)
[78] Multi-catastrophic	(1 in X)	(1 in X)	(1 in X)

Thank you very much for your time in responding to these re-elicitation questions.

Appendix B: Supplementary Material - Chapter 2

Risk Assessment (RA) and Risk Management (RM) requirements in CCS legislation, regulation, or guidance

Legislation, Regulation or Guidance	**No elaboration**		**Elaboration**		**CCS Chain**
	RA	**RM**	**RA**	**RM**	
International					
2006 – IMO - London Convention/London Protocol Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures (RAMF)			V[11] RM - Monitoring		Injection Storage
2007 – London Protocol Guidelines on Assessment of CO_2 Streams for Disposal into a Sub-Seabed Geological Formations			V RM - Monitoring		Injection
2007 OSPAR Convention Guidelines for Risk Assessment and Management			M[1] RM – Mitigation and Monitoring		Injection Storage Post - Injection
2009 EU CCS Directive – projects >100 kilotonnes CO2			M	M Monitoring	Storage
2011 EU CCS Directive – Guidance Documents CO2 Storage Lifecycle RM Framework				V Emphasis on description of RM	Storage
Characterisation of the Storage Complex, CO2 Stream Composition, Monitoring and Corrective Measures			V Storage, Composition	V Monitoring, Mitigation	Capture Storage
Criteria for Transfer of Responsibility to the Competent Authority; Refers to monitoring results	V - how risks evolved				

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[11] V – Voluntary activity; M – Mandatory activity

EU Directive - Integrated Pollution Prevention and Control			M Stream Composition, Stakeholders		Capture Stream
EU Directive – Environmental Assessment Includes effects on human beings	M				Capture Transport
2011 UNFCCC CDM Modalities and Procedures Links to environmental assessment and socio-economic impact assessment			M RA – includes 1 RM type activity: contingency planning RM – Monitoring		Capture Transport Storage
National					
Australia Commonwealth Offshore Petroleum and Greenhouse Gas Storage Act			M Indirect relevance to health		Capture Injection Storage
Greenhouse Gas Injection and Storage Regulations 2011 Mainly operations risks; Reportable incidents includes leakage	M	M Reportable Incidents			
Safety Regulations 2009 – Safety Case			M	M Emergency preparedness	
Environment Regulations 2009 – only environmental effects			M Environment Plan	M Implementation Strategy	
Resource Management and Administration Regulations 2011 Where there is identified new or a significant increase in existing well integrity hazards or risks for the well, during operation	M Site Plan	M Monitoring			Transport Injection
Offshore Miscellaneous Measures Act – Structural integrity of facilities (including pipelines), wells and well-related equipment		M			Capture Storage
2014 NOPSEMA Guidance note, Environment plan content requirements	V Environmental Assessment	V Monitoring			

US EPA Underground Injection Control Class VI Program for Carbon Dioxide Geologic Sequestration Wells (silent)					Injection
Guidance - Well Site Characterization	V - Limited Characterization				
Guidance – Area of Review Evaluation and Corrective Action			V – Limited Abandoned wells	V – Limited Plugging, Re-evaluation	
Guidance – Project Plan Development		V Monitoring			
Guidance – Testing and Monitoring				V – Detailed Testing, Monitoring	
Guidance – Well Construction (silent)					
Sub-national - Provinces and States					
Canada - [12]Alberta Mines and Minerals Act Carbon Sequestration Tenure Regulation		M MMV			Storage
EPEA – Environmental and social impact assessment	Discretionary inclusions	M			Capture Transport
AER Directives 056, 065	M (065) Selected critical parameters[2]	M Emerg Response Plan			Injection Storage
United States - examples Kansas – Carbon Dioxide Reduction Act Permanent Administrative Regulations Refers to threat to public health and safety or to usable water			M Characterization	M Monitoring and Safety Plan	Injection Storage Closure
Mississippi - Geologic Sequestration of Carbon Dioxide Act	M				Storage
North Dakota Geologic Storage of Carbon Dioxide Refers to endangerment of human health and environment		M Monitoring			Storage

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[12] For further analysis, see Golder Associates (2012), *Review of Carbon Capture and Storage Environmental Assessment and Project Approval Requirements in Ex-Alberta Jurisdictions*

Australia - examples Victoria - Greenhouse Gas Geological Sequestration Act and Regulations			M Injection Testing Plan Environment Management Plan RA – Limited elaboration RM - Monitoring	Injection
Queensland - Greenhouse Gas Storage Act and Regulations	M Injection test plans	M Mitigation Monitoring		Injection Storage Closure
South Australia - Petroleum and Geothermal Energy Act and Regulations	M EIA[13], Fitness for Purpose Reporting			Capture Transport Storage

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[13] EIA – Environmental Impact Assessment

Appendix C: Supplementary Material - Chapter 4

Elicitation Experts, Affiliations, Expertise

Australia

- Lincoln Paterson, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia – rock mechanics, deep basin disposal of carbon dioxide, physical processes in rock behavior, thermal effects

Canada

- Stefan Bachu, Alberta Innovates, Technology Futures - fluid flow, sequestration in saline aquifers, well integrity
- Rick Chalaturnyk, University of Alberta - geomechanics, caprock integrity, monitoring, well integrity
- William Gunter, Distinguished Scientist (retired), Alberta Innovates, Technology Futures - geochemistry, fluid-rock reactions
- Richard Jackson, Adjunct Faculty, University of Waterloo – characterization, migration, and fate of non-aqueous phase liquids in subsurface
- Don Lawton, University of Calgary - geophysics, seismology, monitoring
- David Ryan, Natural Resources Canada – Geochemistry of CO2 and impurities in saline reservoirs, wellbore and caprock integrity, monitoring, measurement, and verification technologies

Europe

- Jean-Pierre Deflandre, IFP Energies nouvelles, France – EOR, rock mechanics, hydraulic fracture mapping, monitoring (passive seismic data acquisition, interpretation), gas storage geomechanical survey
- Ton Wildenborg, Netherlands Organisation for Applied Scientific Research (TNO) – sedimentology, basin analysis and exploration geophysics; risk assessment of CO2 storage and radioactive waste disposal in the deep subsurface

Saudi Arabia

- J. Carlos Santamarina, King Abdullah University of Science and Technology, Saudi Arabia – geotechnical engineering, subsurface processes, sequestration in saline aquifers

USA

- Michael Celia, Princeton University - groundwater hydrology, multi-phase flow in porous media, numerical modeling, and subsurface energy systems
- Curtis Oldenburg, Lawrence Berkeley National Laboratory - near-surface leakage and seepage processes, monitoring, detection, and impacts including risk-based frameworks for site selection and certification

Uncertainty in Risk Issues for Carbon Capture and Geological Storage: Findings from a structured expert elicitation

Supplementary Material

Patricia Larkin[1], Robert Gracie[2], Maurice Dusseault[2], Ali Shafiei[2],
Mirhamed (Araz) Sarkarfarshi[2], Willy Aspinall[3], Daniel Krewski[1]

Contents

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Section 1
Experts' paired comparison selections

Notes:
In the tabulated results, 'Coeff of Agreement' measures how closely the patterns of individual experts' pairwise preferences are alike, while 'Coeff of Concordance' indicates how similar the corresponding rank orders are among the group.

'Random preferences p-value' is a test statistic for the strength of evidence that the hypothesis that the group's pairwise preferences are made at random can or cannot be rejected.

In the plots below, ellipses depict 95% confidence areas for factor ranking scores from probabilistic inversion of experts' collective pairwise choices. For cases with alternative scenarios or options, horizontally extended ellipses indicate greater variance in ranking scores for the option on the x-axis option, relative to rankings for the y-axis option; vertically extended ellipses indicate greater variance vice versa.

When only a single scenario or option is considered and plotted, the vertical ellipse size indicates the 95% confidence interval for the factor ranking scores; the horizontal size is held constant for all factors for plotting.

Q1 – Q3 Risks related to activities

In order to rank the relative risk of four chain activities of integrated carbon capture and storage projects (capture, transport, injection, and storage), we need you to indicate which you consider to present the greater risk. Technical (Q1), environmental (Q2), and health risks (Q3) are considered separately.

Rank scores and their variances from group probabilistic inversion:

	Technical risk		**Environ. risk**		**Health risk**	
Activity	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**
Capture	0.57	0.29	0.50	0.30	0.64	0.28
Transport	0.33	0.24	0.39	0.26	0.42	0.26
Injection	0.55	0.26	0.58	0.26	0.57	0.25
Storage	0.54	0.29	0.53	0.29	0.38	0.28
Stats						
Coeff agreement	0.08	low	0.02	very low	0.20	ok
Coeff concordance	0.20	ok	0.10	low	0.18	ok
Random preferences p-value	0.08*	marginal cannot reject	0.30*	cannot reject	0.0036	reject

Q4 Storage options long-term risks

In order to rank the overall relative risk of the three main types of storage options (saline aquifer; coal bed methane seams; enhanced oil recovery), we need you to indicate which you consider to present the greater risk over the long term (>100 years)?

	Long-term risks	
Option	**Score**	**St. dev.**
Saline aquifer	0.46	0.28
Coal bed methane seams	0.50	0.30
Enhanced oil recovery	0.55	0.28
Stats		
Coeff agreement	0.0	none
Coeff concordance	0.03	negligible
Random preferences p-value	0.49*	cannot reject

Q5 Relative health/environ risk causes for low-moderate populated area

In order to rank the relative risks of distinct causes of local health and environmental hazards in a low to moderately populated area, we need you to indicate which you consider to present the greater risk

	Health/environ risks	
Cause	**Score**	**St. dev.**
Brine/gas migration	0.59	0.28
Mag 5+ quake	0.51	0.27
Explosive CO_2 release	0.53	0.29
Hydrofrac caprock failure	0.37	0.27
Stats		
Coeff agreement	0.0	none
Coeff concordance	0.12	low
Random preferences p-value	0.61*	cannot reject

Q6 & 7 Minerals reactivities

In the tables for Questions 6 and 7, we need you to indicate the relative reactivity of five naturally occurring minerals with CO_2 in the pure supercritical state (Q6) and CO_2 in the dissolved state (Q7).

	Supercritical CO_2		CO2 saturated saline	
Mineral	**Score**	**St. dev.**	**Score**	**St. dev.**
Feldspar	0.40	0.25	0.51	0.26
Calcite	0.78	0.16	0.80	0.17
Anhydrite	0.64	0.20	0.61	0.20
Hydrated clays	0.48	0.21	0.40	0.19
Quartz	0.16	0.14	0.16	0.15
Stats				
Coeff agreement	0.79	very good	0.56	good
Coeff concordance	0.82	very good	0.69	very good
Random preferences p-value	0.0000	reject hypothesis	0.0000	reject hypothesis

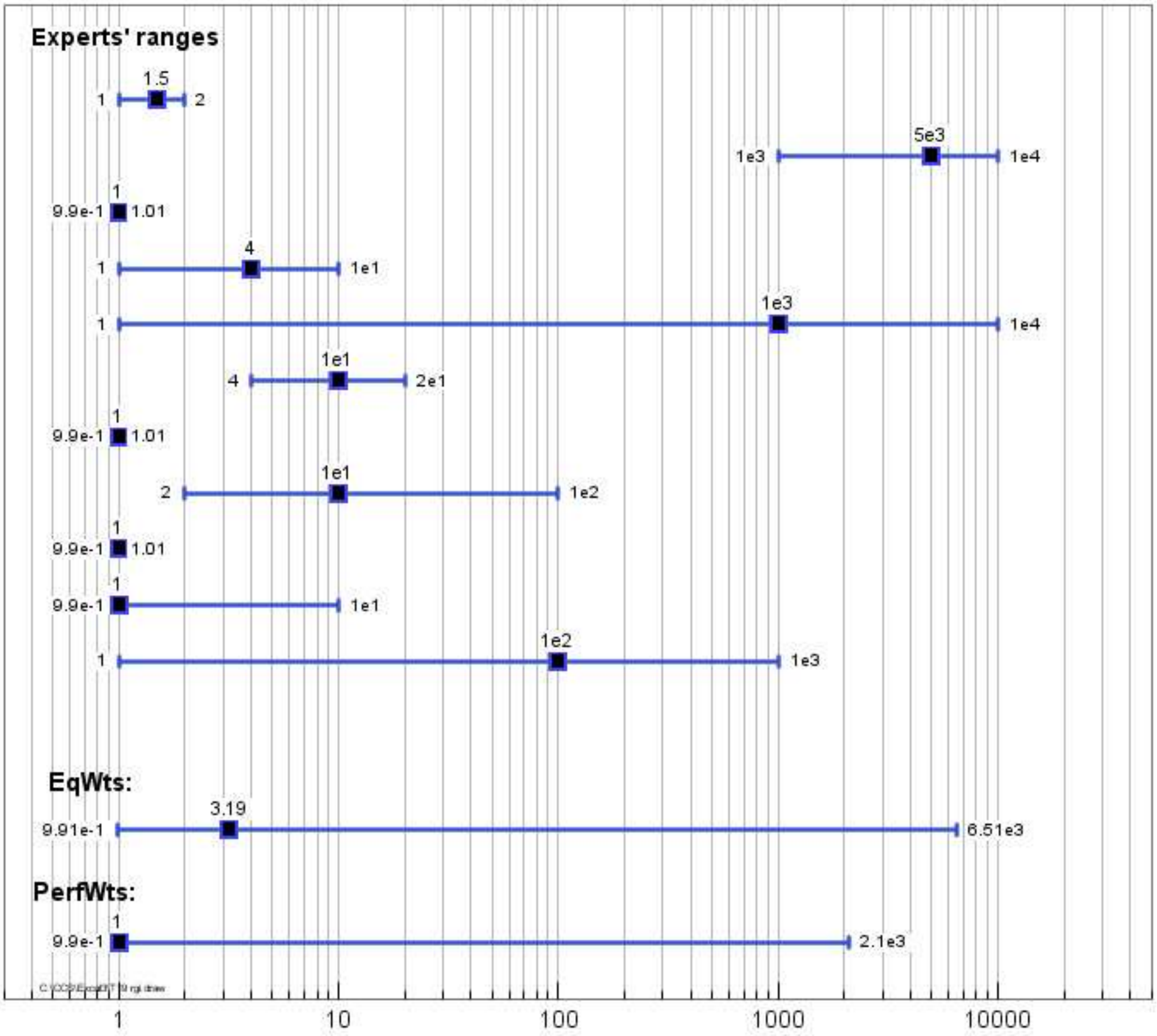
Section 2
Classical Model solutions for CCS Target Items

Experts' performance weight calibration resulted in a Decision Maker weight of 75% using the classical model method of Cooke (Cooke, 1991).

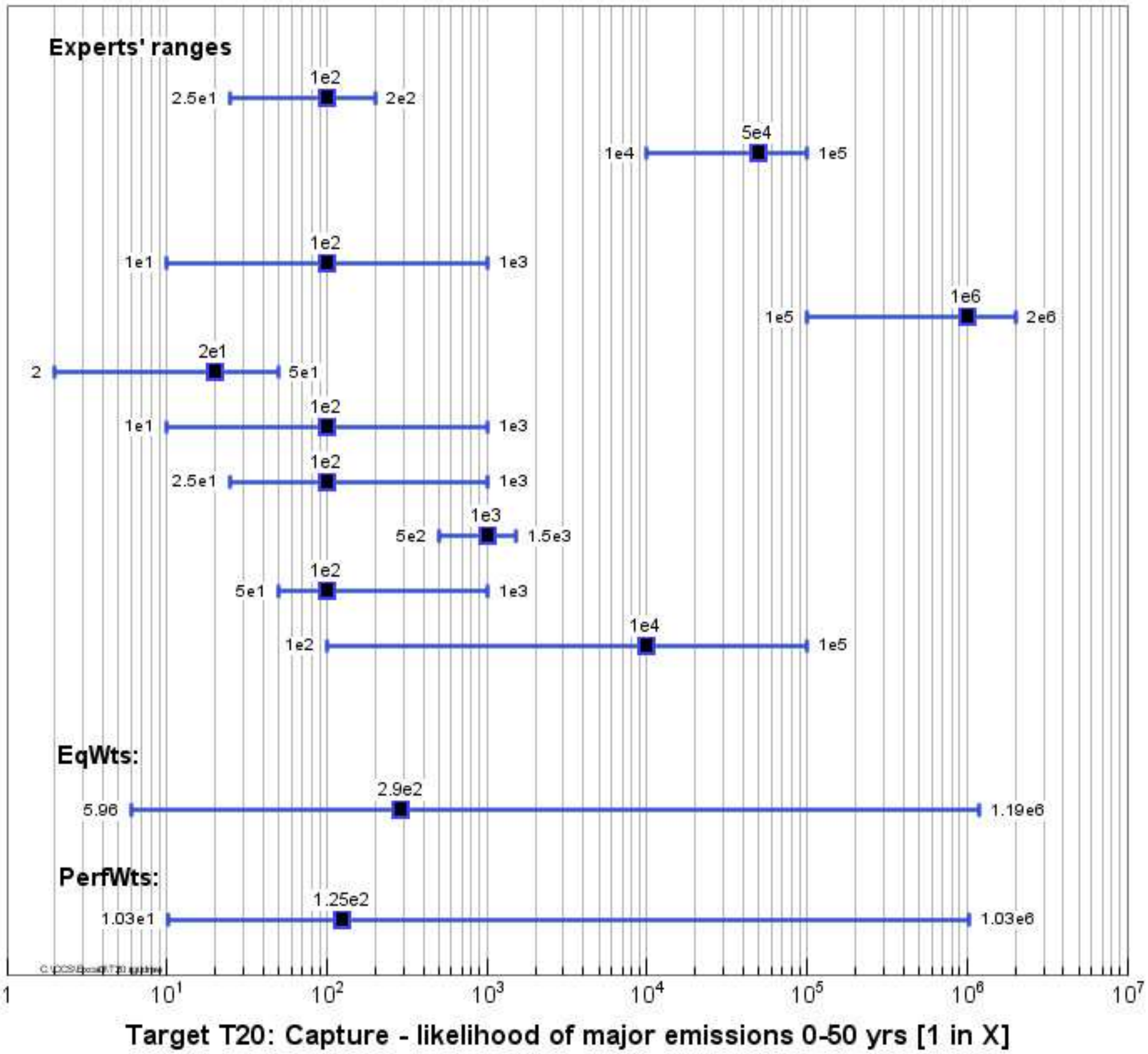
For several Target Items, Performance Weights (PW) solution quantiles are expressed as values of X, where X is a probability or likelihood defined in terms of "1-in-X"; corresponding Equal Weights EW solutions are given in brackets: e.g.: "(1 in X)". Graphs depict individual Expert and pooled uncertainty distribution ranges. Some values are shown in scientific exponent notation "x.xx***e***n" for display compactness.

Targets T19 – T21
In the Capture phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of
e) minor leakage; b) major leakage; and c) catastrophic leakage

Capture				
Assessment criteria	Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
Minor emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products				
[T19] 0-50 years	1 in 2100 (1 in 6500)	1 in 180 (1 in 480)	1 in 1 (1 in 3.2)	1 in 1 (1 in 1)
Major emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products				
[T20] 0-50 years	1 in 1.0×10^6 (1 in 1.2×10^6)	1 in 65600 (1 in 7.8×10^3)	1 in 125 (1 in 290)	1 in 10 (1 in 6)
Catastrophic emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products				
[T21] 0-50 years	1 in 1.5×10^7 (1 in 2.3×10^7)	1 in 95000 (1 in 1.4×10^6)	1 in 1100 (1 in 3200)	1 in 100 (1 in 16)



Target T19: Capture - likelihood of minor emissions 0-50 yrs [1 in X]


Experts' ranges
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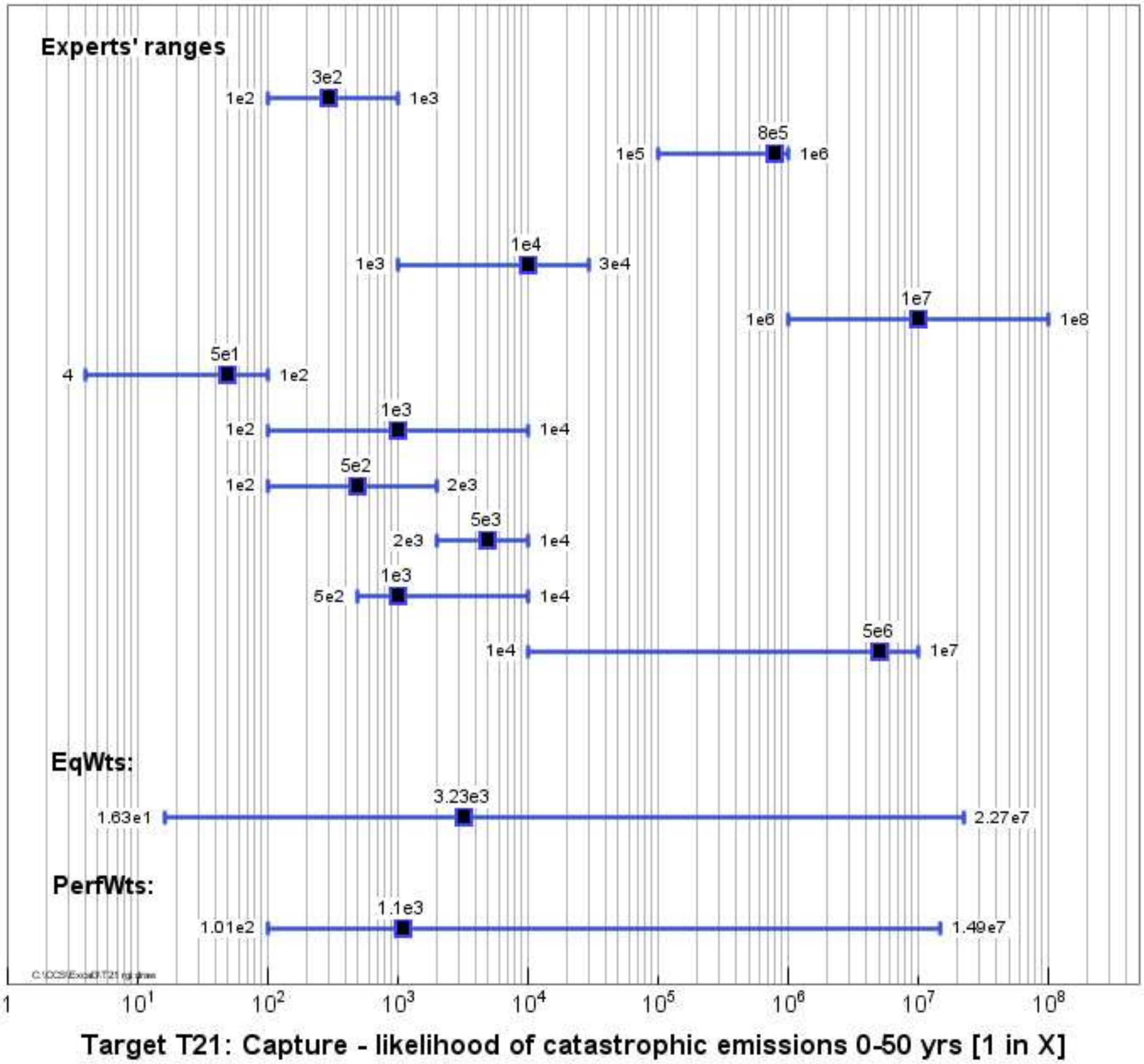
2e2
1e4
5e4
1e5
1e1
1e2
1e3
1e5
1e6
2e6
2
2e1
5e1
1e1
1e2
1e3
2.5e1
1e2
1e3
5e2
1e3
1.5e3
5e1
1e2
1e3
1e2
1e4
1e5
EqWts:
5.96
2.9e2
1.19e6
PerfWts:
1.03e1
1.25e2
1.03e6
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Target T20: Capture - likelihood of major emissions 0-50 yrs [1 in X]

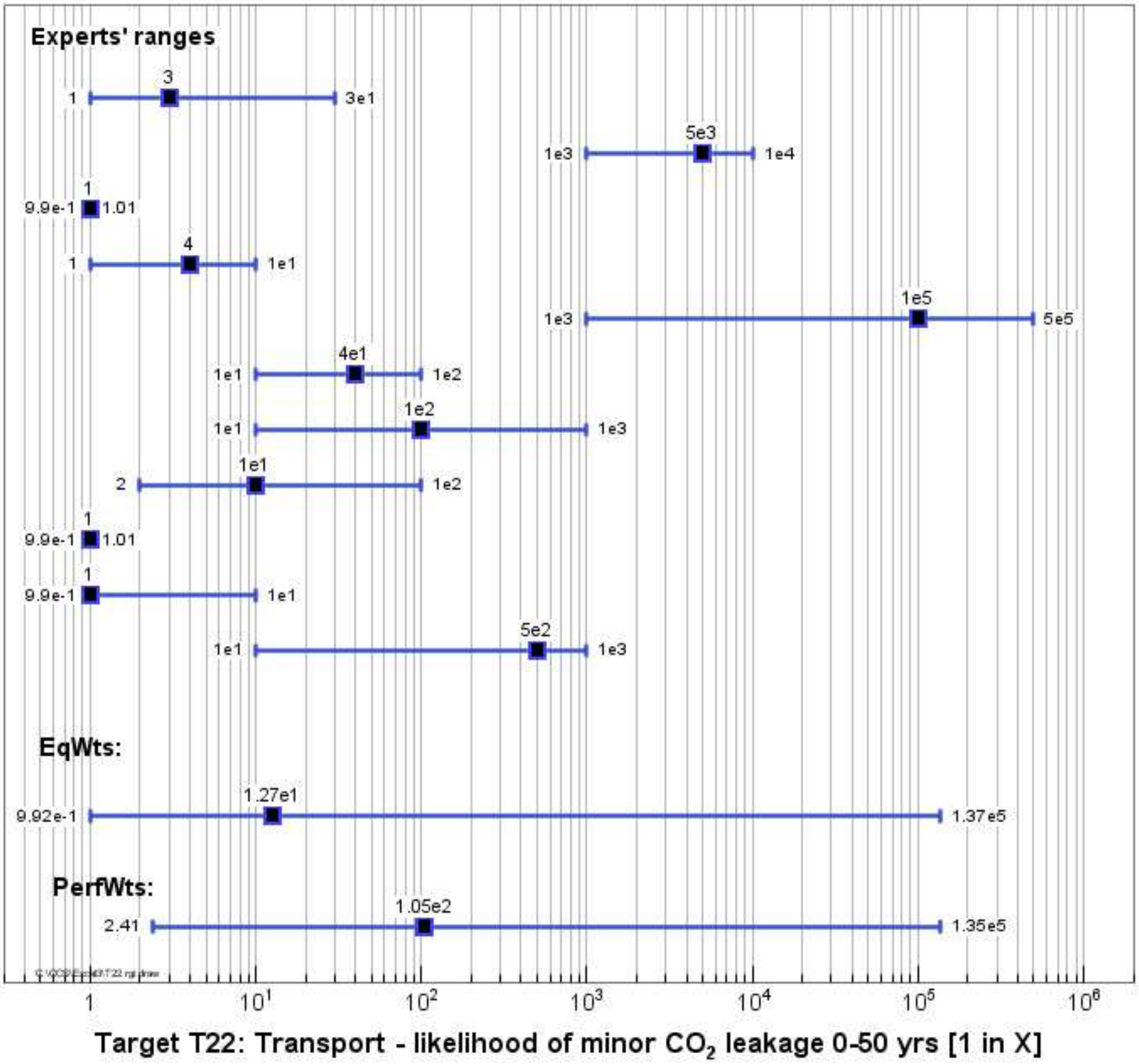

Experts' ranges
3e2
1e2
1e3
8e5
1e5
1e6
1e4
1e3
3e4
1e7
1e6
1e8
5e1
4
1e2
1e3
1e2
1e4
5e2
1e2
2e3
5e3
2e3
1e4
1e3
5e2
1e4
5e6
1e4
1e7
EqWts:
3.23e3
1.63e1
2.27e7
PerfWts:
1.1e3
1.01e2
1.49e7
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Target T21: Capture - likelihood of catastrophic emissions 0-50 yrs [1 in X]

Targets T22 – T24

In the transport phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of

a) minor leakage; b) major leakage; and c) catastrophic leakage

Transport				
Assessment criteria	Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
Minor CO_2 stream leakage				
[T22] 0-50 years	1 in 135000 (1 in 137000)	1 in 12100 (1 in 8850)	1 in 105 (1 in 13)	1 in 2.4 (1 in 1)
Major CO_2 stream leakage				
[T23] 0-50 years	1 in 550000 (1 in 600000)	1 in 50000 (1 in 44000)	1 in 1050 (1 in 350)	1 in 31 (1 in 12)
Catastrophic CO_2 stream leakage				
[T24] 0-50 years	1 in $2.2\text{x}10^6$ (1 in $7.0\text{x}10^6$)	1 in 240000 (1 in 490000)	1 in 10400 (1 in 3000)	1 in 79 (1 in 39.5)


Experts' ranges
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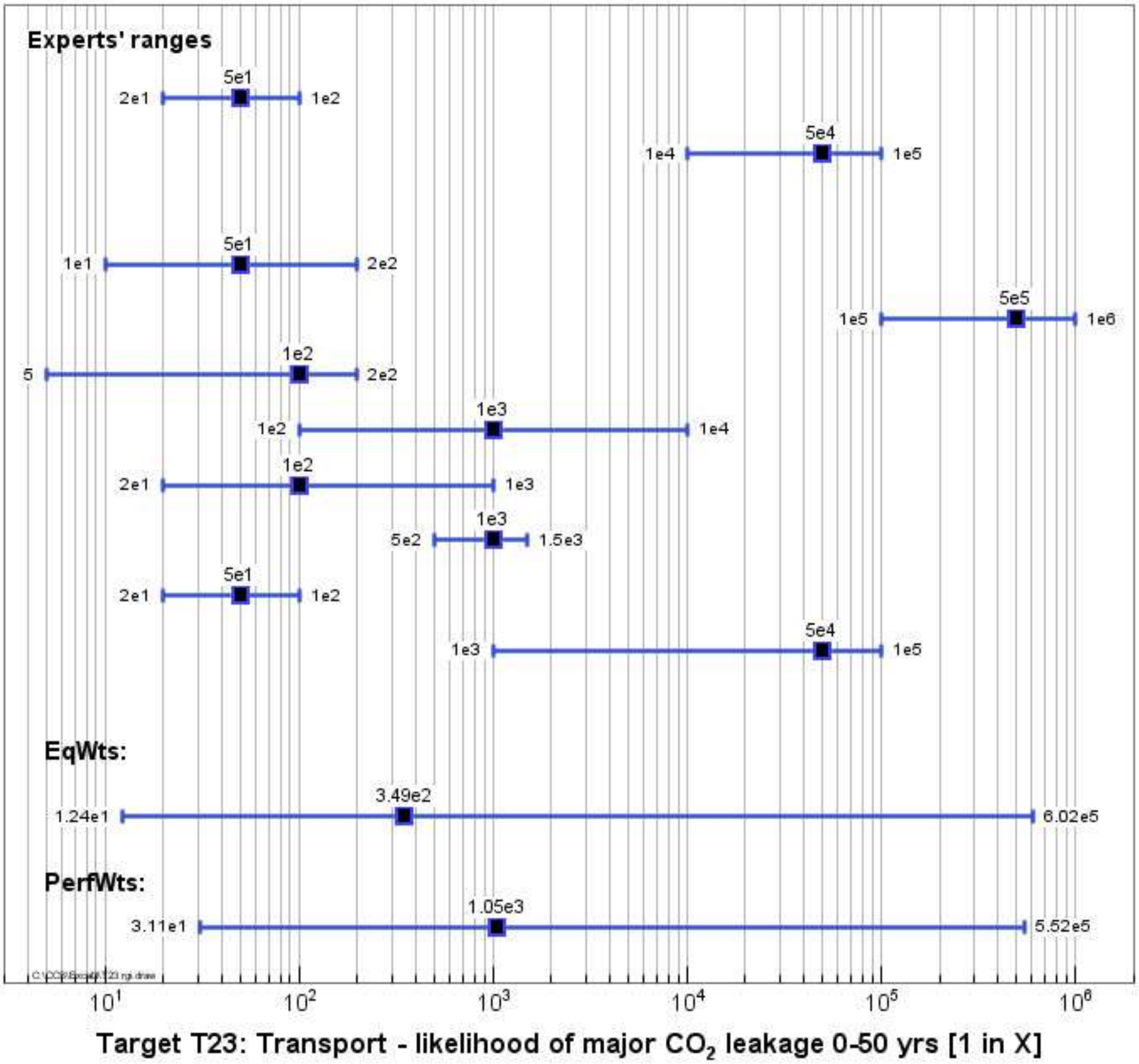
3
3e1
1e3
5e3
1e4
9.9e-1
1
1.01
1
4
1e1
1e3
1e5
5e5
1e1
4e1
1e2
1e1
1e2
1e3
2
1e1
1e2
9.9e-1
1
1.01
9.9e-1
1
1e1
1e1
5e2
1e3
EqWts:
9.92e-1
1.27e1
1.37e5
PerfWts:
2.41
1.05e2
1.35e5
1
10^1
10^2
10^3
10^4
10^5
10^6
Target T22: Transport - likelihood of minor CO_2 leakage 0-50 yrs [1 in X]


Experts' ranges
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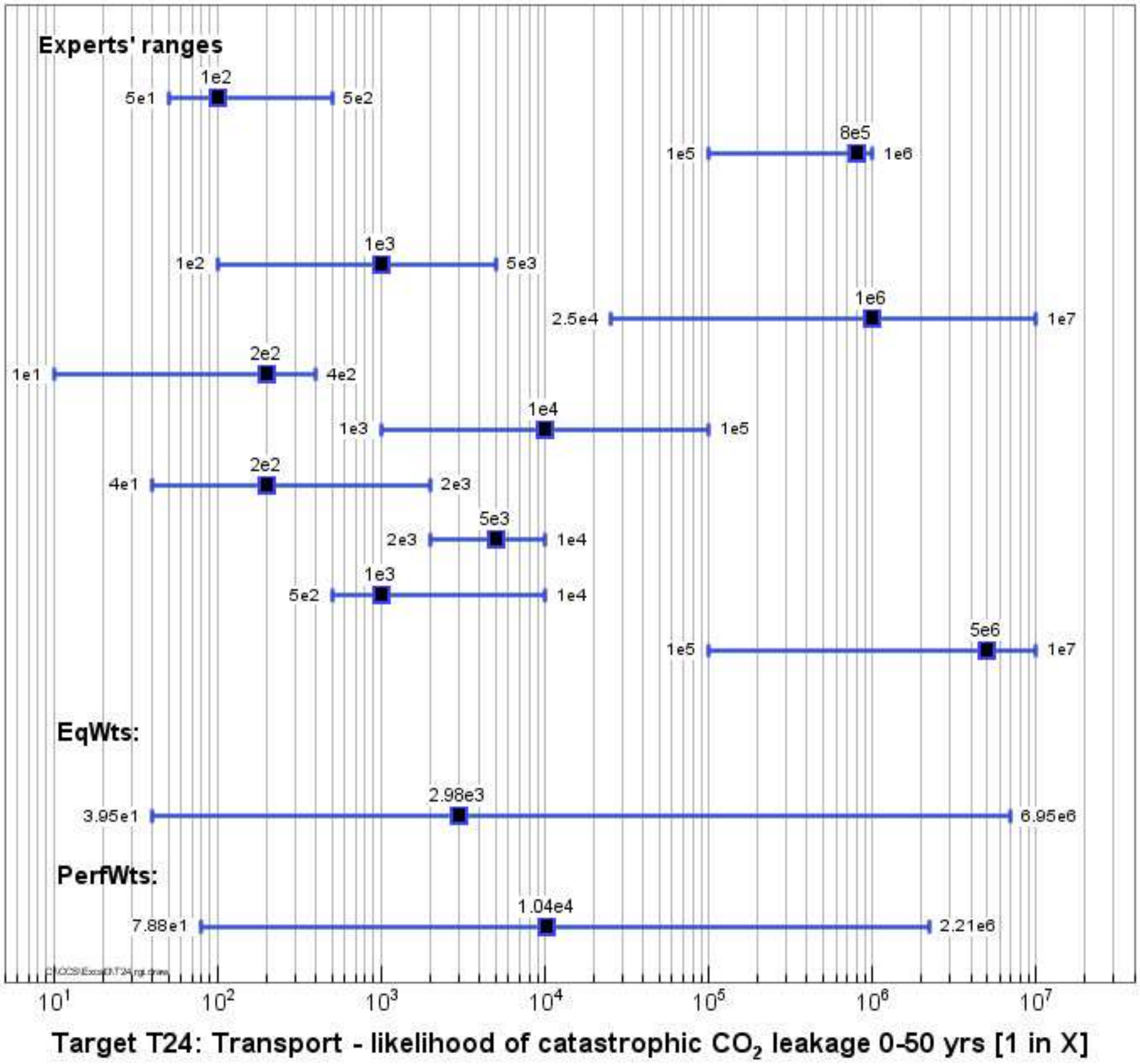
2e1
1e2
5e4
1e4
1e5
5e1
1e1
2e2
5e5
1e5
1e6
1e2
5
2e2
1e3
1e2
1e4
1e2
2e1
1e3
1e3
5e2
1.5e3
5e1
2e1
1e2
5e4
1e3
1e5
EqWts:
3.49e2
1.24e1
6.02e5
PerfWts:
1.05e3
3.11e1
5.52e5
10^1
10^2
10^3
10^4
10^5
10^6
Target T23: Transport - likelihood of major CO_2 leakage 0-50 yrs [1 in X]


Experts' ranges
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5e1
5e2
8e5
1e5
1e6
1e3
1e2
5e3
1e6
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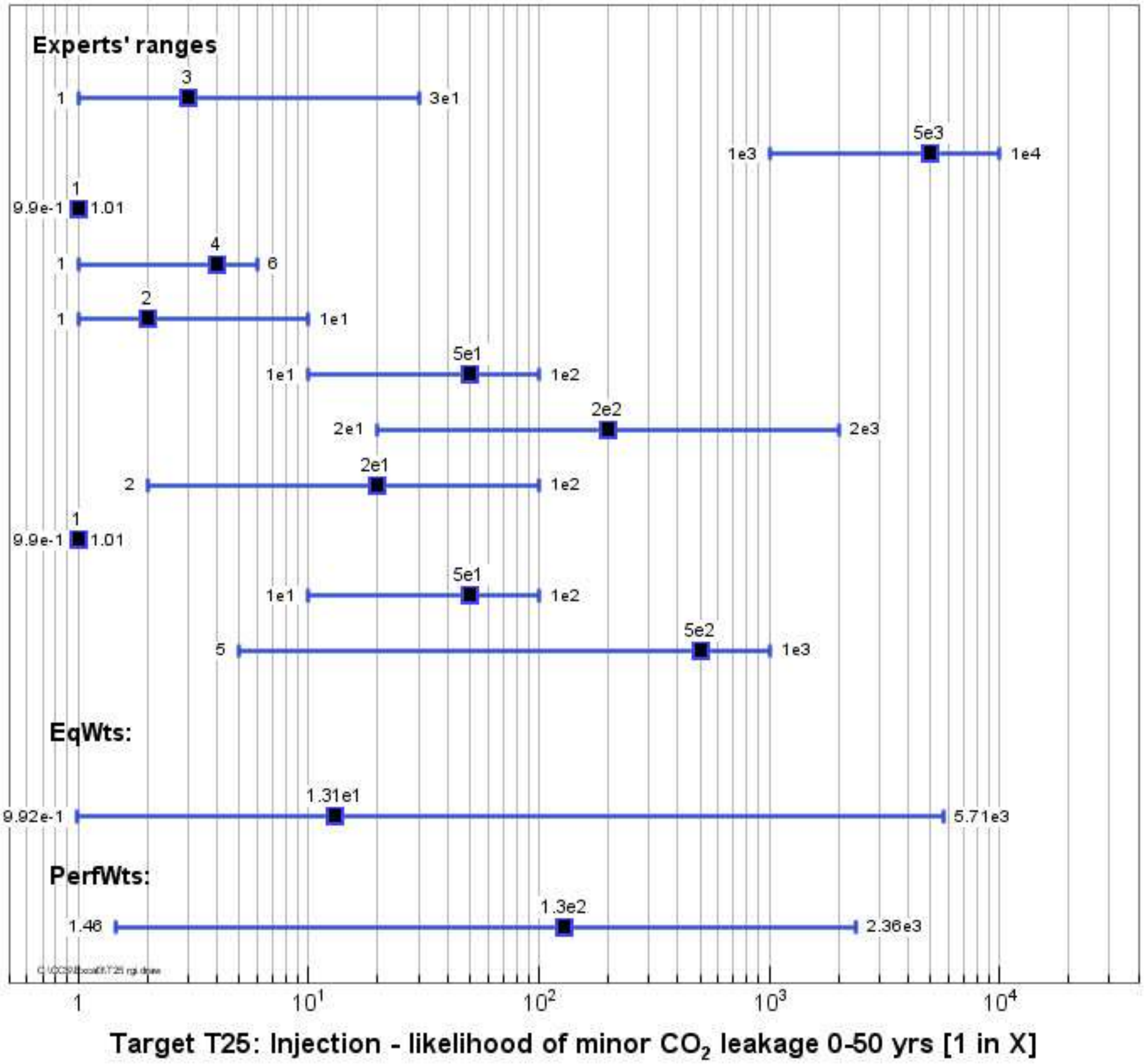
1e7
2e2
1e1
4e2
1e4
1e3
1e5
2e2
4e1
2e3
5e3
2e3
1e4
1e3
5e2
1e4
5e6
1e5
1e7
EqWts:
2.98e3
3.95e1
6.95e6
PerfWts:
1.04e4
7.88e1
2.21e6
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Target T24: Transport - likelihood of catastrophic CO_2 leakage 0-50 yrs [1 in X]

Targets T25 – T27

In the Injection phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of

a) minor leakage; b) major leakage; and c) catastrophic leakage

Injection				
Assessment criteria	Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
Minor CO_2 leakage				
[T25] 0-50 years	1 in 2400 (1 in 5700)	1 in 455 (1 in 500)	1 in 130 (1 in 13)	1 in 1.5 (1 in 1)
Major CO_2 leakage				
[T26] 0-50 years	1 in 23700 (1 in 76700)	1 in 4550 (1 in 6600)	1 in 1290 (1 in 157)	1 in 7.5 (1 in 5)
Catastrophic CO_2 leakage				
[T27] 0-50 years	1 in 270000 (1 in 880000)	1 in 53500 (1 in 92000)	1 in 15700 (1 in 5360)	1 in 69 (1 in 42)


Experts' ranges
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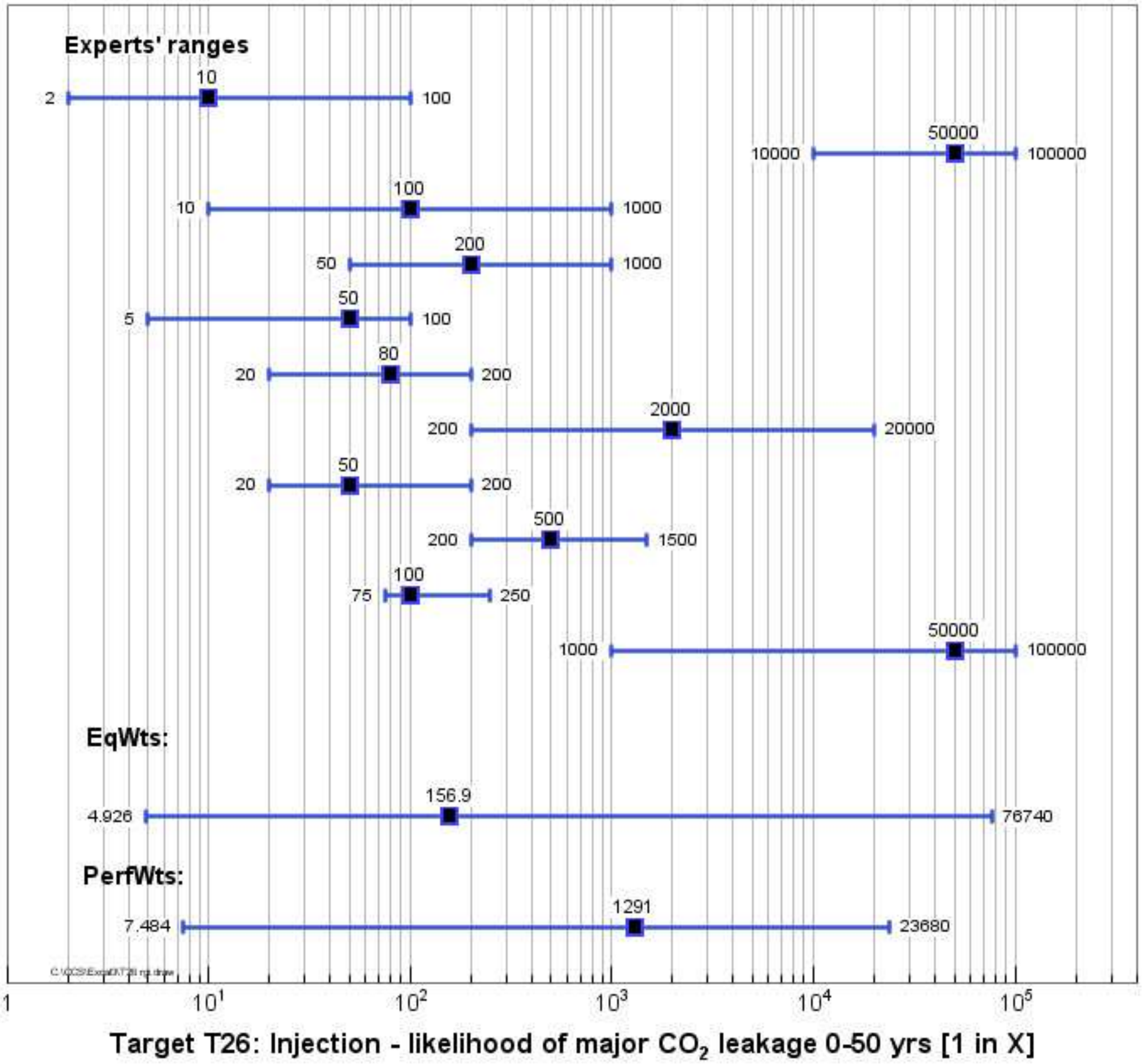
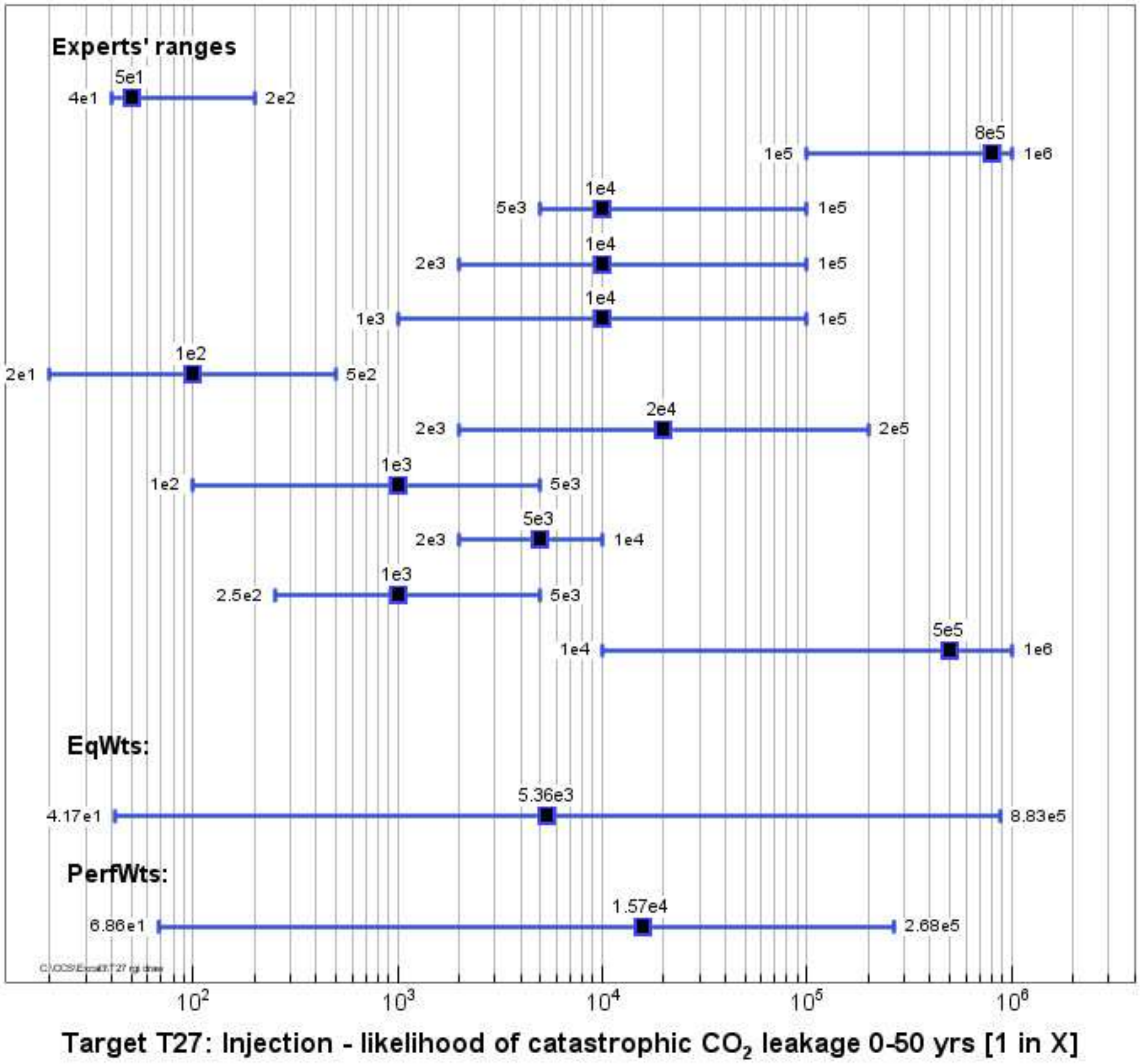
1e3
5e3
1e4
9.9e-1
1
1.01
1
4
6
1
2
1e1
1e1
5e1
1e2
2e1
2e2
2e3
2
2e1
1e2
9.9e-1
1
1.01
1e1
5e1
1e2
5
5e2
1e3
EqWts:
9.92e-1
1.31e1
5.71e3
PerfWts:
1.46
1.3e2
2.36e3
1
10^1
10^2
10^3
10^4
Target T25: Injection - likelihood of minor CO_2 leakage 0-50 yrs [1 in X]


Experts' ranges
2
10
100
10000
50000
100000
10
100
1000
50
200
1000
5
50
100
20
80
200
200
2000
20000
20
50
200
200
500
1500
75
100
250
1000
50000
100000
EqWts:
4.926
156.9
76740
PerfWts:
7.484
1291
23680
1
10^1
10^2
10^3
10^4
10^5
Target T26: Injection - likelihood of major CO_2 leakage 0-50 yrs [1 in X]


Experts' ranges
4e1 5e1 2e2
1e5 8e5 1e6
5e3 1e4 1e5
2e3 1e4 1e5
1e3 1e4 1e5
2e1 1e2 5e2
2e3 2e4 2e5
1e2 1e3 5e3
2e3 5e3 1e4
2.5e2 1e3 5e3
1e4 5e5 1e6
EqWts:
4.17e1 5.36e3 8.83e5
PerfWts:
6.86e1 1.57e4 2.68e5
10^2
10^3
10^4
10^5
10^6
Target T27: Injection - likelihood of catastrophic CO_2 leakage 0-50 yrs [1 in X]

T28-30Rev: In the first 50 years of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

b) Minor leakage b) Major leakage c) Catastrophic leakage

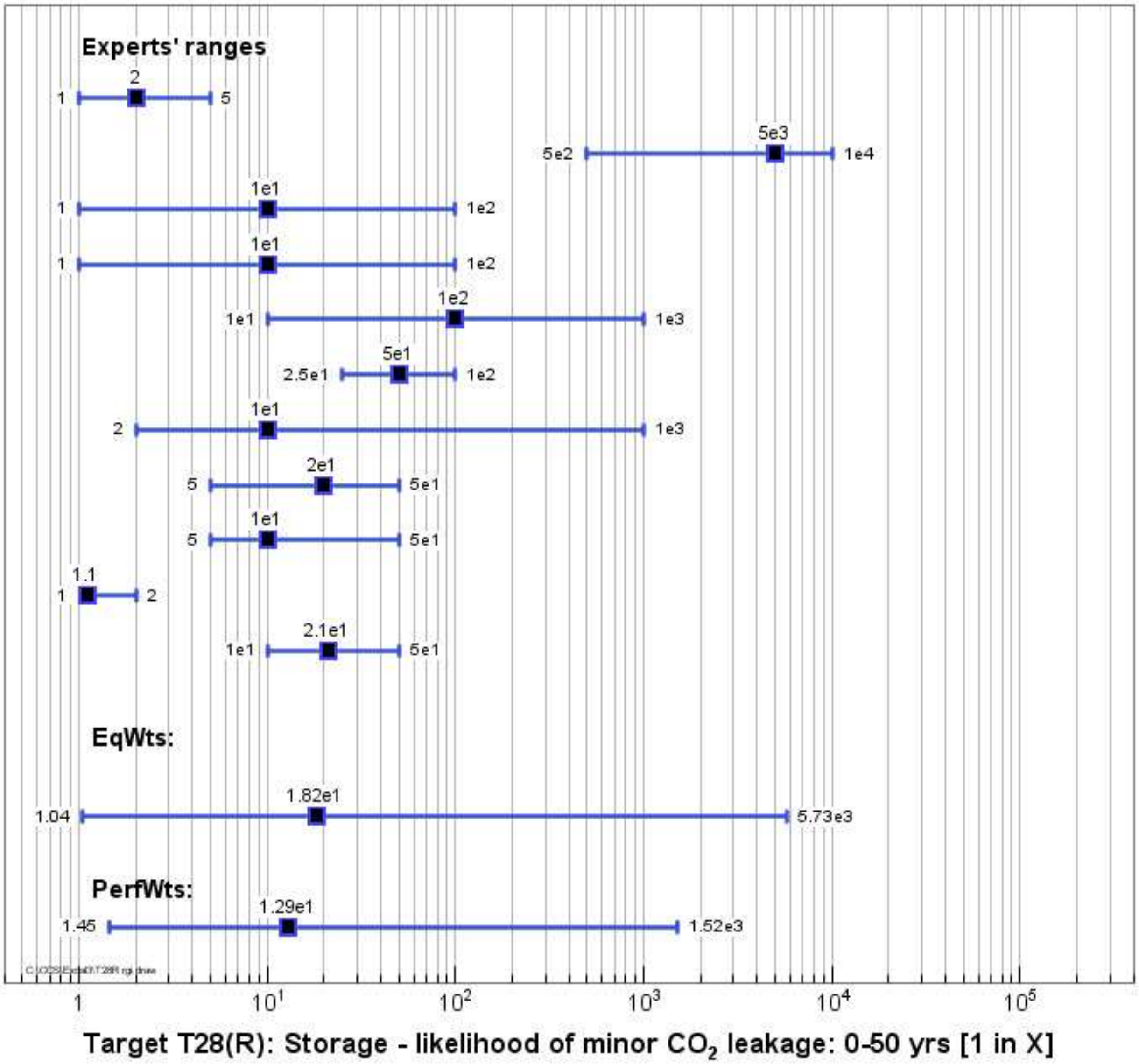
T31-33Rev: From year 51-499 of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

b) Minor leakage b) Major leakage c) Catastrophic leakage

T34-36Rev: From year 500 onwards of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

b) Minor leakage b) Major leakage c) Catastrophic leakage

Storage Leakage Likelihood				
Period/Leakage	Lower limit (5th percentile)	Mean	Central value (median)	Upper limit (95th percentile)
0-50 years				
[T28R] Minor	1 in 1520 (1 in 5730)	170 (530)	1 in 13 (1 in 18)	1 in 1.4 (1 in 1.0)
[T29R] Major	1 in 96,400 (1 in 78,400)	11,200 (6900)	1 in 1030 (1 in 180)	1 in 35 (1 in 12)
[T30R] Catastrophic	1 in 1 million (1 in 1 million)	116,000 (95,500)	1 in 10,300 (1 in 3440)	1 in 83 (1 in 59)
51-499 years				
[T31R] Minor	1 in 2070 (1 in 25,000)	210 (1910)	1 in 9.9 (1 in 24)	1 in 2 (1 in 1)
[T32R] Major	1 in 16,100 (1 in 75,000)	2900 (7500)	1 in 890 (1 in 360)	1 in 57 (1 in 7)
[T33R] Catastrophic	1 in 1 million (1 in 1 million)	119,000 (92,000)	1 in 11,300 (1 in 2750)	1 in 595 (1 in 80)
Over 500 years				
[T34R] Minor	1 in 8,340 (1 in 152,000)	780 (11,000)	1 in 27 (1 in 86)	1 in 2 (1 in 1)
[T35R] Major	1 in 172,000 (1 in 630,000)	18,300 (52,900)	1 in 1200 (1 in 1000)	1 in 100 (1 in 8)
[T36R] Catastrophic	1 in 1 million (1 in 1 million)	122,000 (136,000)	1 in 12,500 (1 in 20,000)	1 in 1020 (1 in 86)


Experts' ranges
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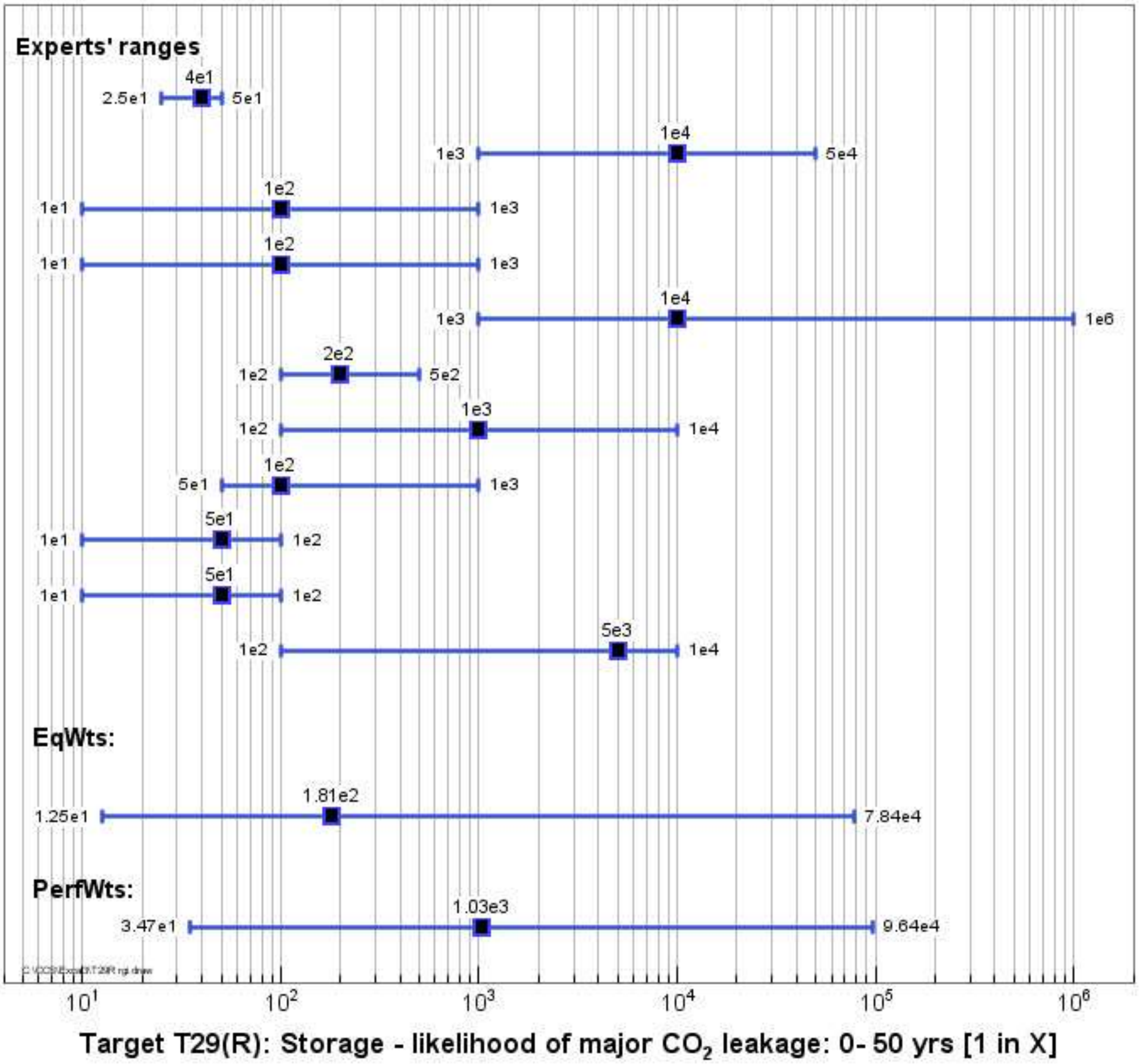
5e2 5e3 1e4
1 1e1 1e2
1 1e1 1e2
1e1 1e2 1e3
2.5e1 5e1 1e2
2 1e1 1e3
5 2e1 5e1
5 1e1 5e1
1 1.1 2
1e1 2.1e1 5e1
EqWts:
1.04 1.82e1 5.73e3
PerfWts:
1.45 1.29e1 1.52e3
1
10^1
10^2
10^3
10^4
10^5
Target T28(R): Storage - likelihood of minor CO_2 leakage: 0-50 yrs [1 in X]


Experts' ranges
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2.5e1
5e1
1e4
1e3
5e4
1e2
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1e3
1e2
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1e3
1e4
1e3
1e6
2e2
1e2
5e2
1e3
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1e4
1e2
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1e3
5e1
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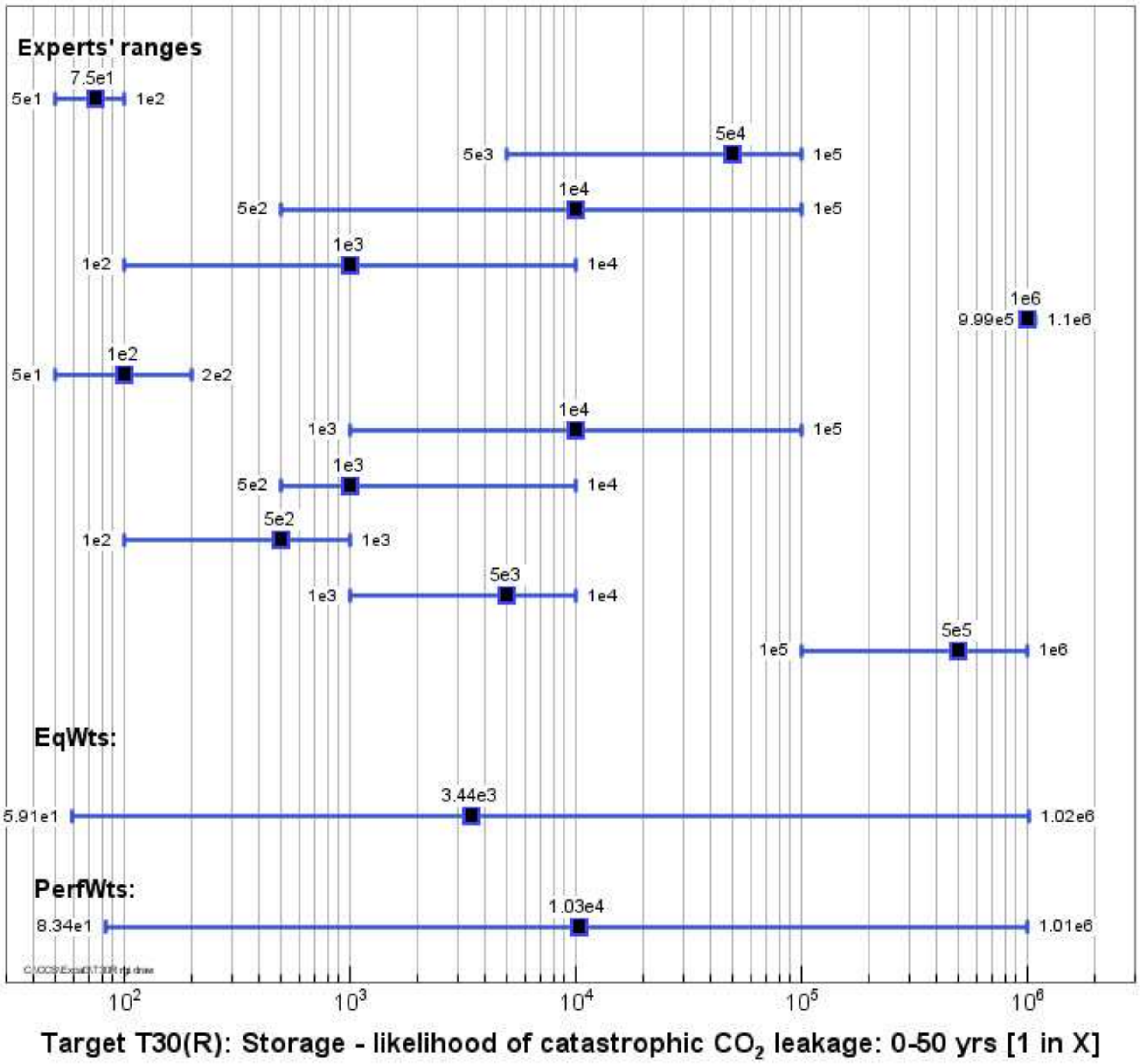
1e2
5e1
1e1
1e2
5e3
1e2
1e4
EqWts:
1.81e2
1.25e1
7.84e4
PerfWts:
1.03e3
3.47e1
9.64e4
10^1
10^2
10^3
10^4
10^5
10^6
Target T29(R): Storage - likelihood of major CO_2 leakage: 0- 50 yrs [1 in X]


Experts' ranges
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5e3
1e5
1e4
5e2
1e5
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1e4
1e6
9.99e5
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1e2
5e1
2e2
1e4
1e3
1e5
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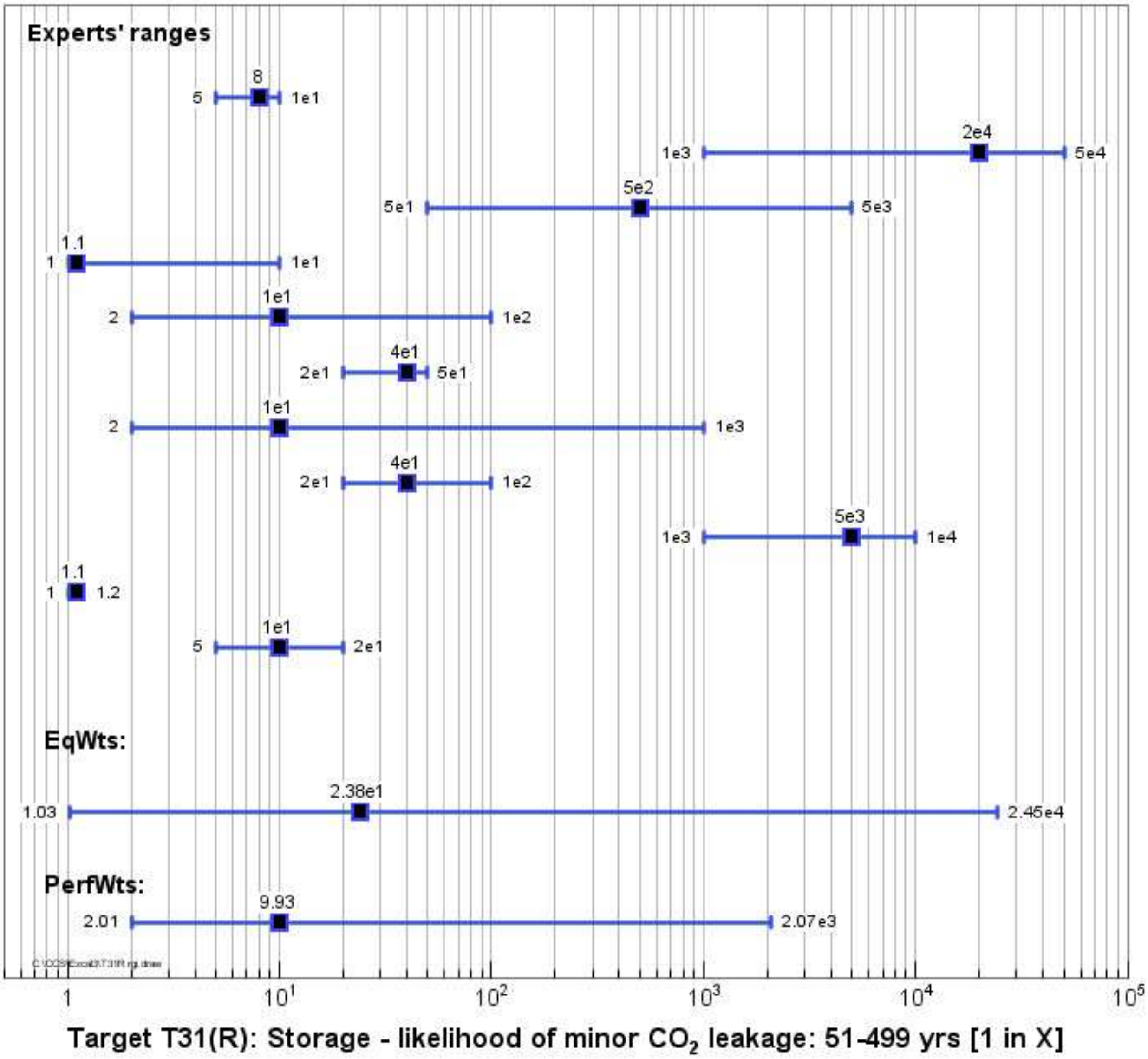
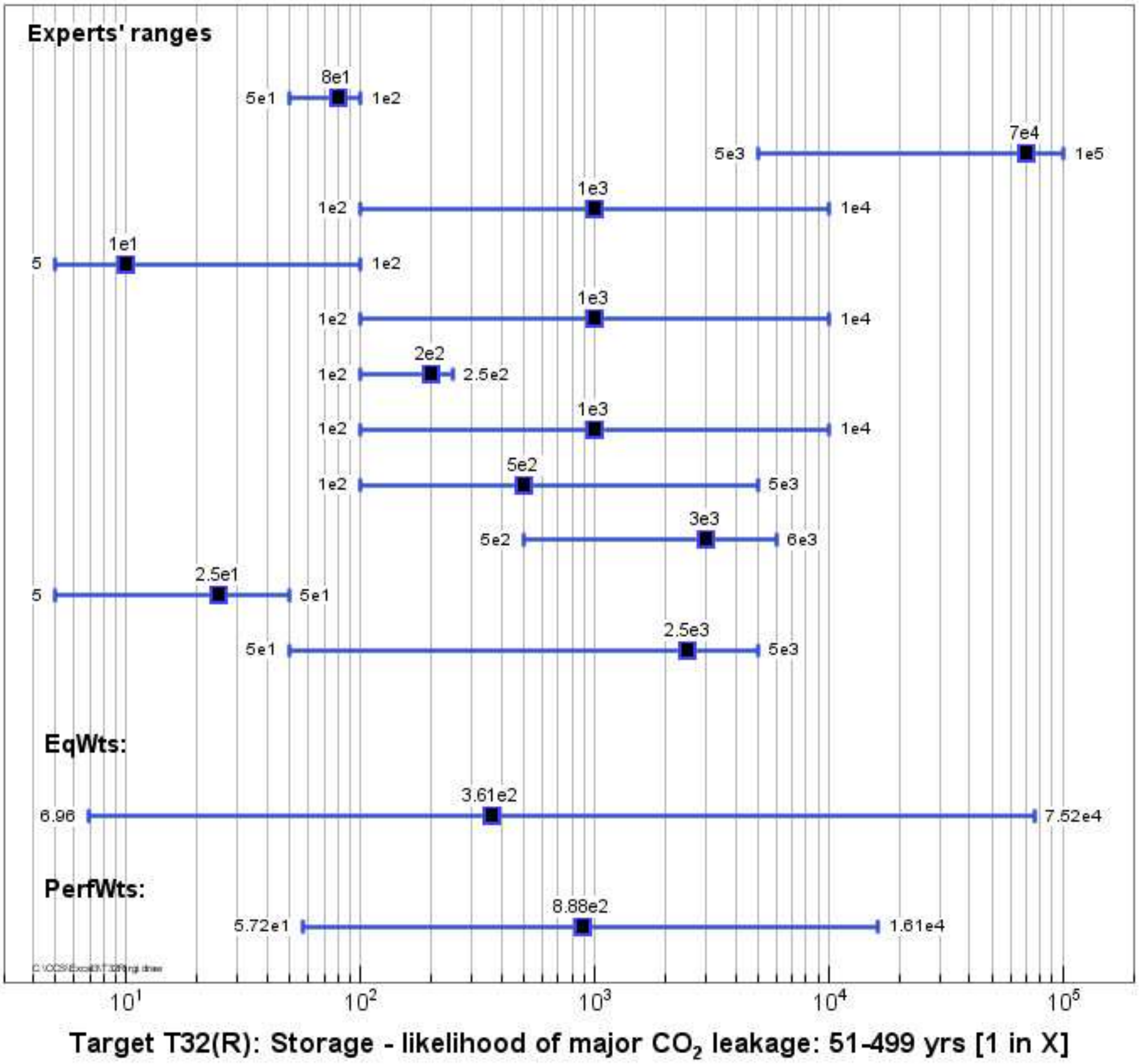
1e4
5e2
1e2
1e3
5e3
1e3
1e4
5e5
1e5
1e6
EqWts:
3.44e3
5.91e1
1.02e6
PerfWts:
1.03e4
8.34e1
1.01e6
10^2
10^3
10^4
10^5
10^6
Target T30(R): Storage - likelihood of catastrophic CO_2 leakage: 0-50 yrs [1 in X]


Experts' ranges
5 8 1e1
1e3 2e4 5e4
5e1 5e2 5e3
1 1.1 1e1
2 1e1 1e2
2e1 4e1 5e1
2 1e1 1e3
2e1 4e1 1e2
1e3 5e3 1e4
1 1.1 1.2
5 1e1 2e1
EqWts:
1.03 2.38e1 2.45e4
PerfWts:
2.01 9.93 2.07e3
1
10^1
10^2
10^3
10^4
10^5
Target T31(R): Storage - likelihood of minor CO_2 leakage: 51-499 yrs [1 in X]


Experts' ranges
8e1
5e1
1e2
7e4
5e3
1e5
1e3
1e2
1e4
1e1
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1e3
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1e4
2e2
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2.5e2
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1e2
1e4
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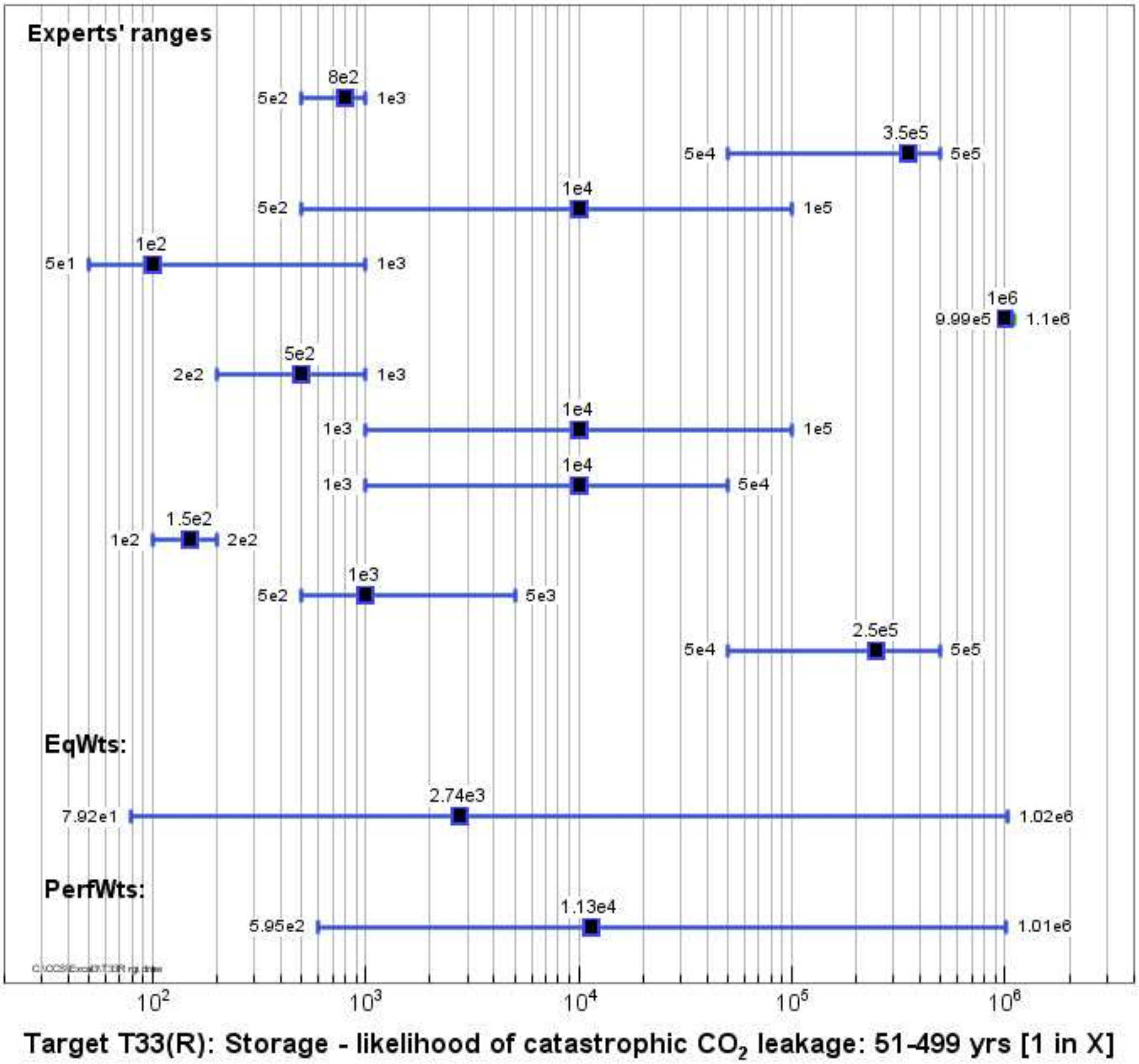
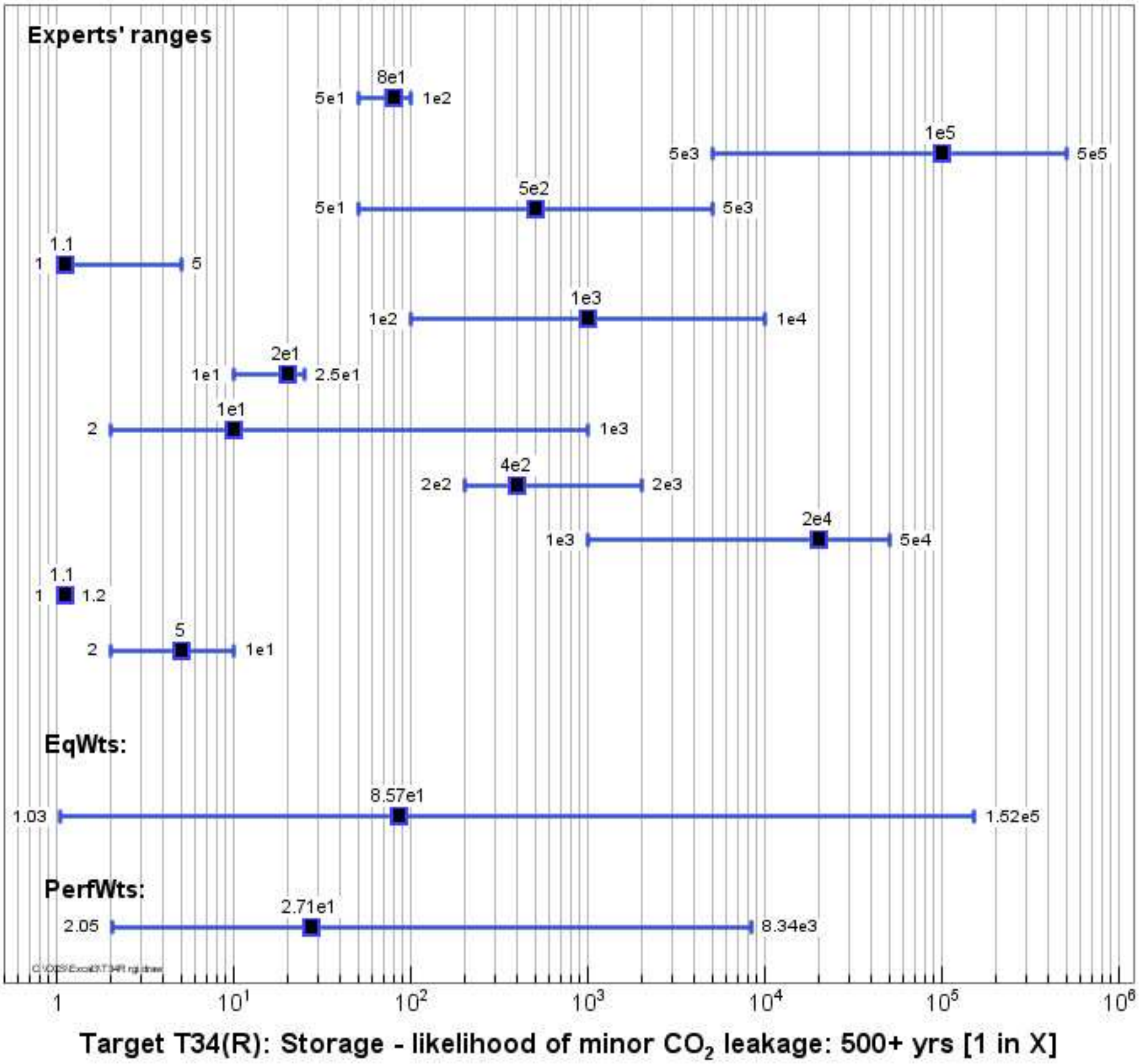
1e2
5e3
3e3
5e2
6e3
2.5e1
5
5e1
2.5e3
5e1
5e3
EqWts:
3.61e2
6.96
7.52e4
PerfWts:
8.88e2
5.72e1
1.61e4
10^1
10^2
10^3
10^4
10^5
Target T32(R): Storage - likelihood of major CO_2 leakage: 51-499 yrs [1 in X]


Experts' ranges
5e2 8e2 1e3
5e4 3.5e5 5e5
5e2 1e4 1e5
5e1 1e2 1e3
9.99e5 1e6 1.1e6
2e2 5e2 1e3
1e3 1e4 1e5
1e3 1e4 5e4
1e2 1.5e2 2e2
5e2 1e3 5e3
5e4 2.5e5 5e5
EqWts:
7.92e1 2.74e3 1.02e6
PerfWts:
5.95e2 1.13e4 1.01e6
10^2
10^3
10^4
10^5
10^6
Target T33(R): Storage - likelihood of catastrophic CO_2 leakage: 51-499 yrs [1 in X]


Experts' ranges
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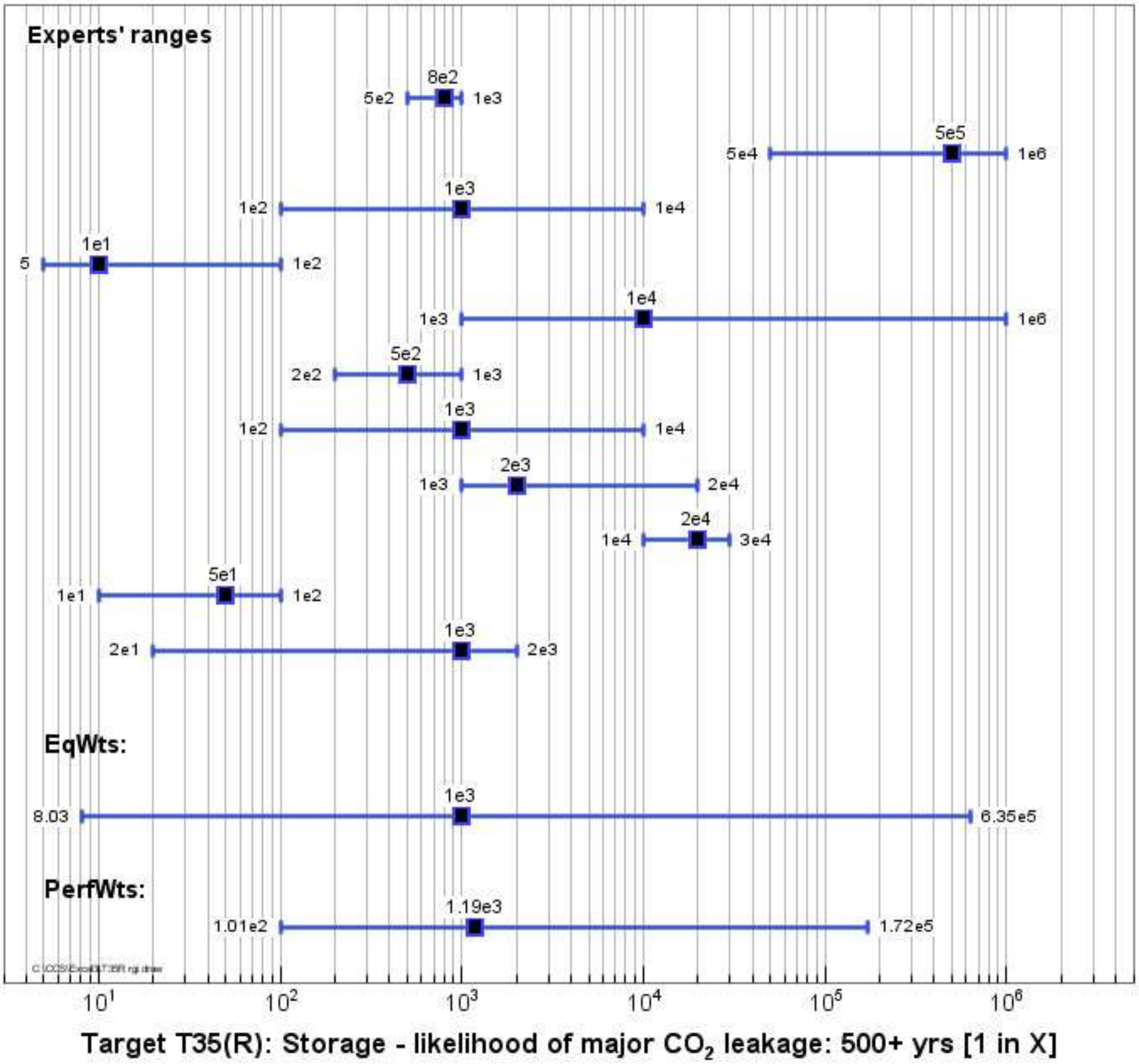
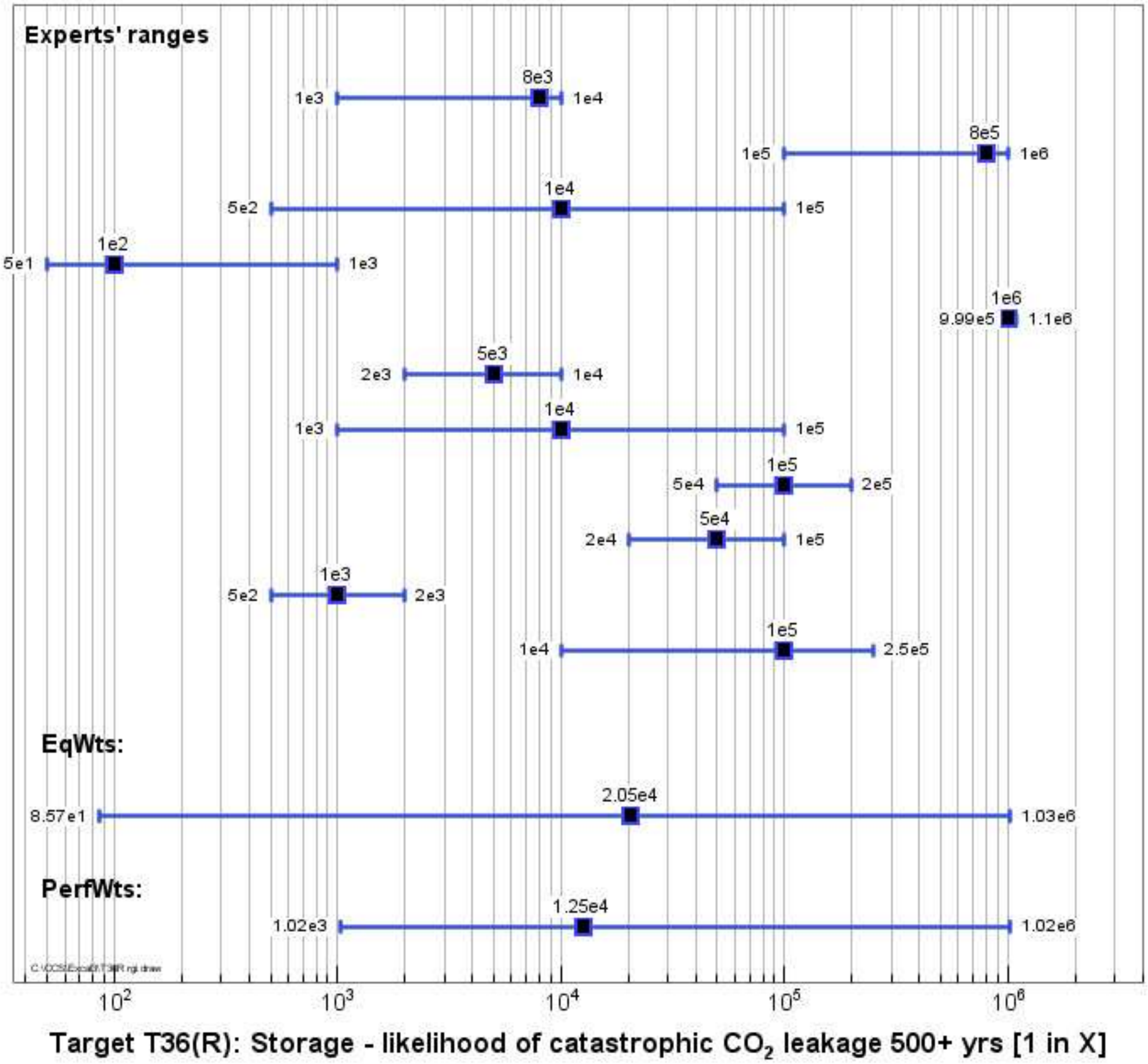
5e1
1e2
1e5
5e3
5e5
5e2
5e1
5e3
1.1
1
5
1e3
1e2
1e4
2e1
1e1
2.5e1
1e1
2
1e3
4e2
2e2
2e3
2e4
1e3
5e4
1.1
1
1.2
5
2
1e1
EqWts:
8.57e1
1.03
1.52e5
PerfWts:
2.71e1
2.05
8.34e3
1
10^1
10^2
10^3
10^4
10^5
10^6
Target T34(R): Storage - likelihood of minor CO_2 leakage: 500+ yrs [1 in X]


Experts' ranges
8e2
5e2
1e3
5e5
5e4
1e6
1e3
1e2
1e4
1e1
5
1e2
1e4
1e3
1e6
5e2
2e2
1e3
1e3
1e2
1e4
2e3
1e3
2e4
2e4
1e4
3e4
5e1
1e1
1e2
1e3
2e1
2e3
EqWts:
1e3
8.03
6.35e5
PerfWts:
1.19e3
1.01e2
1.72e5
10^1
10^2
10^3
10^4
10^5
10^6
Target T35(R): Storage - likelihood of major CO_2 leakage: 500+ yrs [1 in X]


Experts' ranges
1e3
8e3
1e4
1e5
8e5
1e6
5e2
1e4
1e5
5e1
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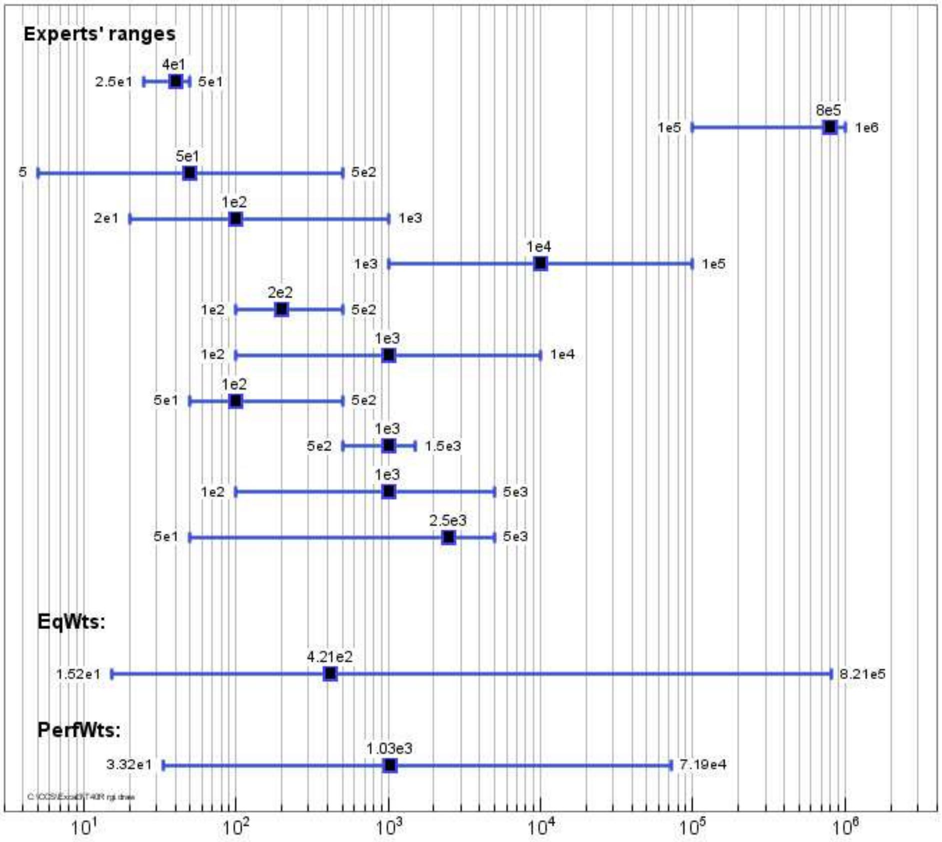
1e3
9.99e5
1e6
1.1e6
2e3
5e3
1e4
1e3
1e4
1e5
5e4
1e5
2e5
2e4
5e4
1e5
5e2
1e3
2e3
1e4
1e5
2.5e5
EqWts:
8.57e1
2.05e4
1.03e6
PerfWts:
1.02e3
1.25e4
1.02e6
10^2
10^3
10^4
10^5
10^6
Target T36(R): Storage - likelihood of catastrophic CO_2 leakage 500+ yrs [1 in X]

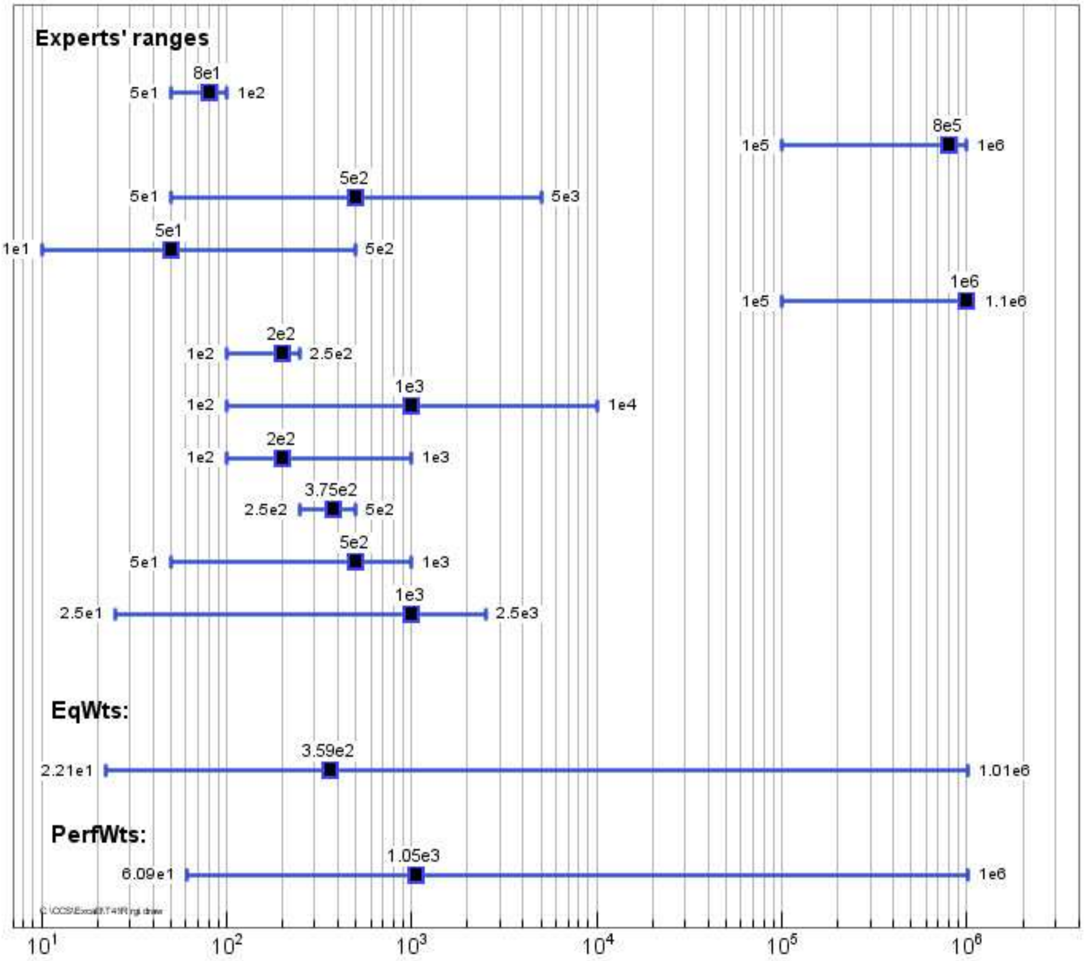
T40-T42Rev: This triplet of questions concerns the likelihood of major CO_2 leakage in a typical saline aquifer that would result in significant effects on the local environment or human health, in each of three time periods: 0-50 yrs; 51-499 yrs; and over 500 yrs.

T40-42Rev: In a typical saline aquifer storage site, what is the likelihood of major CO_2 leakage that would result in measurable negative environmental impact or adverse public health impact in each of the time periods (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

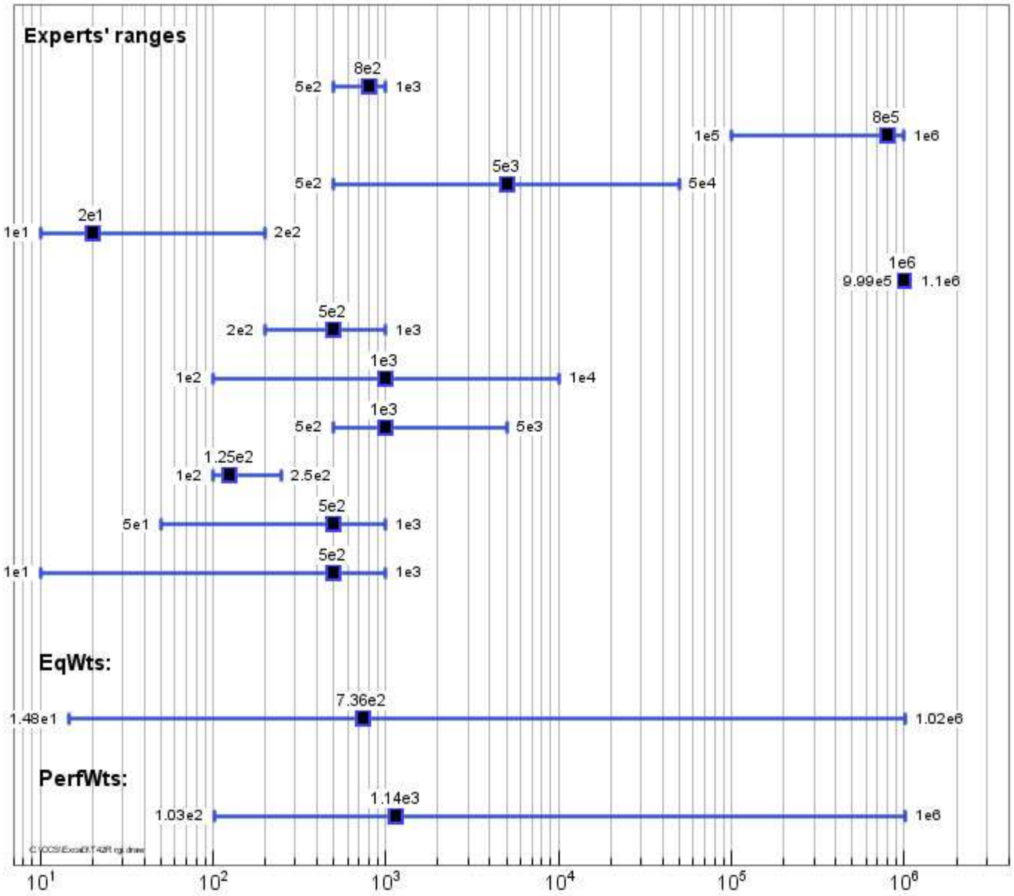
Time period (years)	Lower limit (5th percentile)	Mean	Central Value (median)	Upper limit (95th percentile)
[T40R] 0-50 yrs	1 in 71,900 (1 in 821,000)	8900 (58,900)	1 in 1030 (1 in 420)	1 in 33 (1 in 15)
[T41R] 51-499 yrs	1 in 1 million (1 in 1 million)	78,900 (69,700)	1 in 1050 (1 in 360)	1 in 61 (1 in 22)
[T42R] 500+ yrs	1 in 1 million (1 in 1 million)	79,900 (76,100)	1 in 1140 (1 in 736)	1 in 103 (1 in 15)



Target T40(R): Saline aquifer storage - likelihood of major CO_2 leakage with environ/health impacts 0-50 yrs [1 in X]



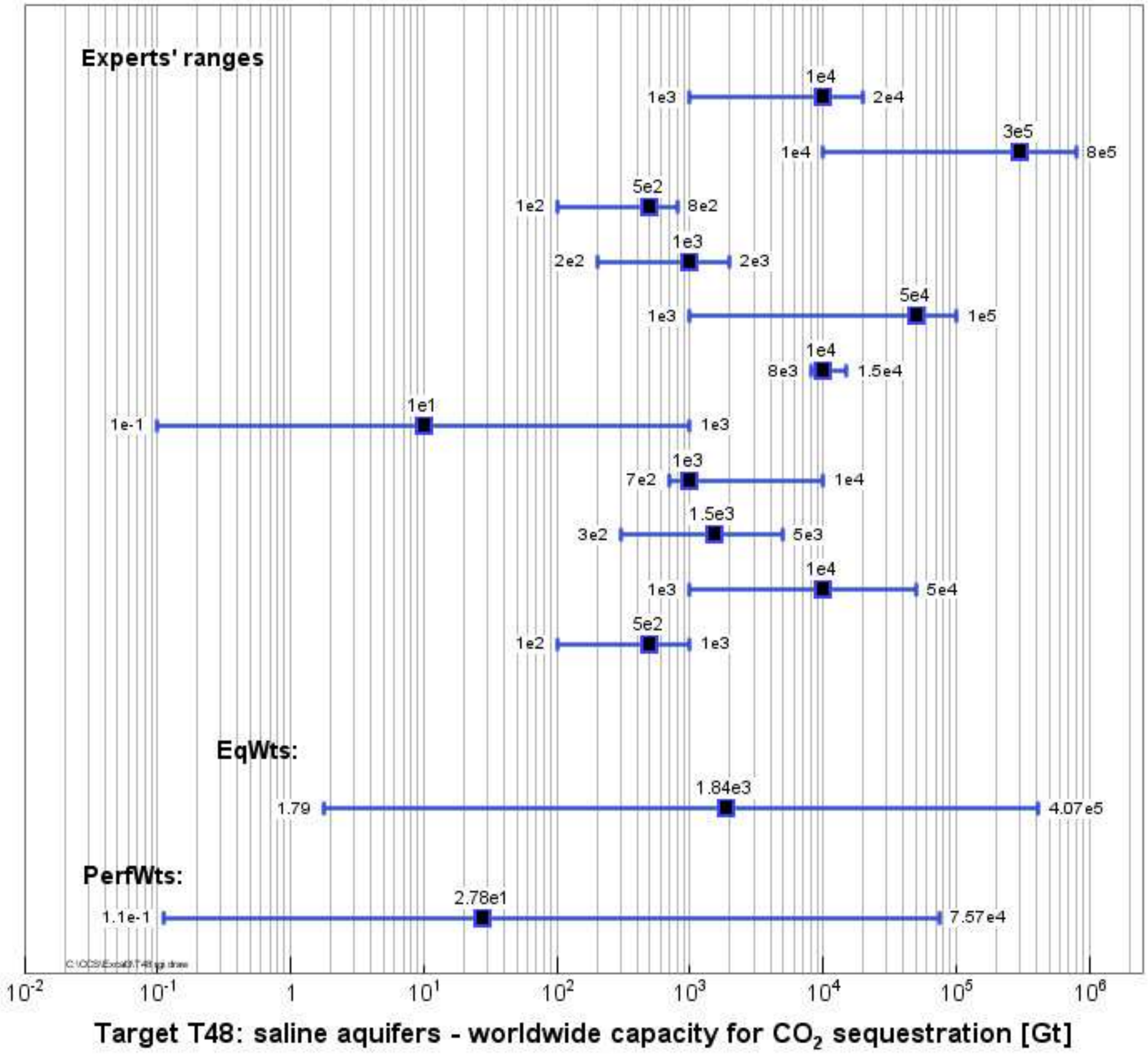
Target T41(R): Saline aquifer storage - likelihood of major CO_2 leakage with environ/health impacts 51 - 499 yrs [1 in X]



Target T42(R): Saline aquifer storage - likelihood of major CO_2 leakage with environ/health impacts 500+ yrs [1 in X]

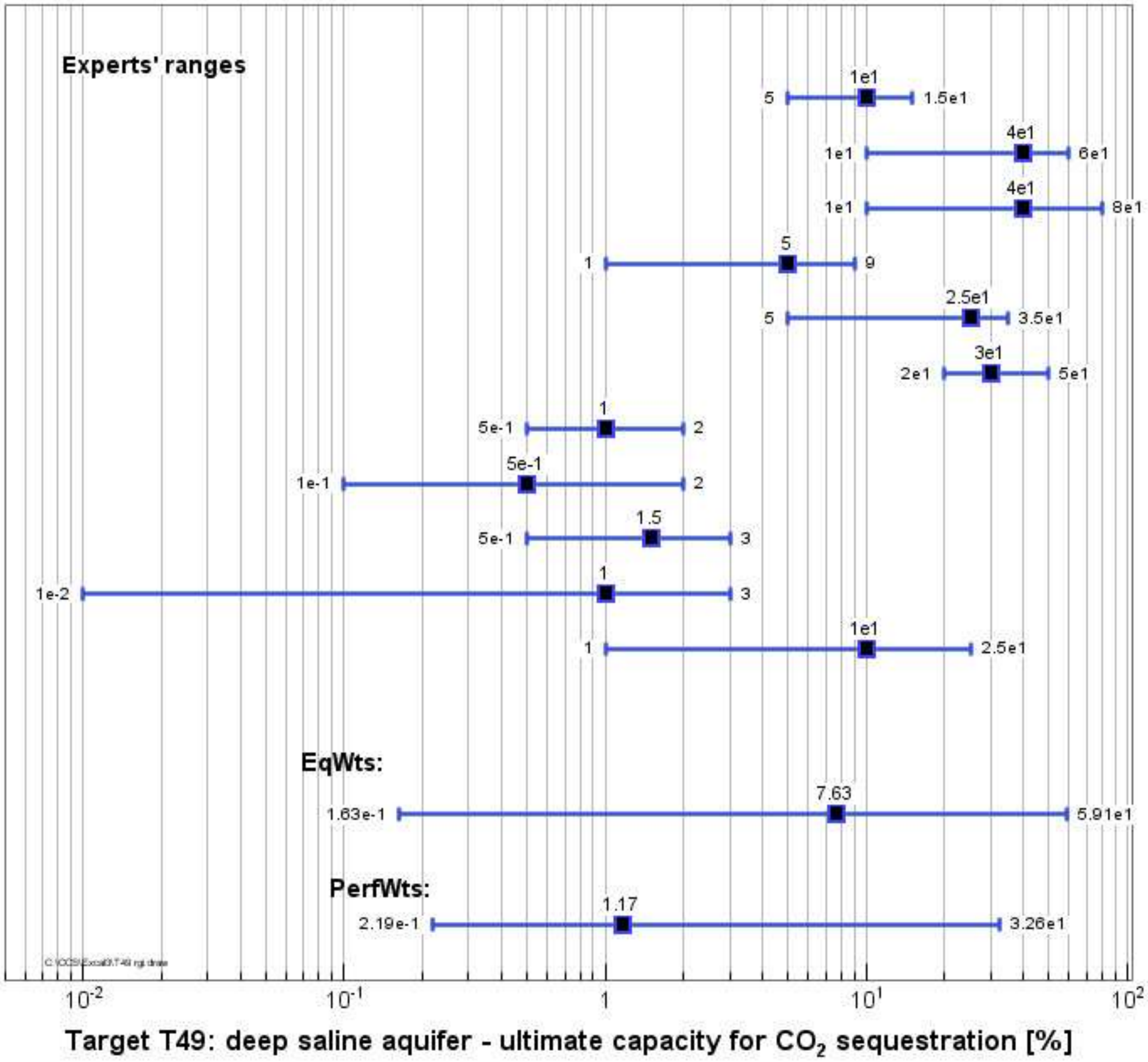
T48: What is the worldwide capacity for geological CO_2 sequestration in saline aquifers ($GtCO_2$)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
0.1 Gt (2 Gt)	5100 Gt (40000 Gt)	28 Gt (1840 Gt)	76000 Gt (410000 Gt)



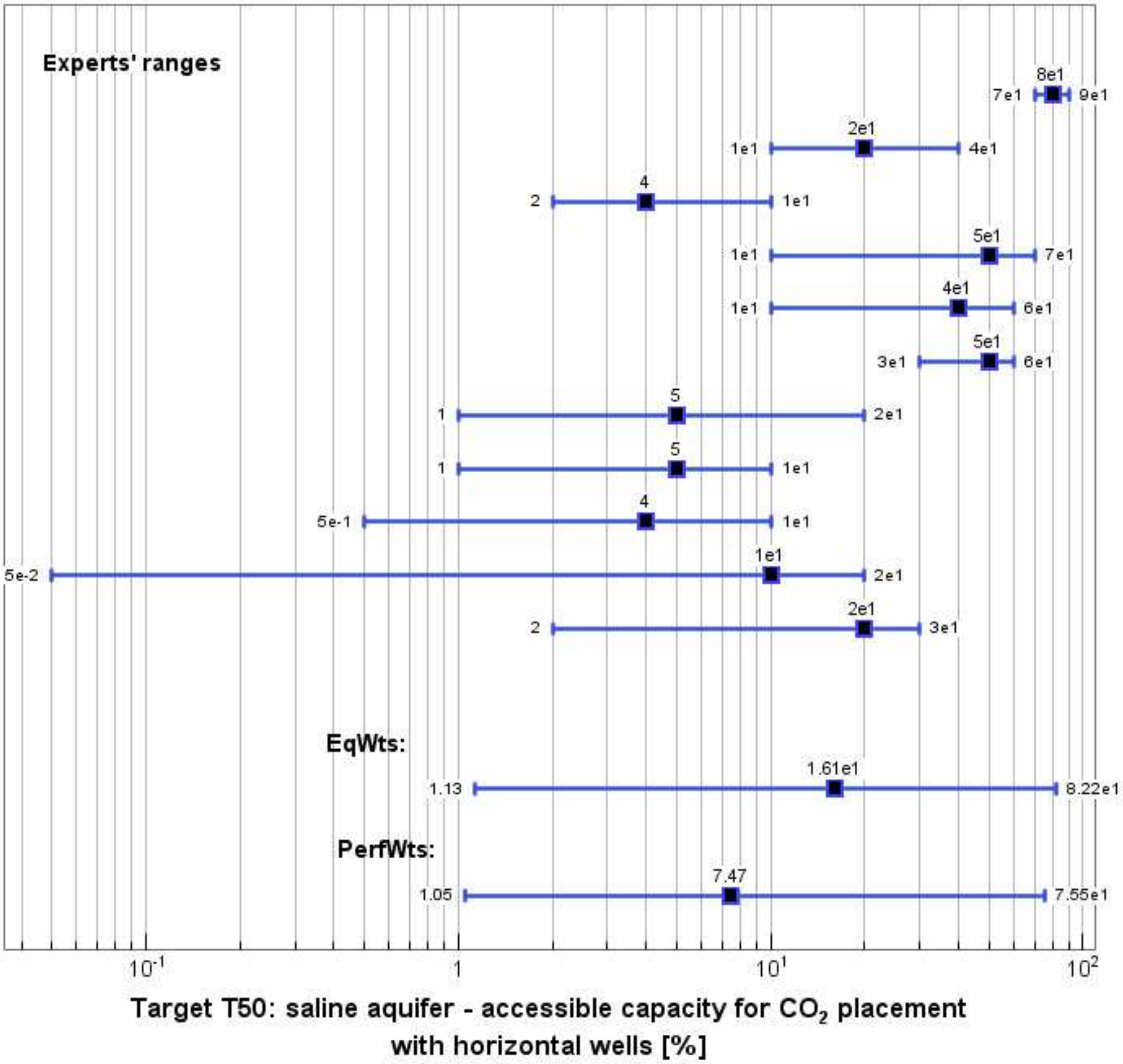
T49: What is the ultimate CO_2 sequestration capacity in solution as a percent (%) of a deep saline aquifer?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
0.2% (0.2%)	9% (19%)	1.2% (7.6%)	33% (59%)



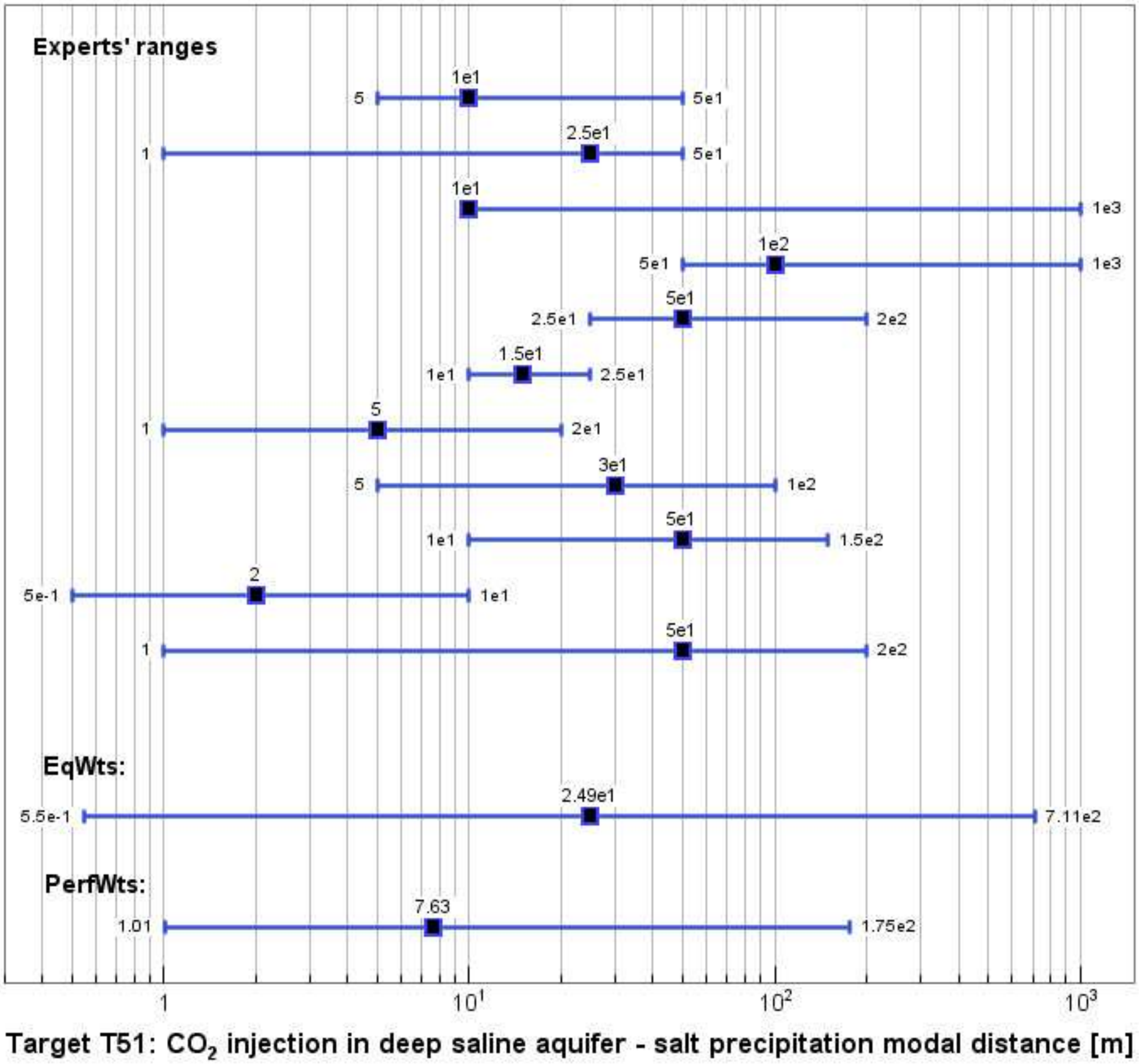
T50: What percentage of a theoretical repository capacity for a reasonable quality saline aquifer would you generally expect could be accessed by carbon dioxide placement using horizontal wells (%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.0% (1.1%)	16% (29%)	7.5% (16%)	76% (82%)



T51: In a CO_2 injection scheme in deep saline aquifer (~1 $MtCO_2$/year), what is the modal distance from the injection well that is likely to be affected by salt precipitation (metres)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1 m (0.55 m)	49 m (195 m)	7.6 m (25 m)	175 m (710 m)



Section 3
Composite plots of linked piecewise uncertainty distributions

The following plots show the Performance Weights (PW) solution quantiles and piecewise cumulative uncertainty distributions for compound target questions – i.e. those items which have one or more counterpart scenarios with different or alternative conditions.

The piecewise distributions are ‘minimum information’ representations of uncertainty, simply defined by the three quantiles (i.e. 5th, 50th and 95th percentiles) derived by aggregating the weighted combination of experts’ judgements.

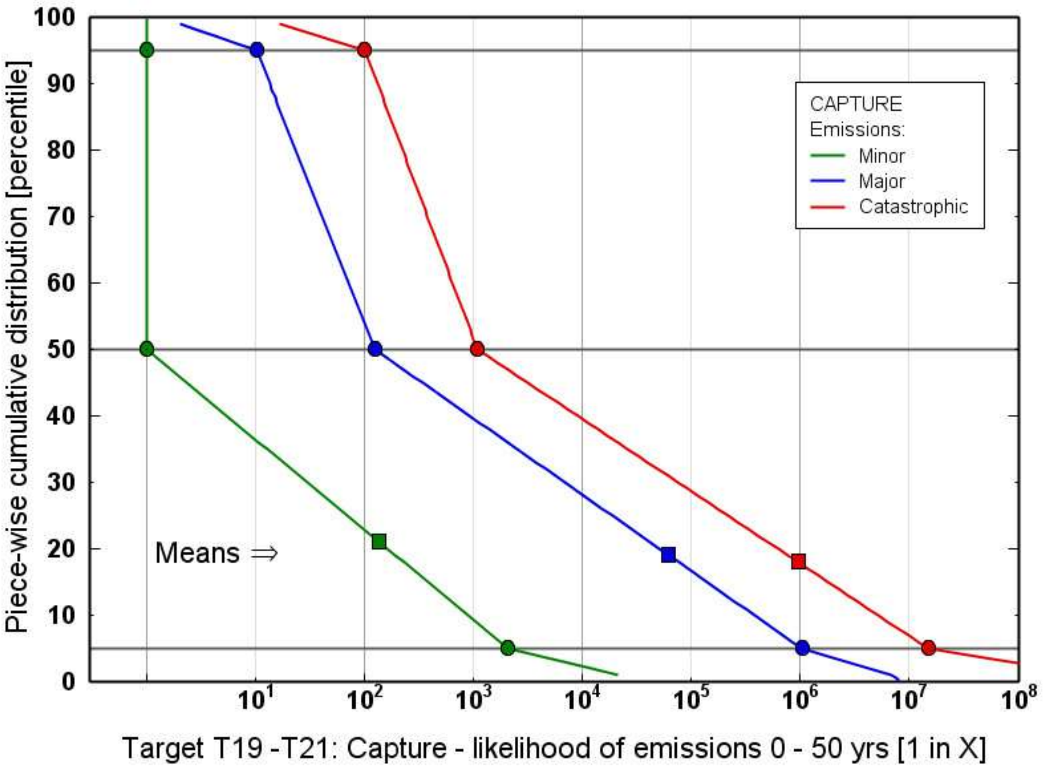
In risk assessment practice, standard distribution forms may be fitted as appropriate to the quantiles, e.g. normal, lognormal, beta, Weibull …..

Targets T19 – T21

In the Capture phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of

f) minor leakage; b) major leakage; and c) catastrophic leakage

Capture				
Assessment criteria	Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
Minor emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products				
[T19] 0-50 years	1 in 2100 (1 in 6500)	1 in 180 (1 in 480)	1 in 1 (1 in 3.2)	1 in 1 (1 in 1)
Major emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products				
[T20] 0-50 years	1 in 1.0x10^6 (1 in 1.2x10^6)	1 in 65600 (1 in 7.8x10^3)	1 in 125 (1 in 290)	1 in 10 (1 in 6)
Catastrophic emissions of dense phase CO_2, NO_2, $PM_{2.5}$, Amines and their degradation products				
[T21] 0-50 years	1 in 1.5x10^7 (1 in 2.3x10^7)	1 in 95000 (1 in 1.4x10^6)	1 in 1100 (1 in 3200)	1 in 100 (1 in 16)

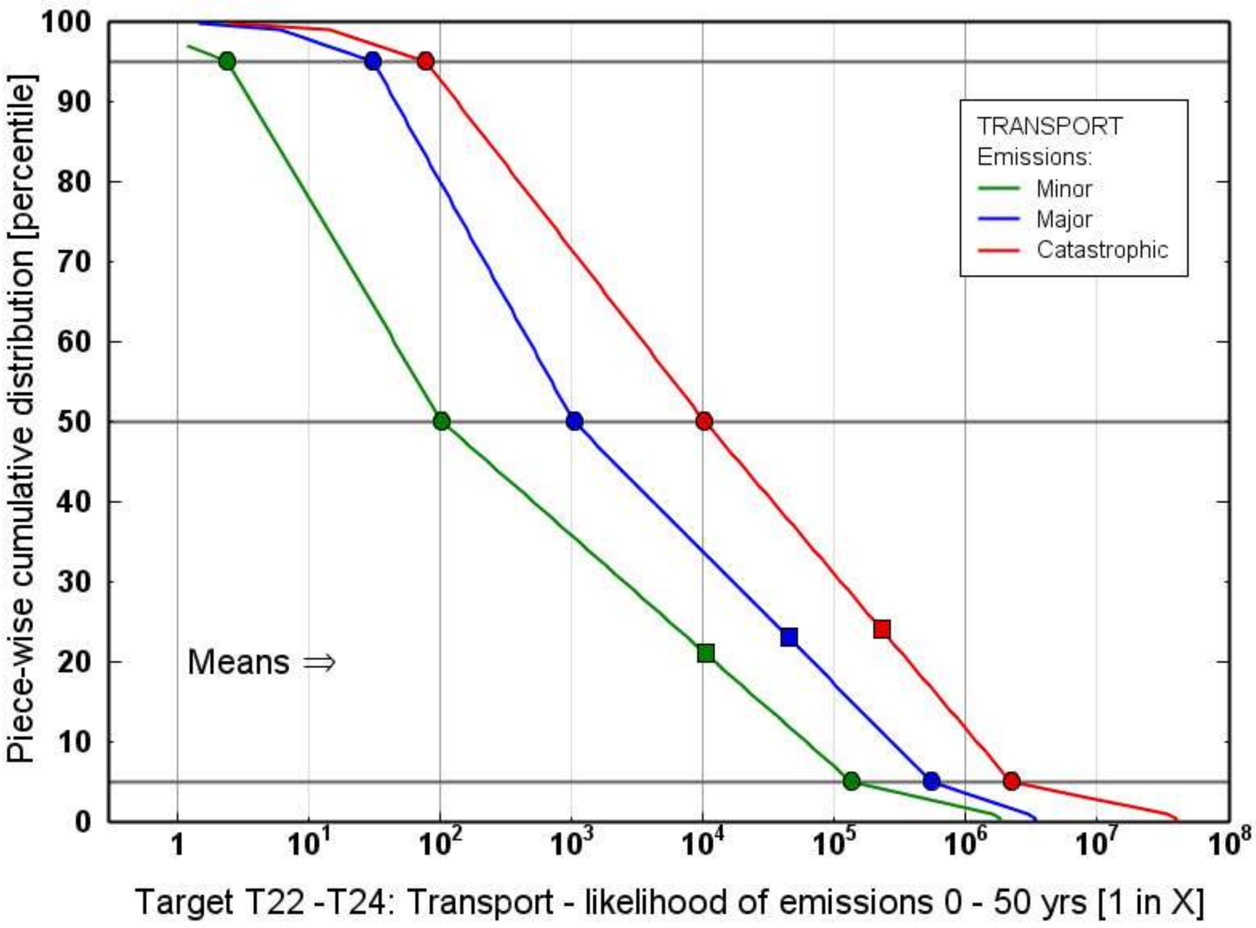


Targets T22 – T24

In the Transport phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of

a) minor leakage; b) major leakage; and c) catastrophic leakage

Transport				
Assessment criteria	Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
Minor CO_2 stream leakage				
[T22] 0-50 years	1 in 135000 (1 in 137000)	1 in 12100 (1 in 8850)	1 in 105 (1 in 13)	1 in 2.4 (1 in 1)
Major CO_2 stream leakage				
[T23] 0-50 years	1 in 550000 (1 in 600000)	1 in 50000 (1 in 44000)	1 in 1050 (1 in 350)	1 in 31 (1 in 12)
Catastrophic CO_2 stream leakage				
[T24] 0-50 years	1 in 2.2×10^6 (1 in 7.0×10^6)	1 in 240000 (1 in 490000)	1 in 10400 (1 in 3000)	1 in 79 (1 in 39.5)

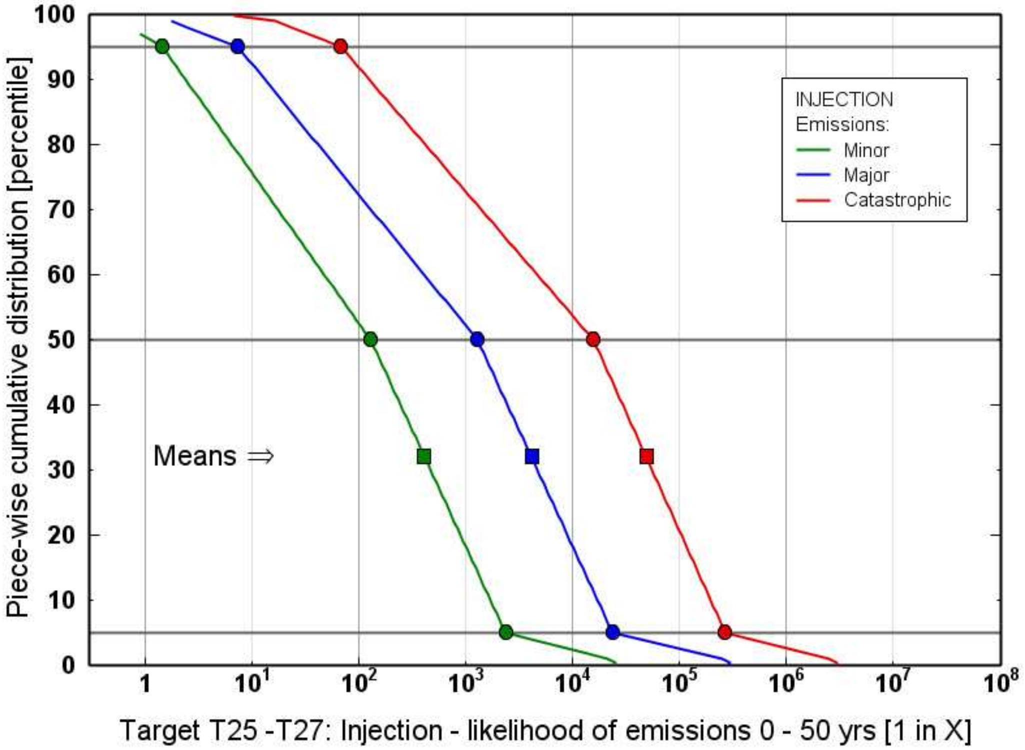


Targets T25 – T27
In the Injection phase of an integrated CCS project, in which there is a 50 year active phase followed by a purely storage phase, what in your opinion is the likelihood of

a) minor leakage; b) major leakage; and c) catastrophic leakage

Injection				
Assessment criteria	Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
Minor CO_2 leakage				
[T25] 0-50 years	1 in 2400 (1 in 5700)	1 in 455 (1 in 500)	1 in 130 (1 in 13)	1 in 1.5 (1 in 1)
Major CO_2 leakage				
[T26] 0-50 years	1 in 23700 (1 in 76700)	1 in 4550 (1 in 6600)	1 in 1290 (1 in 157)	1 in 7.5 (1 in 5)
Catastrophic CO_2 leakage				

[T27] 0-50 years	1 in 270000 (1 in 880000)	1 in 53500 (1 in 92000)	1 in 15700 (1 in 5360)	1 in 69 (1 in 42)



28-T30Rev: In the first 50 years of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage b) Major leakage c) Catastrophic leakage

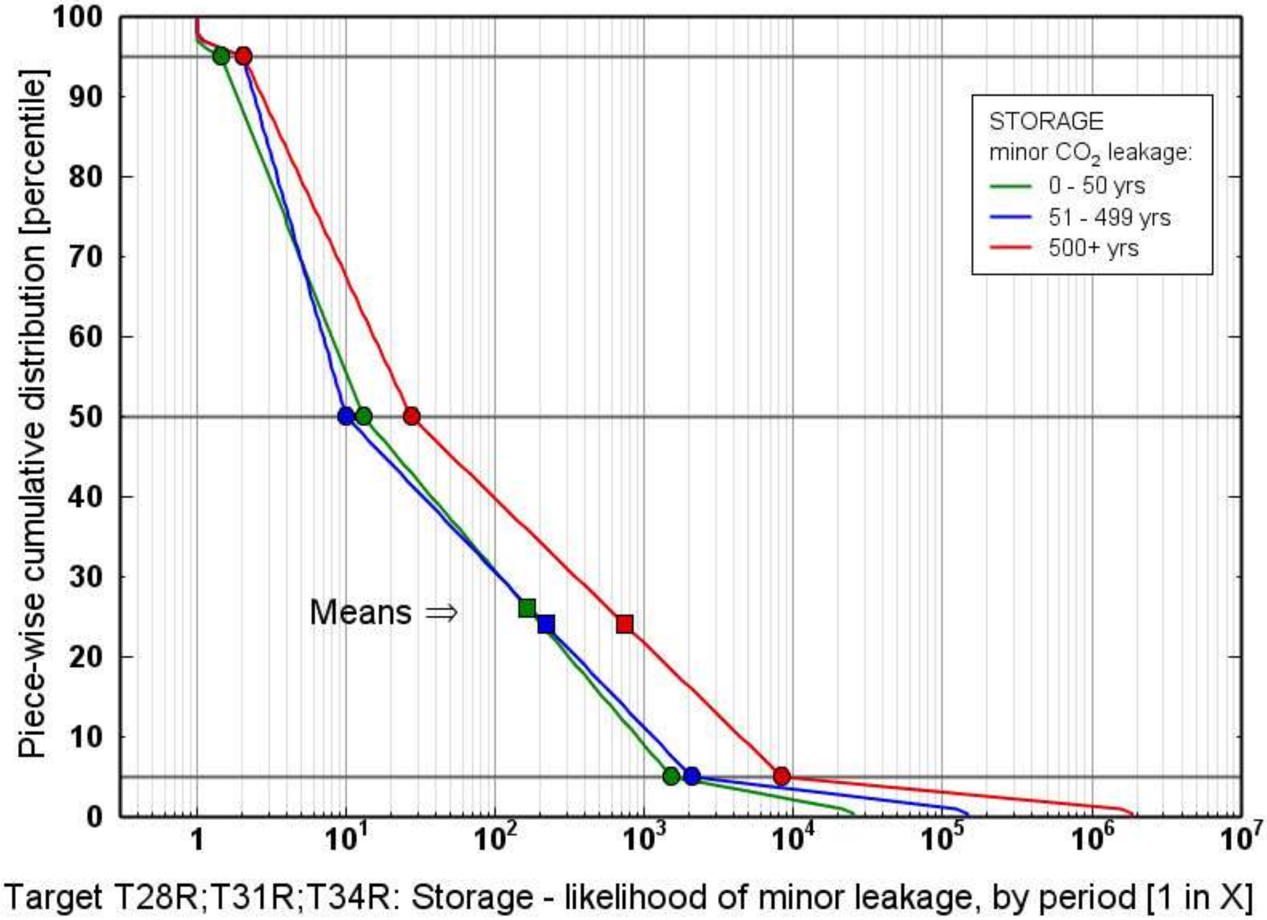
T31-T33Rev: From year 51-499 of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage b) Major leakage c) Catastrophic leakage

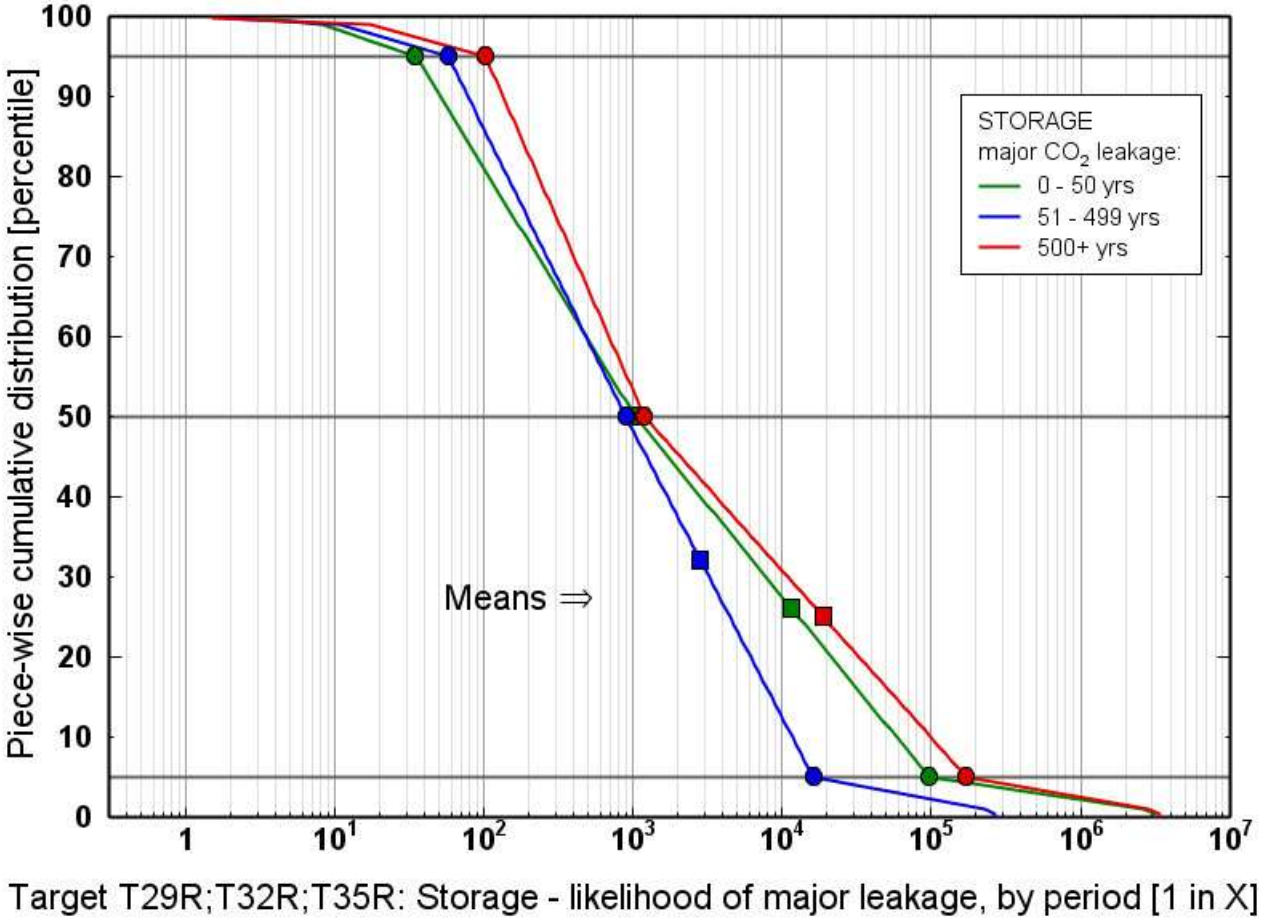
T34-T36Rev: From year 500 onwards of an integrated carbon sequestration project, what is the likelihood of the following leakage scenarios (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

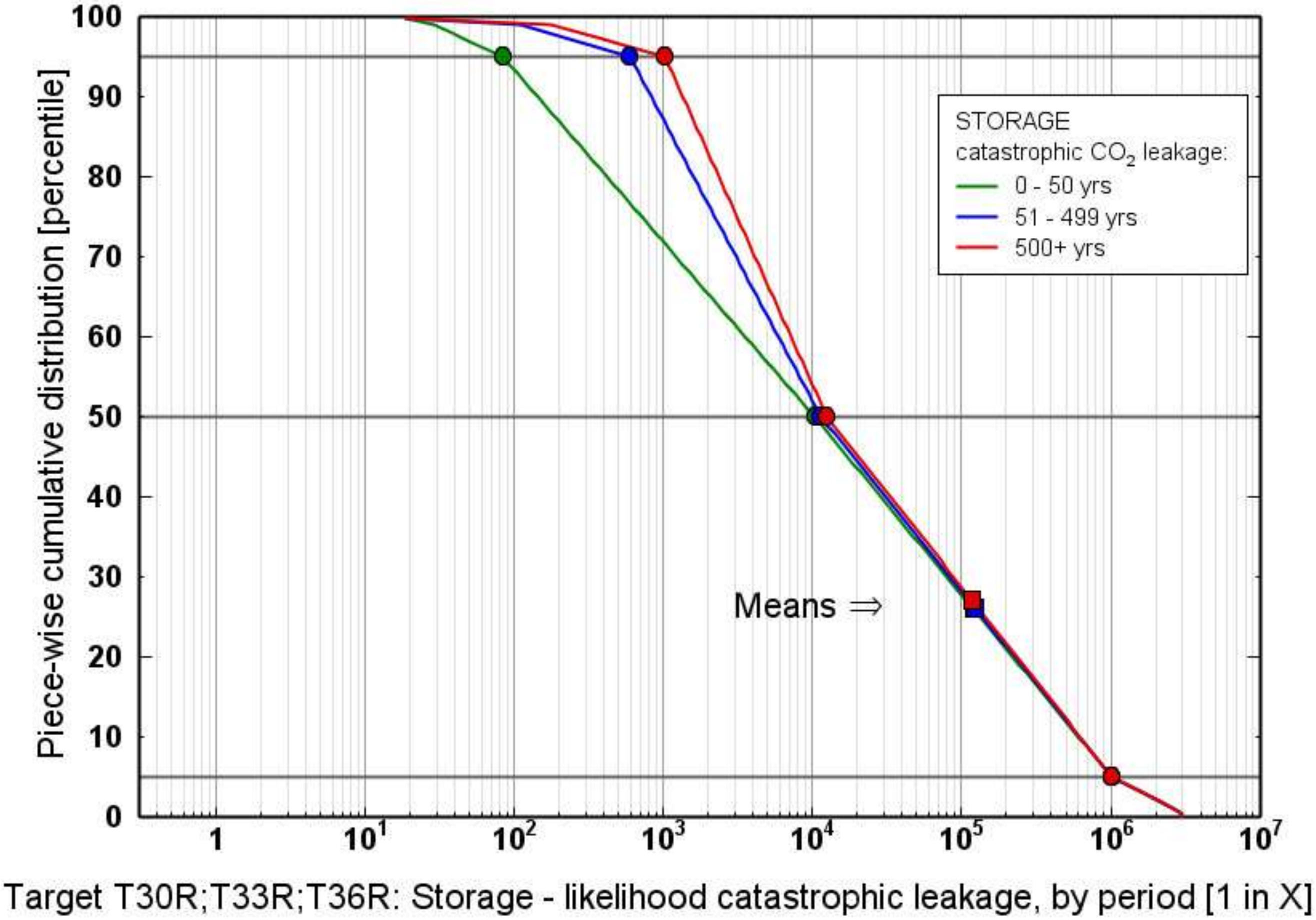
a) Minor leakage b) Major leakage c) Catastrophic leakage

Storage Leakage Likelihood				
Period/Leakage	Lower limit (5th percentile)	Mean	Central value (median)	Upper limit (95th percentile)
0-50 years				
[T28R] Minor	1 in 1520 (1 in 5730)	170 (530)	1 in 13 (1 in 18)	1 in 1.4 (1 in 1.0)
[T29R] Major	1 in 96,400 (1 in 78,400)	11,200 (6900)	1 in 1030 (1 in 180)	1 in 35 (1 in 12)
[T30R] Catastrophic	1 in 1 million (1 in 1 million)	116,000 (95,500)	1 in 10,300 (1 in 3440)	1 in 83 (1 in 59)
51-499 years				
[T31R] Minor	1 in 2070 (1 in 25,000)	210 (1910)	1 in 9.9 (1 in 24)	1 in 2 (1 in 1)
[T32R] Major	1 in 16,100 (1 in 75,000)	2900 (7500)	1 in 890 (1 in 360)	1 in 57 (1 in 7)
[T33R] Catastrophic	1 in 1 million (1 in 1 million)	119,000 (92,000)	1 in 11,300 (1 in 2750)	1 in 595 (1 in 80)
Over 500 years				
[T34R] Minor	1 in 8,340 (1 in 152,000)	780 (11,000)	1 in 27 (1 in 86)	1 in 2 (1 in 1)
[T35R] Major	1 in 172,000 (1 in 630,000)	18,300 (52,900)	1 in 1200 (1 in 1000)	1 in 100 (1 in 8)
[T36R] Catastrophic	1 in 1 million (1 in 1 million)	122,000 (136,000)	1 in 12,500 (1 in 20,000)	1 in 1020 (1 in 86)



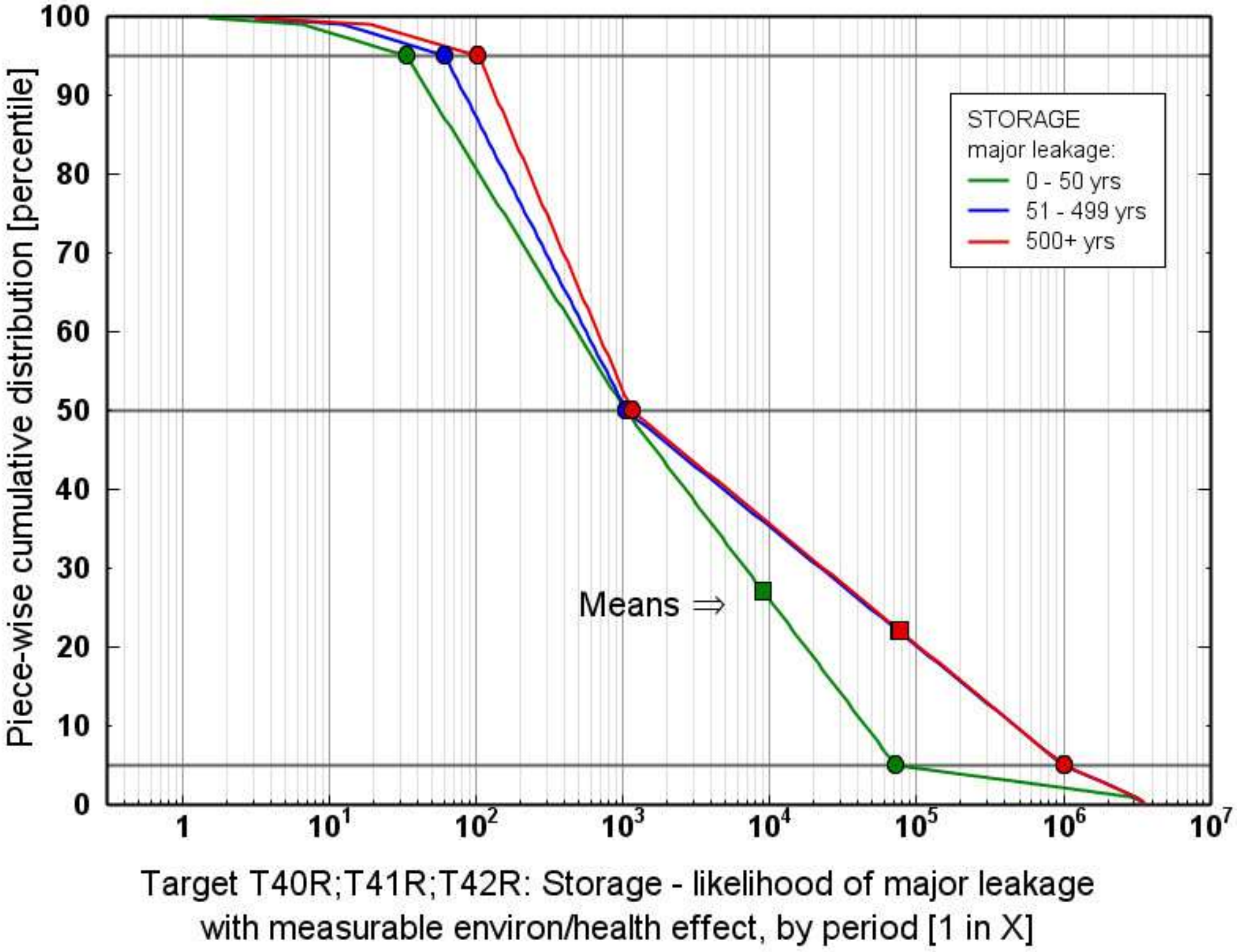
100
90
80
70
60
50
40
30
20
10
0
Piece-wise cumulative distribution [percentile]
STORAGE
minor CO_2 leakage:
0 - 50 yrs
51 - 499 yrs
500+ yrs
Means ⇒
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Target T28R;T31R;T34R: Storage - likelihood of minor leakage, by period [1 in X]


100
90
80
70
60
50
40
30
20
10
0
Piece-wise cumulative distribution [percentile]
STORAGE
major CO_2 leakage:
0 - 50 yrs
51 - 499 yrs
500+ yrs
Means ⇒
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Target T29R;T32R;T35R: Storage - likelihood of major leakage, by period [1 in X]


Piece-wise cumulative distribution [percentile]
100
90
80
70
60
50
40
30
20
10
0
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
STORAGE
catastrophic CO$_2$ leakage:
0 - 50 yrs
51 - 499 yrs
500+ yrs
Means ⇒
Target T30R;T33R;T36R: Storage - likelihood catastrophic leakage, by period [1 in X]

T40-42Rev: In a typical saline aquifer storage site, what is the likelihood of major CO_2 leakage that would result in measurable negative environmental impact or adverse public health impact in each of the time periods (1 in X, where X≥1; for example, 1 in 100 would represent a 1% likelihood)?

Time period (years)	Lower limit (5th percentile)	Mean	Central Value (median)	Upper limit (95th percentile)
[T40R] 0-50 yrs	1 in 71,900 (1 in 821,000)	8900 (58,900)	1 in 1030 (1 in 420)	1 in 33 (1 in 15)
[T41R] 51-499 yrs	1 in 1 million (1 in 1 million)	78,900 (69,700)	1 in 1050 (1 in 360)	1 in 61 (1 in 22)
[T42R] 500+ yrs	1 in 1 million (1 in 1 million)	79,900 (76,100)	1 in 1140 (1 in 736)	1 in 103 (1 in 15)



Section 4 – Likelihood and Severity
Injection and Storage Hazards

Part A: Likelihood and severity mean rating and uncertainty

Four hazard circumstances were assessed: Leakage from Wells, Injection, Inherent Storage Hazards and Induced Storage Hazards. The following charts and graphs depict (i) the count of the likelihood and severity responses for each level and (ii) the mean rating value with standard error. The latter was calculated by first assigning a multiplier to each level of the Likert scale: 1 for Level 1; 2 for Level 2 … through 5 points for Level 5 responses; the total sum of points including all experts was then divided by the number of expert responses.

Questions:

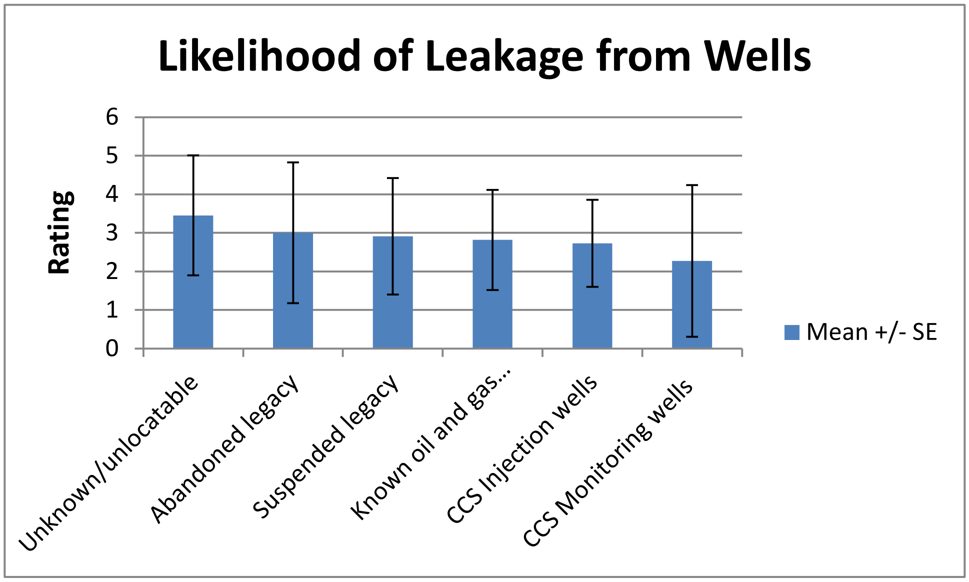
Please rate the likelihood of each of the hazards associated with injection and storage phases of CCS using the following 5-point Likert scale:

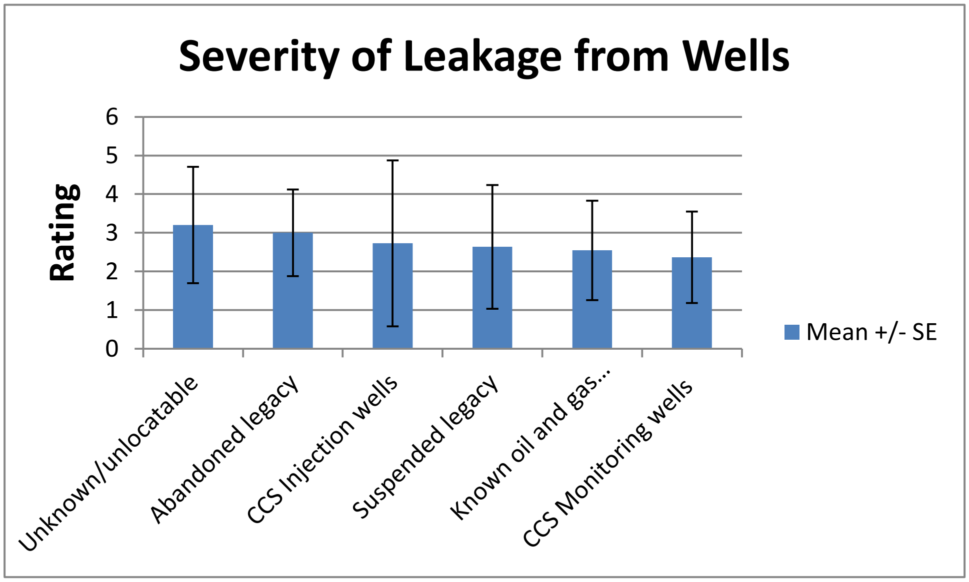
Likelihood	**Level**	**If there were 100 similar projects, frequency of this hazard element would occur . . .**
Improbable	1	Probably not at all, never
Unlikely	2	Fewer than three times among the 100 projects
Possible	3	5–10 times among the 100 projects
Likely	4	In around half of the 100 projects
Probable	5	In most or nearly all of the projects

Should a hazard exist, please rate the severity using the following 5-point Likert scale:

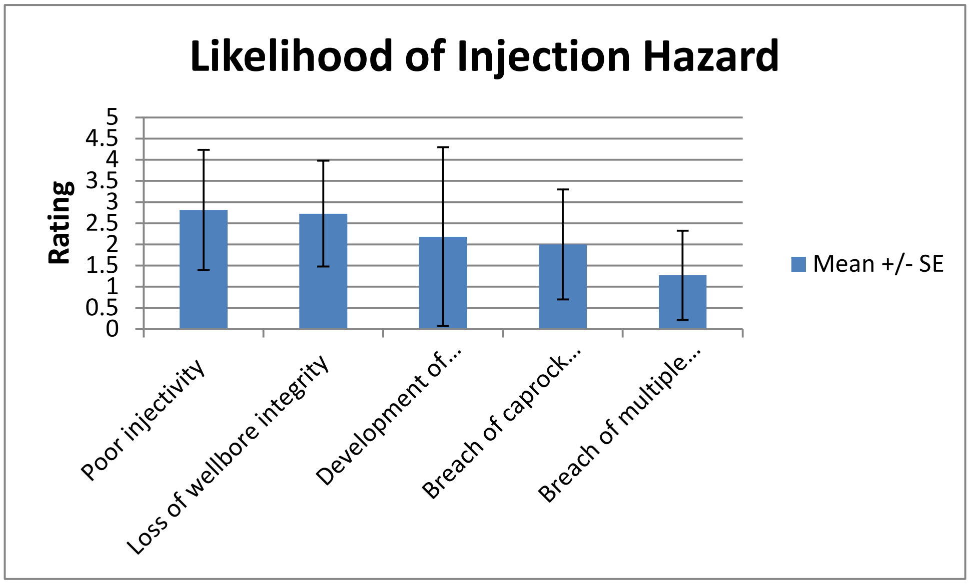
Severity	**Level**	**Change in state**
Light	1	No modification to initial state
Serious	2	Modification to initial state within acceptable limits
Major	3	Modification to initial state above acceptable limits but without damage
Catastrophic	4	Modification to initial state above acceptable limit with repairable damage
Multi-catastrophic	5	Considerable modifications to initial state which is not repairable with existing technologies

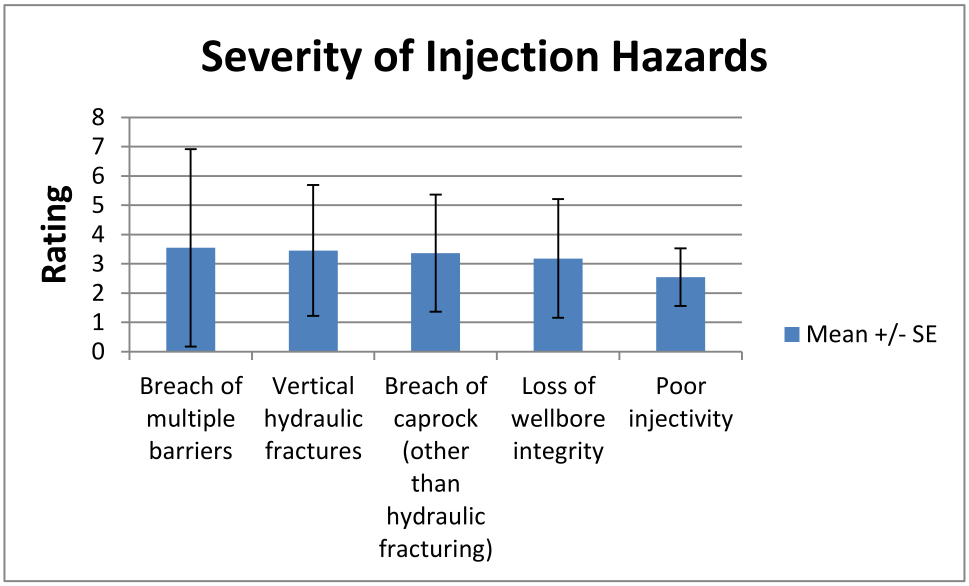
Well leakage hazards



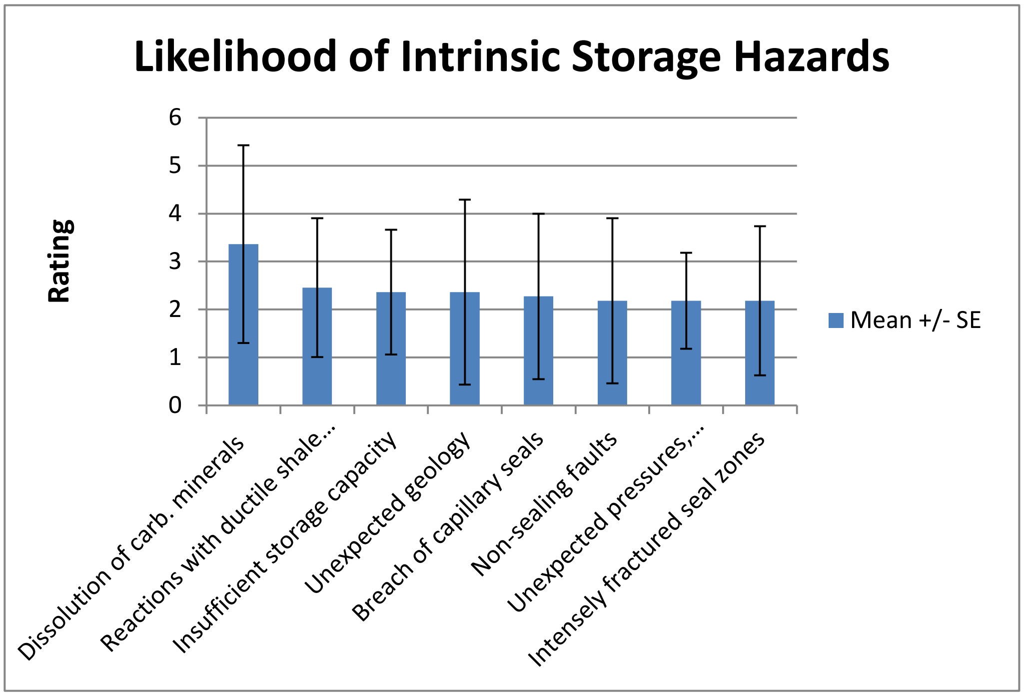


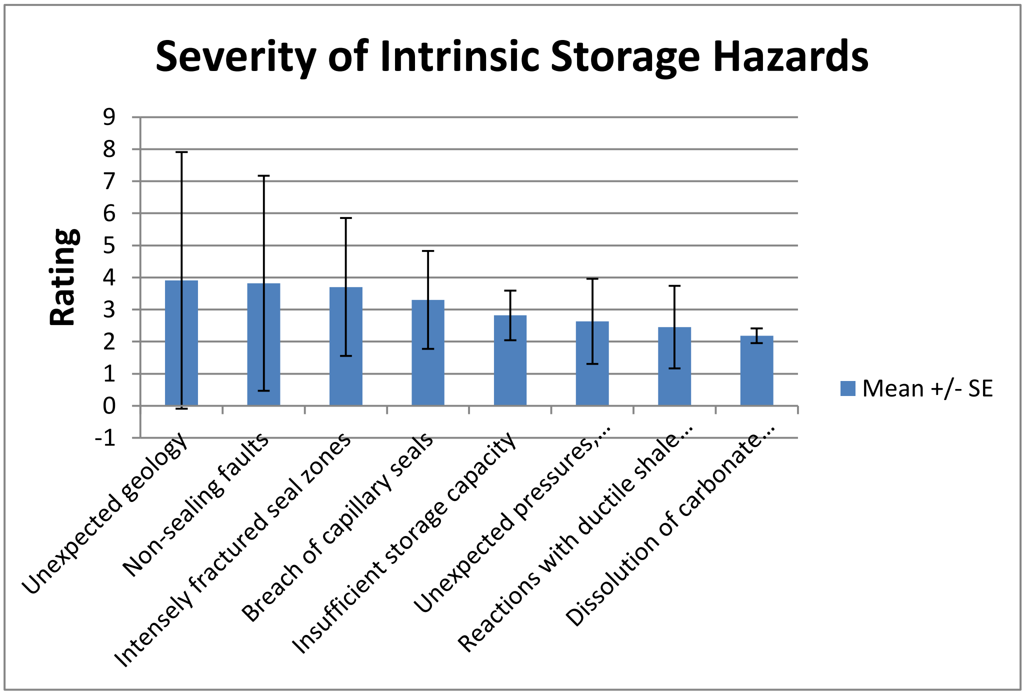
Injection Hazards



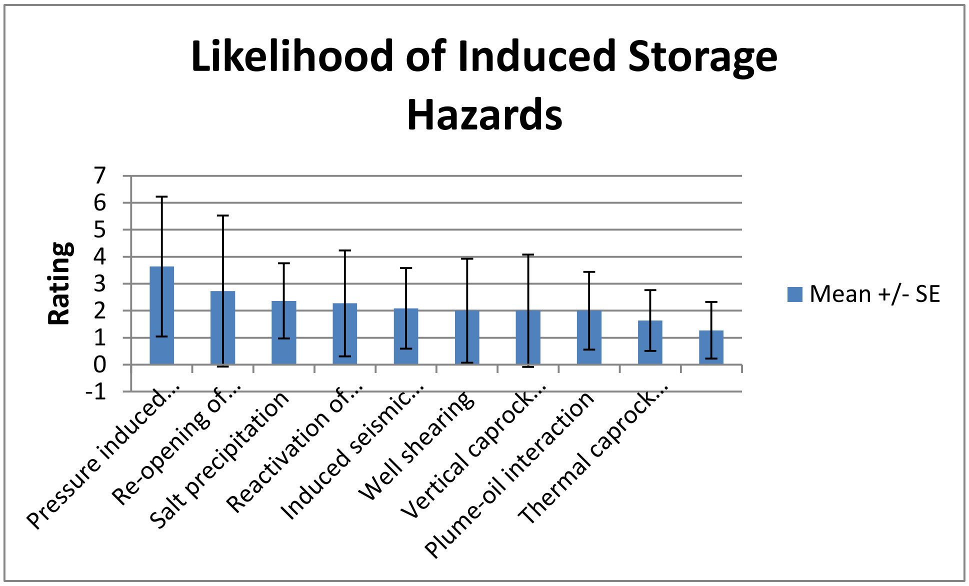


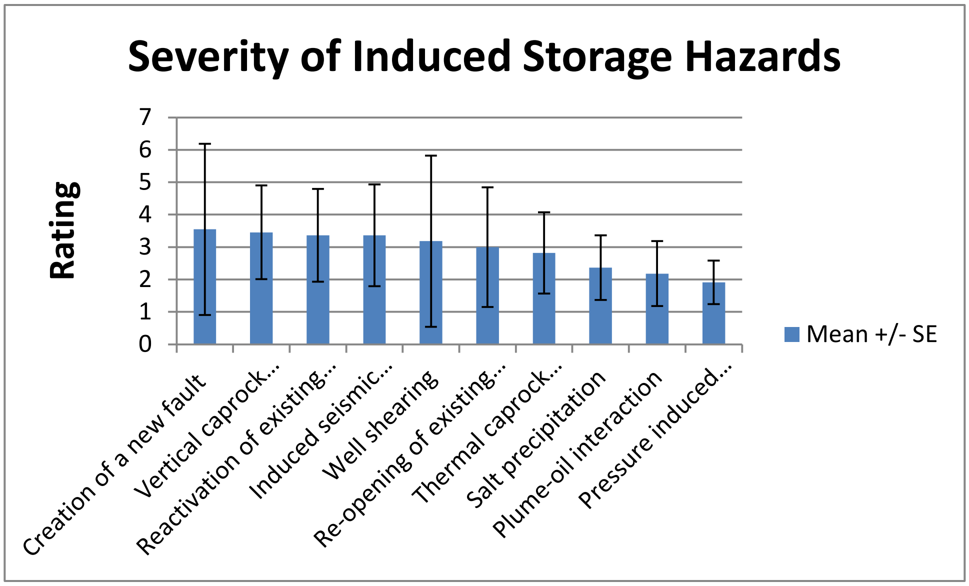
Intrinsic storage hazards





Induced Storage Hazards





Risk Matrix guide

Risk matrices reflect classes of risk based on combined likelihood (probability) and severity (consequence) of hazards.

	Severity						
			1	2	3	4	5
			Light	Serious	Major	Catastrophic	Multi Catastrophic
Likelihood	5	Probable	Medium	High	High	Very high	Very high
	4	Likely	Low	Medium	High	High	Very high
	3	Possible	Low	Medium	Medium	High	High
	2	Unlikely	Low	Medium	Medium	Medium	High
	1	Improbable	Low	Low	Low	Medium	High

Section 5 –
Estimates of Leakage Amounts, Probabilities, or Failure Rates

Chain activity	Context	Value	Reference
Estimated quantities			
Transport	Gorgon aquifer sequestration project Compression or transport failure	$1.4x10^{-3}$ - $1.4x10^{-1}$ t/yr/ m^2	Koornneef et al. (2012)
Transport	Upper limit constrained by pipeline flow rates	(e.g., ~3 ktonnes/day at the Sleipner field)	Jones et al. (2015)
Transport	Failure scenarios, pressure, pipeline diameter, section length, assumed critical CO2 exposure threshold, calculated maximum distance to threshold, distance to individual	Various	Koornneef et al. (2012)
Transport	Seepage Catastrophic operational failures	<1 tonne/day >1 ktonne d/day	IEA, 2008 in Jones et al. (2015).
Abandoned wells		10–100 t/day	IEA, 2008 in Jones et al. (2015).
Storage	Seepage Geological discontinuities Catastrophic operational failures	<1 tonne/day 10–100 tonnes/day >1 ktonne d/day	IEA, 2008 in Jones et al. (2015)
Storage	Shell Quest project (Alberta, Canada): Mass of CO_2 emissions	Zero	Shell Canada Limited (2011b)
Storage	FutureGen Project Leakage into non-target aquifer Leakage through caprock, induced faults	$1.39x10^{-3}$ - $2.36x10^{-1}$ t/yr/m^2 $1.39x10^{-3}$ - $4.17x10^{-2}$ t/yr/m^2	Koornneef et al. (2012)
To surface	Gorgon aquifer sequestration project Migration along wells, faults or fractures Failure of structural seals	$1.4x10^{-3}$ - $1.4x10^{-1}$ t/yr/ m^2	Koornneef et al. (2012)
Estimated percentage			
Intact caprock	North Sea - Mass of CO_2 as a fraction of total mass injected (providing thickness is greater than 50 m and permeability is less than 0.01mD):	Less than 0.001% after 200 years	Matthias (2012)
To surface	Frio Formation – aquifer sequestration	10% of CO_2 in place (max 3750 t) returned to the surface over a 1-year period	Koornneef et al. (2012)
Estimated probability			
Injection well	FutureGen – Jewett site Equipment rupture	6-in-100,000 (0.006%)	
Injection well	North Sea: 5-well project over a 20 year operating period; probability of migration not necessarily into biosphere	0.1% probable injection well failure	Bellarby (2012)
Abandoned wells	North Sea: Migration to an upper horizon outside the storage complex, not necessarily into biosphere	Probability 0.22 over 1000 years	Bellarby (2012)
Geological leakage	FutureGen – Jewett site		Trabucchi et al.

scenarios	Rapid leakage through caprock Slow leakage through caprock Release through existing, induced faults	2-in-10 billion 4-in-100,000 2-in-100 million	(2012)
Geological leakage scenarios	CO2CRC's Otway Project risk assessment workshops – eg 2 of 13 risk events Fault Junction Local overpressurization	Normalised Risk Quotient ~0.02 – 0.15 1E-08	Watson (2014)

References – Estimates of Leakage Amounts

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Appendix D: Supplementary Material – Chapter 5

Elicitation Experts, Affiliations, Expertise

Australia

- Lincoln Paterson, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia – rock mechanics, deep basin disposal of carbon dioxide, physical processes in rock behavior, thermal effects

Canada

- Stefan Bachu, Alberta Innovates, Technology Futures - fluid flow, sequestration in saline aquifers, well integrity
- Rick Chalaturnyk, University of Alberta - geomechanics, caprock integrity, monitoring, well integrity
- William Gunter, Distinguished Scientist (retired), Alberta Innovates, Technology Futures - geochemistry, fluid-rock reactions
- Richard Jackson, Adjunct Faculty, University of Waterloo – characterization, migration, and fate of non-aqueous phase liquids in subsurface
- Don Lawton, University of Calgary - geophysics, seismology, monitoring
- David Ryan, Natural Resources Canada – Geochemistry of CO2 and impurities in saline reservoirs, wellbore and caprock integrity, monitoring, measurement, and verification technologies

Europe

- Jean-Pierre Deflandre, IFP Energies nouvelles, France – EOR, rock mechanics, hydraulic fracture mapping, monitoring (passive seismic data acquisition, interpretation), gas storage geomechanical survey
- Ton Wildenborg, Netherlands Organisation for Applied Scientific Research (TNO) – sedimentology, basin analysis and exploration geophysics; risk assessment of CO2 storage and radioactive waste disposal in the deep subsurface

Saudi Arabia

- J. Carlos Santamarina, King Abdullah University of Science and Technology, Saudi Arabia – geotechnical engineering, subsurface processes, sequestration in saline aquifers

USA

- Michael Celia, Princeton University - groundwater hydrology, multi-phase flow in porous media, numerical modeling, and subsurface energy systems
- Curtis Oldenburg, Lawrence Berkeley National Laboratory - near-surface leakage and seepage processes, monitoring, detection, and impacts including risk-based frameworks for site selection and certification

Risk Management in Carbon Capture and Geological Storage: Insights from a structured expert elicitation

Supplementary Material

Patricia Larkin[1], Robert Gracie[2], Maurice Dusseault[2], Ali Shafiei[2],
Mirhamed (Araz) Sarkarfarshi[2], Willy Aspinall[3], Daniel Krewski[1]

Contents

[1]University of Ottawa
[2]University of Waterloo
[3]University of Bristol

Section 1
Classical Model solutions for CCS Target Items

Using the Classical Model method of Cooke (1991), a positive performance weight was achieved on the calibration questions with a Decision Maker weight of 75%.

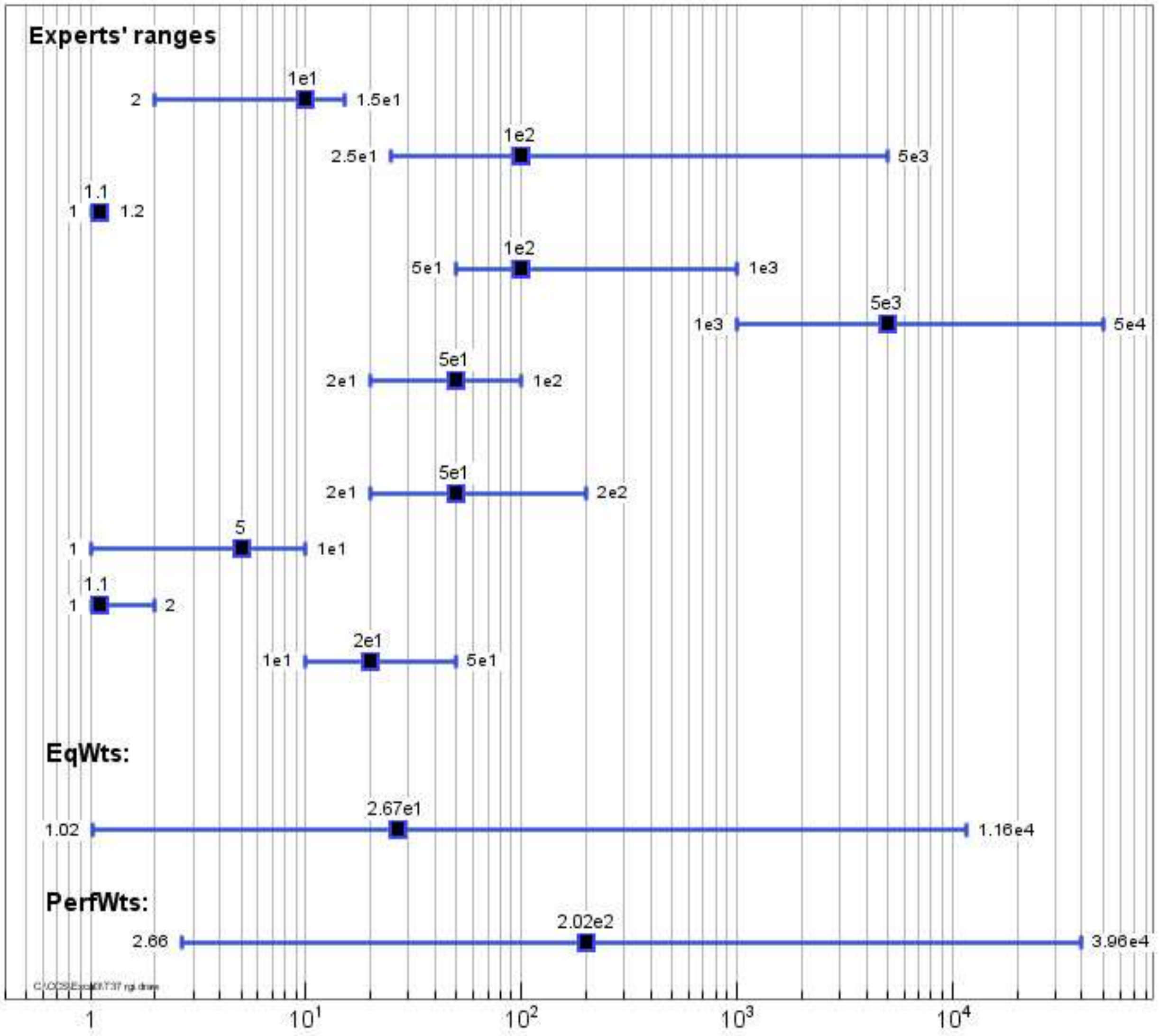
For several Target Items, Performance Weights (PW) solution quantiles are expressed as values of X, where X is a probability or likelihood defined in terms of “1-in-X”; corresponding Equal Weights EW solutions are given in brackets: e.g.: “(1 in X)”. Graphs depict individual Expert and pooled uncertainty distribution ranges. Some values are shown in scientific exponent notation “x.xx***e***n” for display compactness.

T37-T39Rev: From an engineering design perspective for CO_2 storage, this triplet of questions concerns the upper limit on the likelihood of minor, major, and catastrophic leakage.

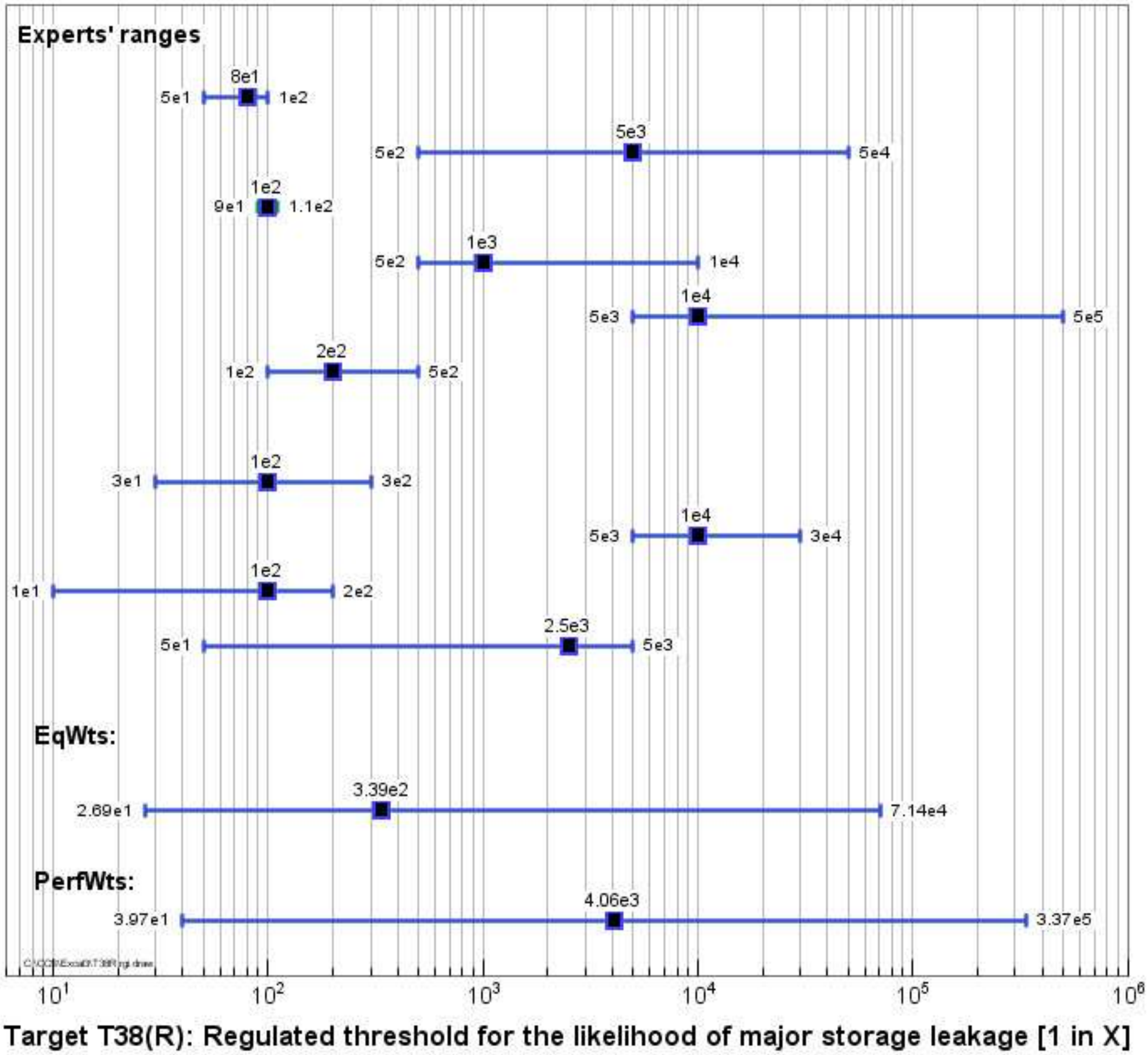
Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014).

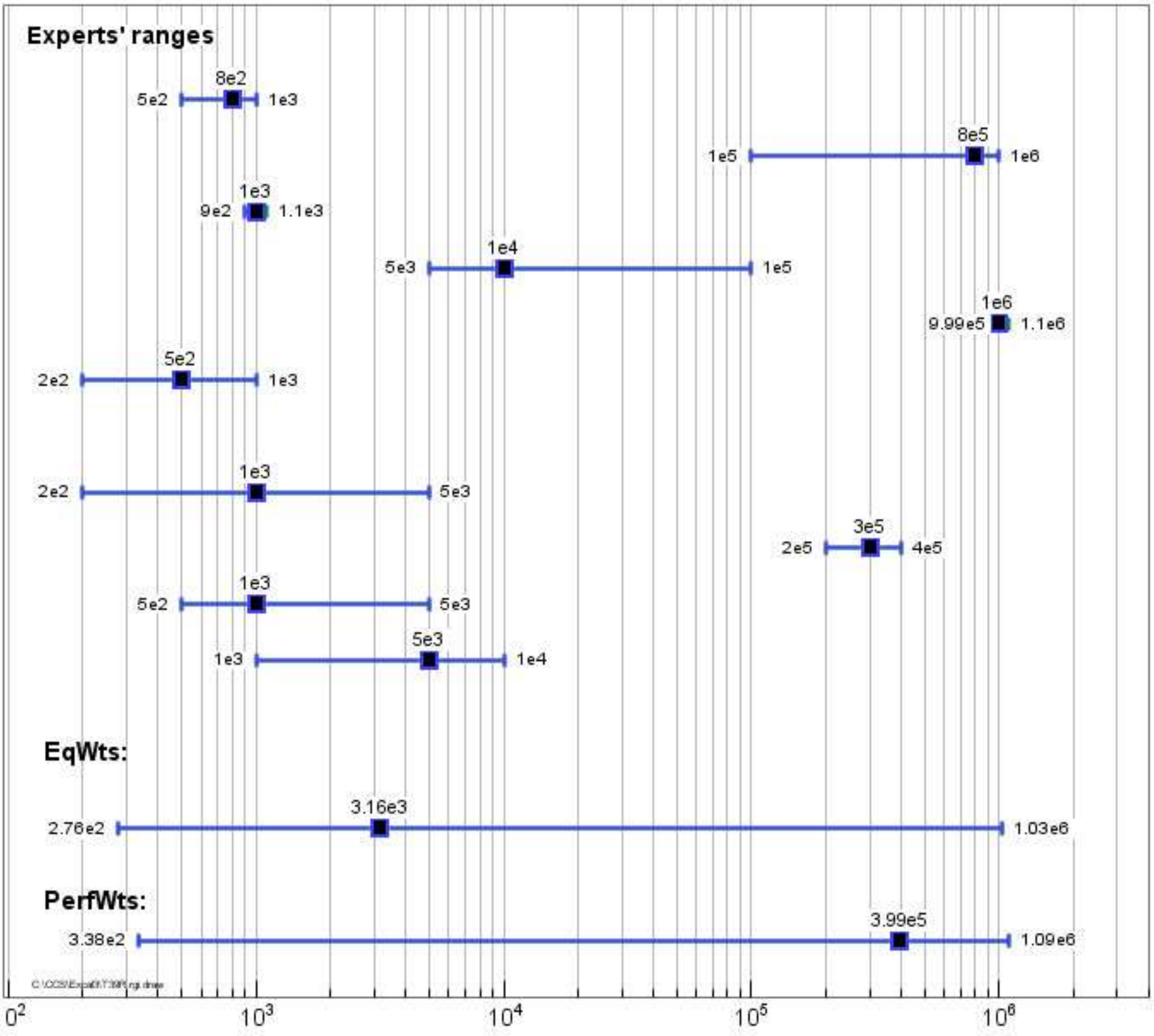
T37-39Rev. What should be the regulated threshold for the likelihood of minor, major or catastrophic storage leakage in a LSIP sequestration project (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?
e) Minor leakage b) Major leakage c) Catastrophic leakage

Leakage	Lower limit (5th percentile)	Mean	Central Value (median)	Upper limit (95th percentile)
[T37R] Minor	1 in 39,600 (1 in 11,600)	4000 (1020)	1 in 202 (1 in 27)	1 in 2.7 (1 in 1)
[T38R] Major	1 in 337,000 (1 in 71,400)	40,000 (7100)	1 in 4060 (1 in 340)	1 in 40 (1 in 27)
[T39R] Catastrophic	1 in 1.1 million (1 in 1 million)	378,000 (95,000)	1 in 399,000 (1 in 3160)	1 in 338 (1 in 276)



Target T37(R): Regulated threshold for the likelihood of minor storage leakage [1 in X]


Experts' ranges
8e1
5e1
1e2
5e3
5e2
5e4
1e2
9e1
1.1e2
1e3
5e2
1e4
1e4
5e3
5e5
2e2
1e2
5e2
1e2
3e1
3e2
1e4
5e3
3e4
1e2
1e1
2e2
2.5e3
5e1
5e3
EqWts:
3.39e2
2.69e1
7.14e4
PerfWts:
4.06e3
3.97e1
3.37e5
10^1
10^2
10^3
10^4
10^5
10^6
Target T38(R): Regulated threshold for the likelihood of major storage leakage [1 in X]



Target T39(R): Regulated threshold for the likelihood of catastrophic storage leakage [1 in X]

T43-T45Rev: This triplet of questions considers how long a typical saline aquifer storage site would remain safe at ‘low-end’, ‘median’ and ‘high-end’ safe storage periods.

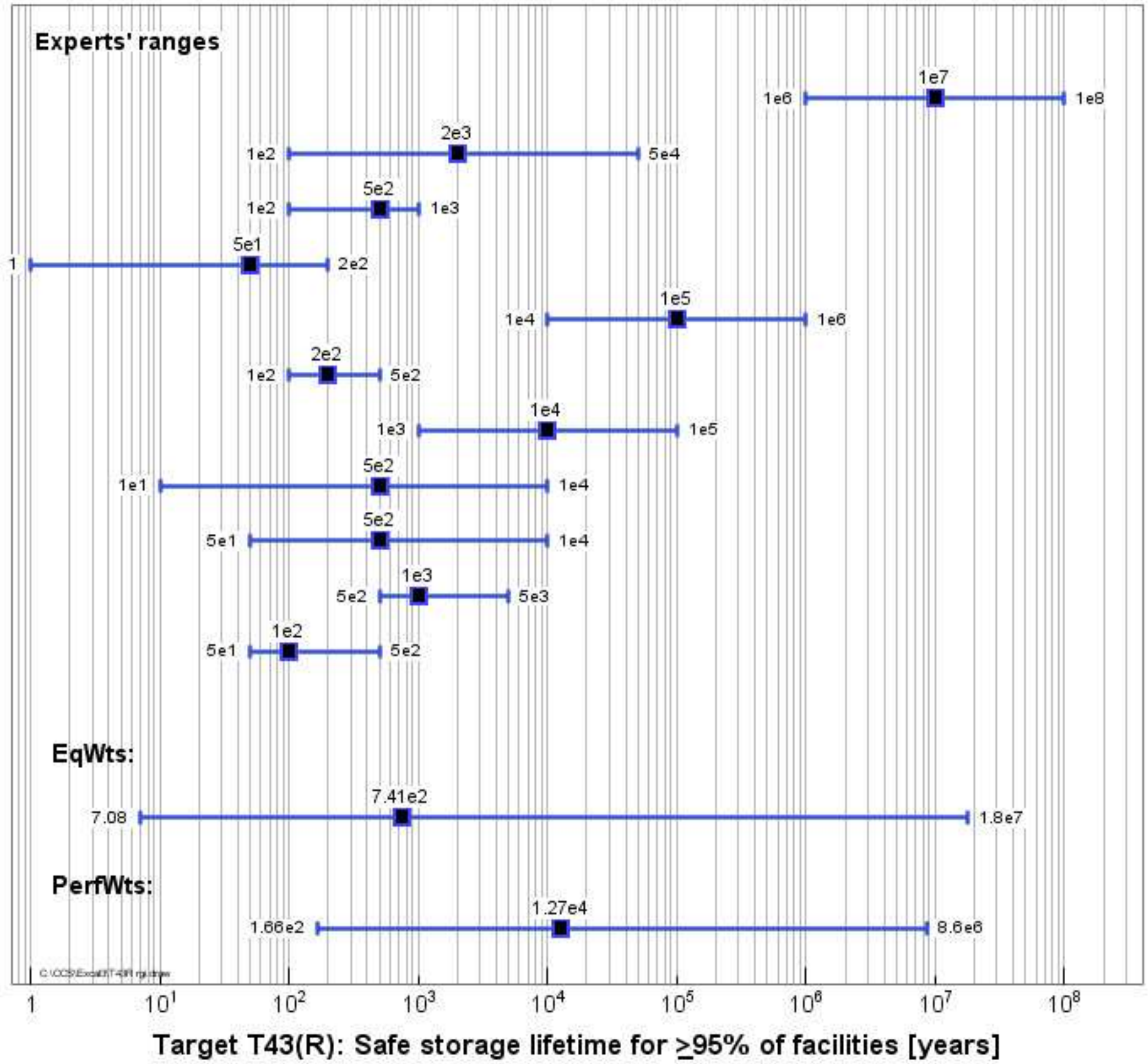
Large scale integrated projects (LSIPs) have capacity for at least 800,000 tonnes of CO_2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation) (GCCSI, 2014). Assuming no fundamental change in technology, what is the safe storage lifetime of a typical saline aquifer storage site at the following confidence levels? Please give three durations to express your uncertainty.

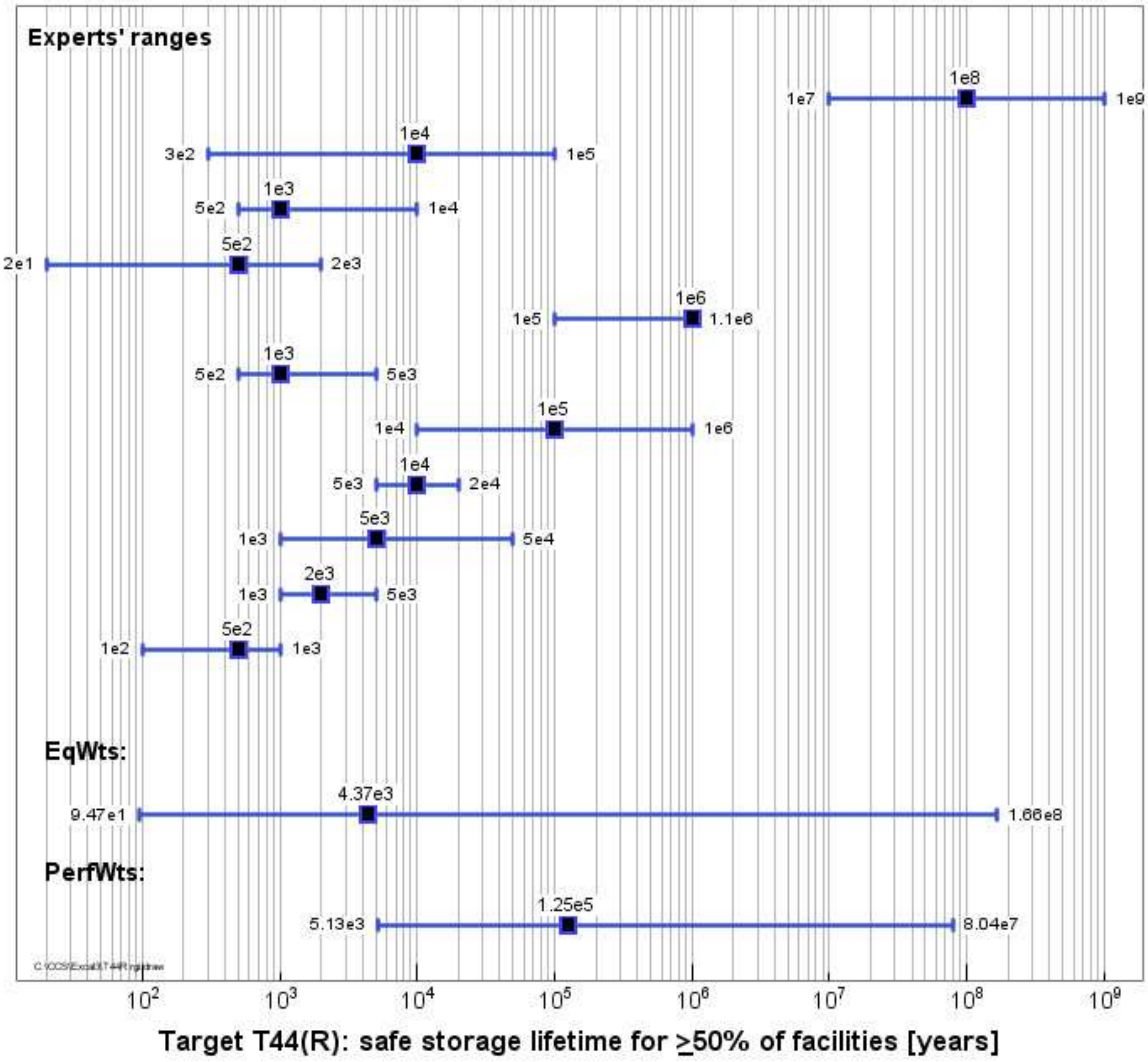
T43Rev: How long will a typical saline aquifer storage site remain safe, where safe means 95% or more facilities will not fail in the time periods you specify (years)?

T44Rev: How long will a typical saline aquifer storage site remain safe, where safe means 50% or more facilities will not fail in the time periods you specify (years)?

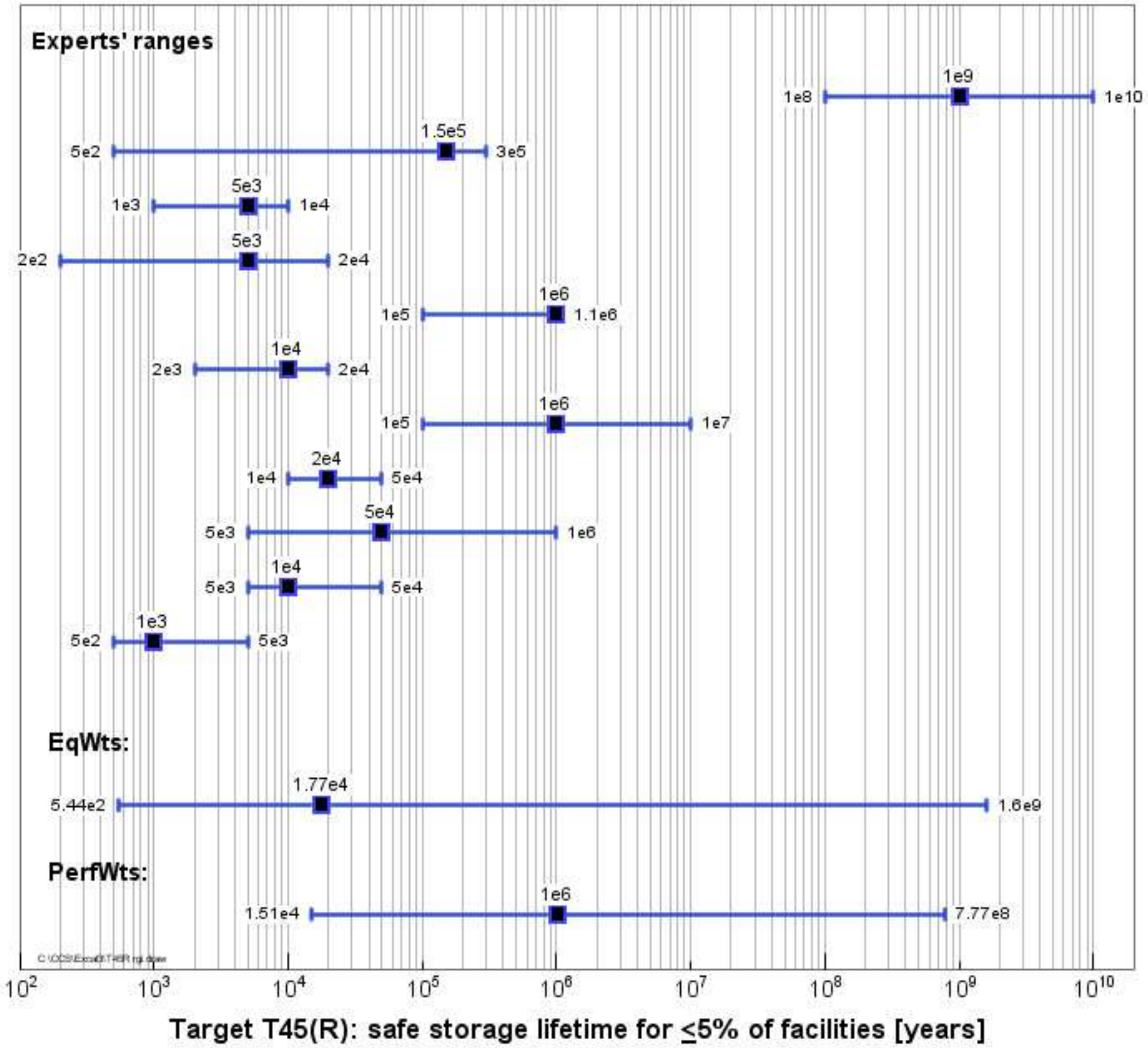
T45Rev: How long will a typical saline aquifer storage site remain safe, where safe means 5% or fewer facilities will not fail in the time periods you specify (years)?

Facilities that will not fail	Safe Storage Lifetime			
	Lower limit (5th percentile)	Mean	Central Value (median)	Upper limit (95th percentile)
[T43R] 95% or more facilities	8.6 million yrs (18 million yrs)	70,900 (994,000)	12,700 yrs (740 yrs)	166 yrs (7 yrs)
[T44R] 50% or more facilities	80 million yrs (166 million yrs)	6.7e+6 (8.8e+6)	125,000 yrs (4370 yrs)	5130 yrs (95 yrs)
[T45R] 5% or fewer facilities	780 million yrs (1,600 million yrs)	63e+6 (79e+6)	1 million yrs (17,700 yrs)	15,100 yrs (544 yrs)


Experts' ranges
1e6
1e7
1e8
1e2
2e3
5e4
1e2
5e2
1e3
1
5e1
2e2
1e4
1e5
1e6
1e2
2e2
5e2
1e3
1e4
1e5
1e1
5e2
1e4
5e1
5e2
1e4
5e2
1e3
5e3
5e1
1e2
5e2
EqWts:
7.08
7.41e2
1.8e7
PerfWts:
1.66e2
1.27e4
8.6e6
1
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Target T43(R): Safe storage lifetime for ≥95% of facilities [years]



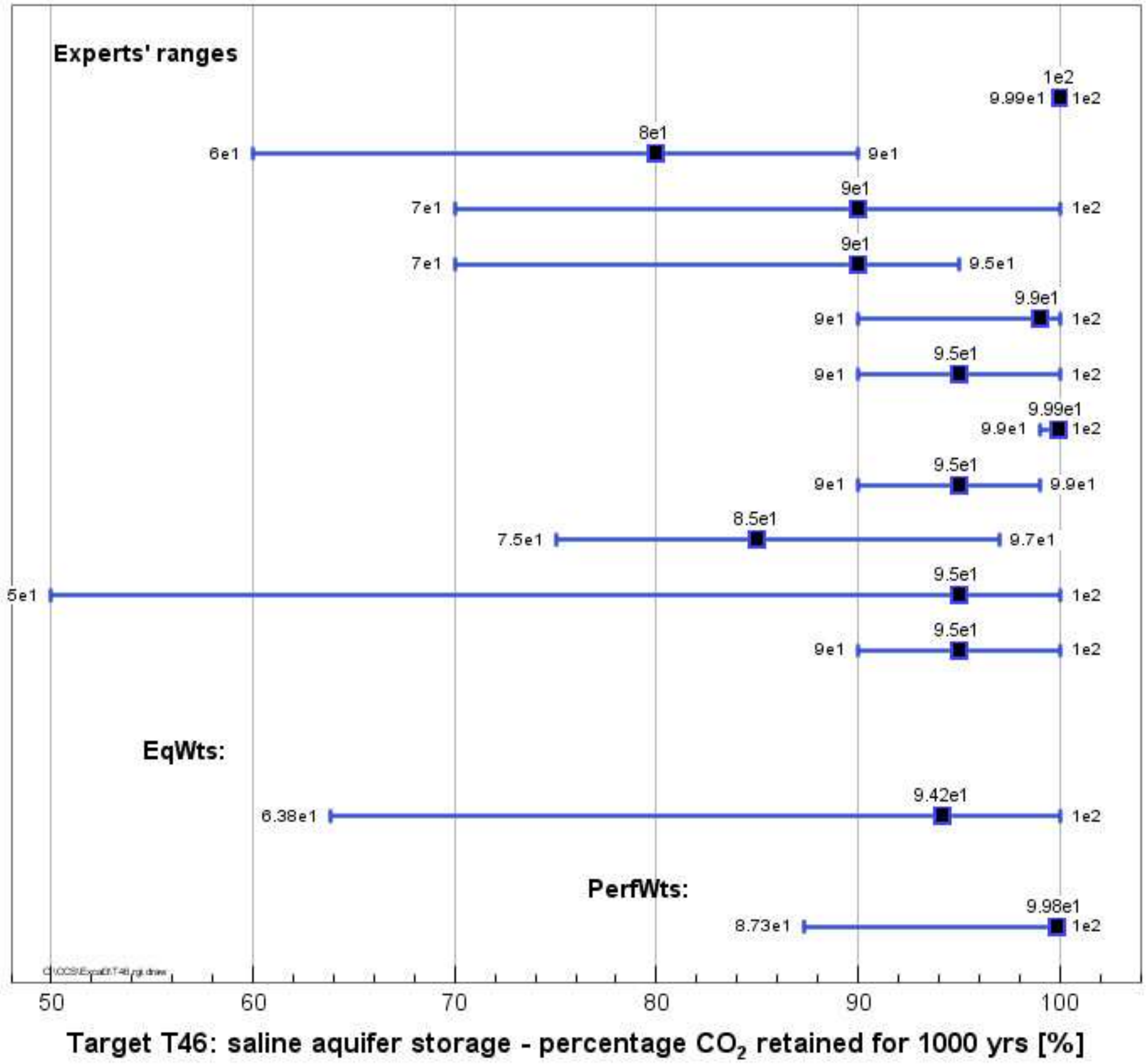
Experts' ranges
1e7
1e8
1e9
3e2
1e4
1e5
5e2
1e3
1e4
2e1
5e2
2e3
1e5
1e6
1.1e6
5e2
1e3
5e3
1e4
1e5
1e6
5e3
1e4
2e4
1e3
5e3
5e4
1e3
2e3
5e3
1e2
5e2
1e3
EqWts:
9.47e1
4.37e3
1.66e8
PerfWts:
5.13e3
1.25e5
8.04e7
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Target T44(R): safe storage lifetime for ≥50% of facilities [years]



Experts' ranges
1e8
1e9
1e10
5e2
1.5e5
3e5
1e3
5e3
1e4
2e2
5e3
2e4
1e5
1e6
1.1e6
2e3
1e4
2e4
1e5
1e6
1e7
1e4
2e4
5e4
5e3
5e4
1e6
5e3
1e4
5e4
5e2
1e3
5e3
EqWts:
5.44e2
1.77e4
1.6e9
PerfWts:
1.51e4
1e6
7.77e8
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Target T45(R): safe storage lifetime for ≤5% of facilities [years]

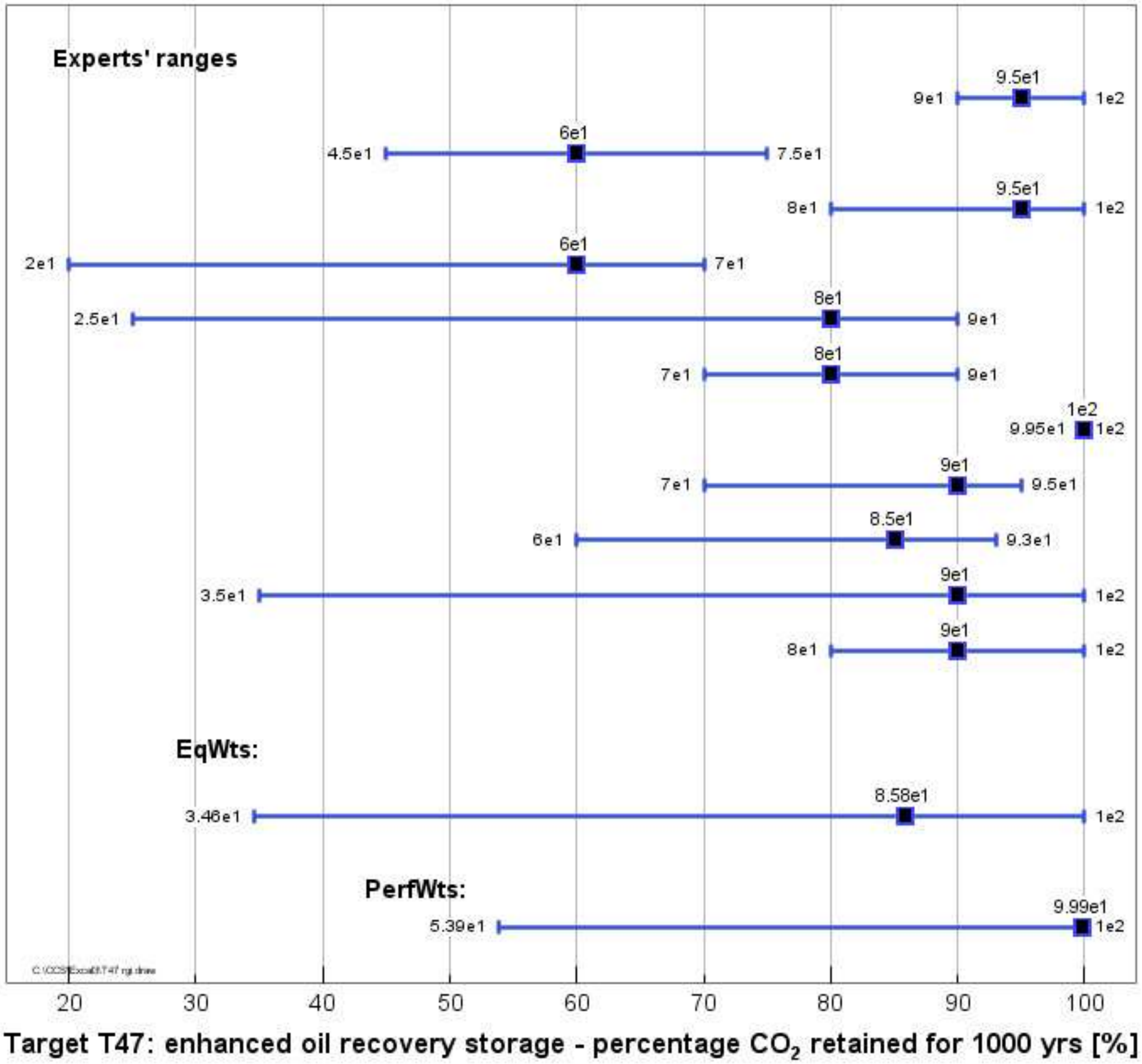
T46: In a typical large scale integrated *saline aquifer storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
87.% (63.8%)	97.7% (89%)	99.8% (94.2%)	100% (100%)



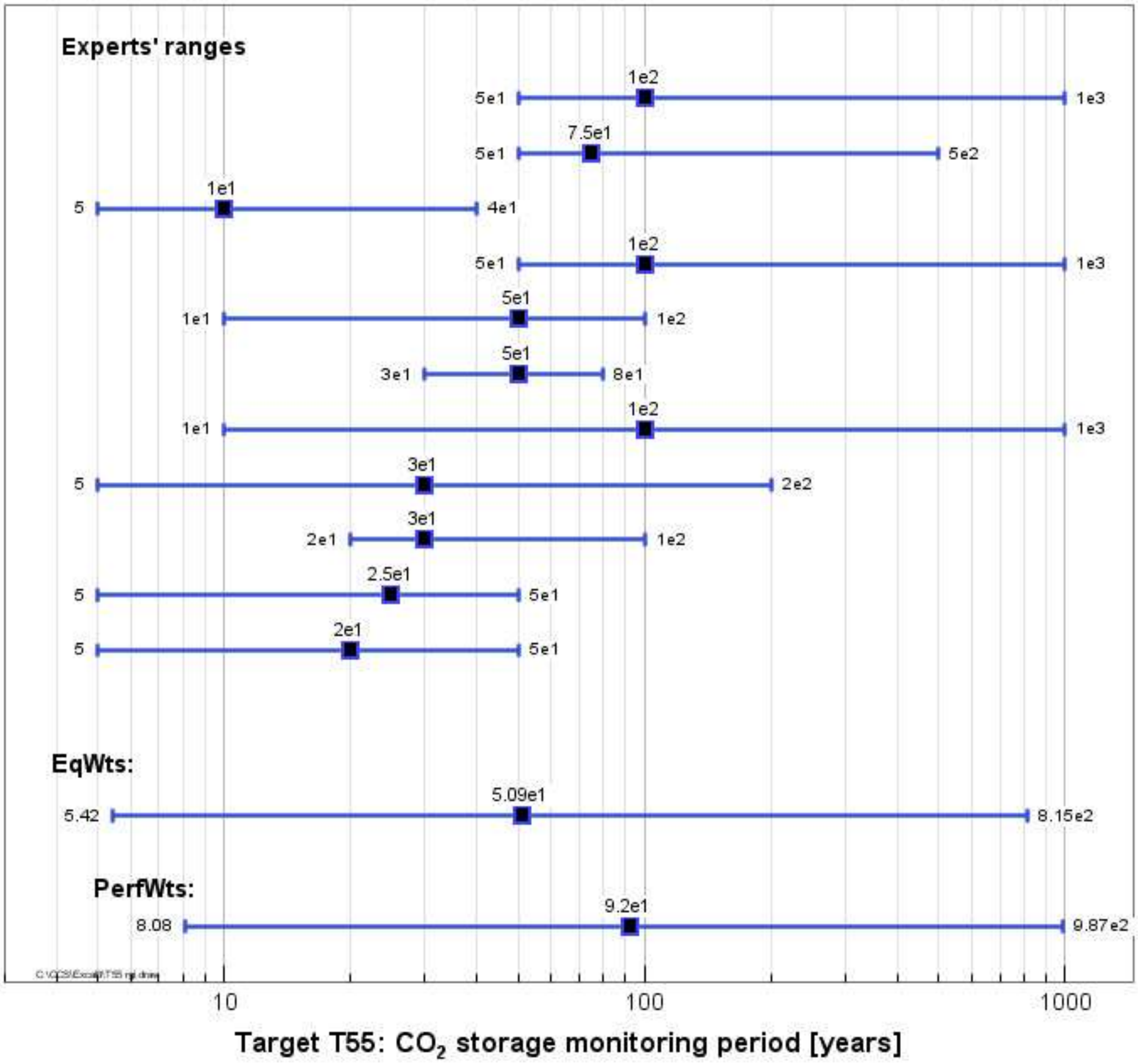
T47: In a typical large scale integrated *enhanced oil recovery storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
54% (35%)	89% (77%)	99.85% (85.8%)	100% (99.98%)



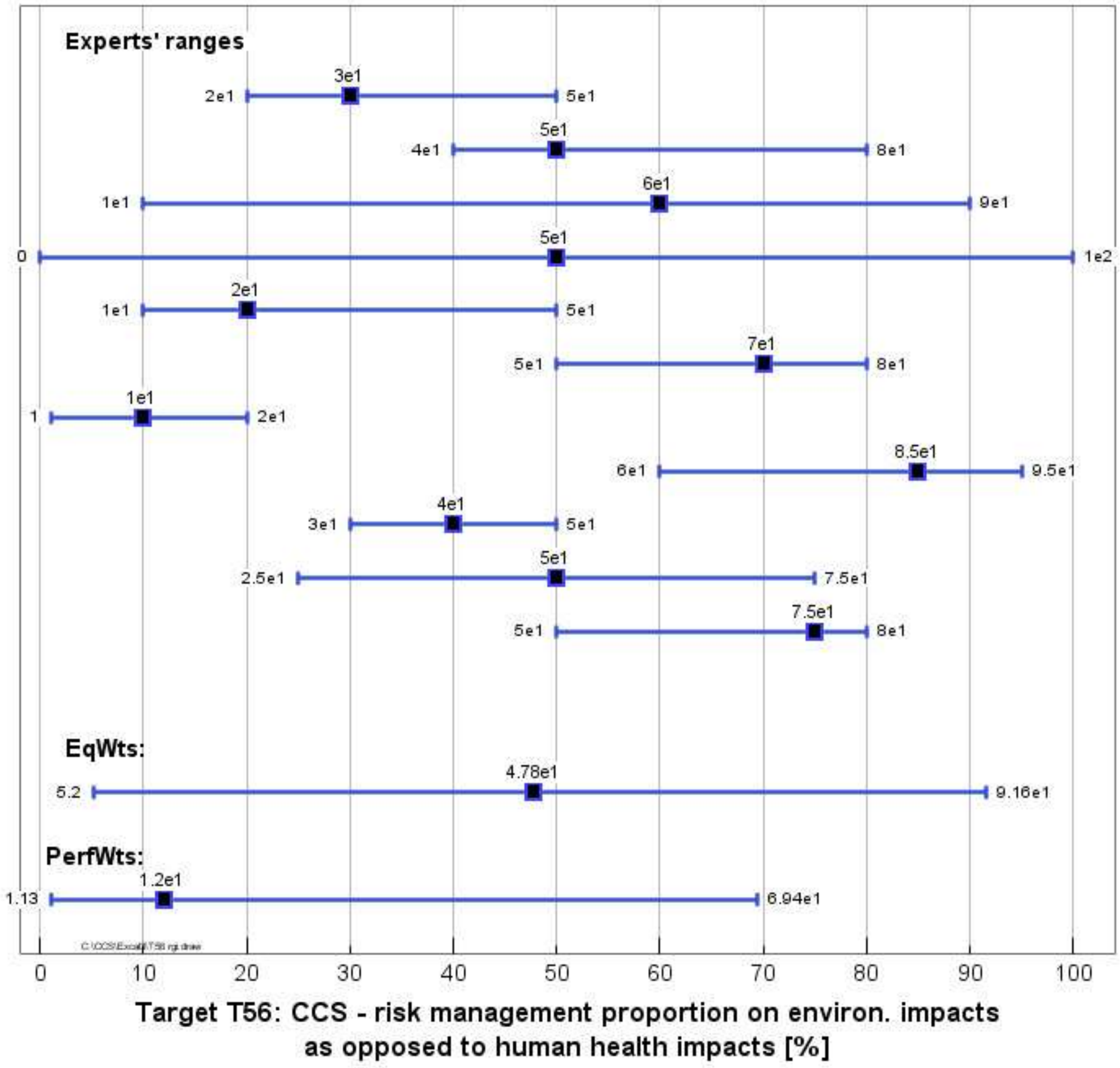
T55: What should be the storage project monitoring period (years)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
8 yrs (5.4 yrs)	300 yrs (235 yrs)	92 yrs (51 yrs)	990 yrs (815 yrs)



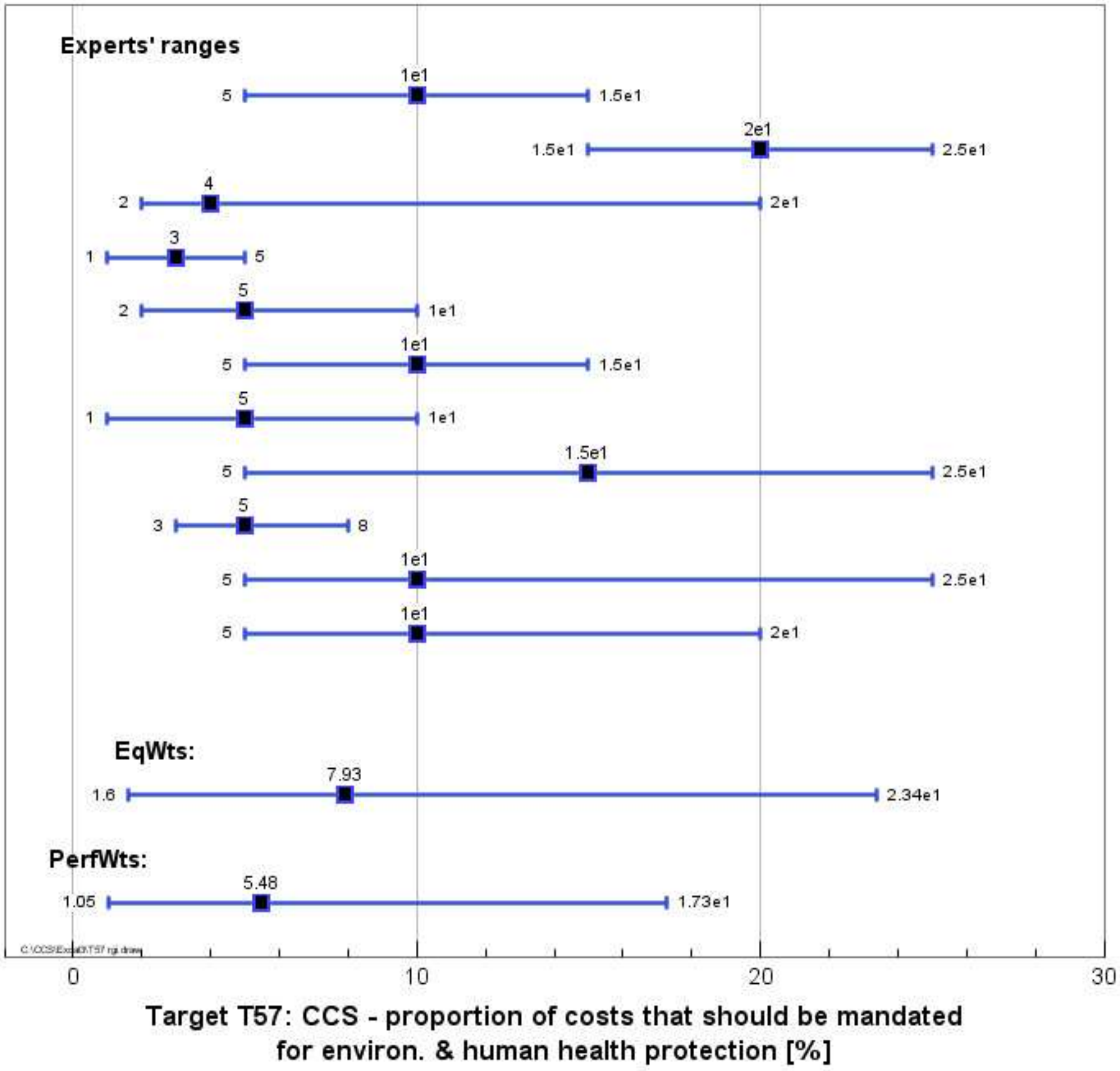
T56: Considering potential negative impacts of CCS on either the environment or human health, what proportion of risk management should be focused on mitigating environmental impacts as opposed to human health impacts (0-100%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (5.2%)	24% (49%)	12% (48%)	69% (92%)



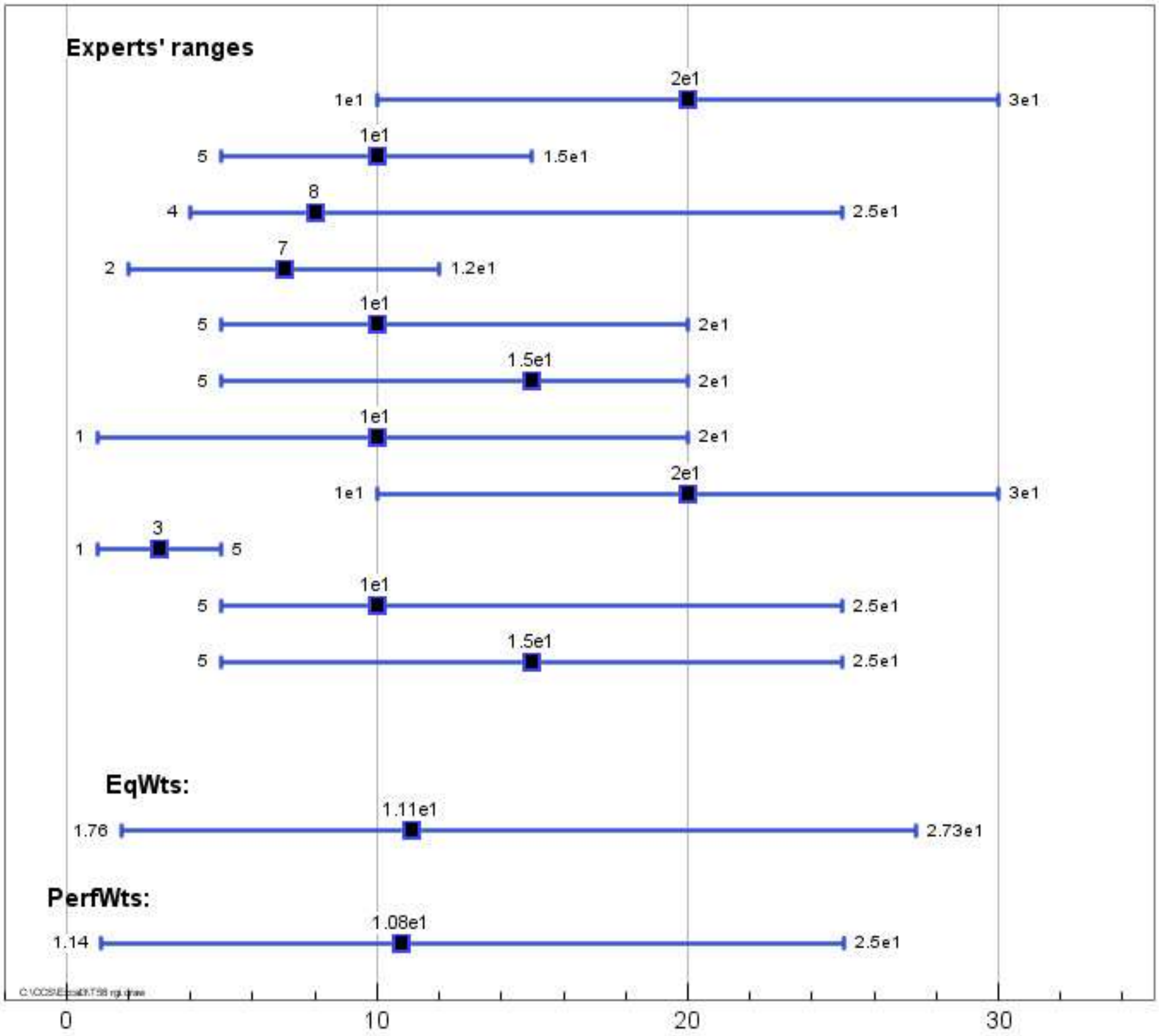
T57: On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (1.6%)	7.3% (10%)	5.5% (7.9%)	17% (23%)



T58: Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (1.8%)	11% (13%)	11% (11%)	25% (27%)



Target T58: CCS - avoiding gross negligence exposure: proportion of annual budget that should be commited to mitigating environ. & human health impacts [%]

Section 2
Composite plots of linked piecewise uncertainty distributions

The following plots show the Performance Weights (PW) solution quantiles and piecewise cumulative uncertainty distributions for compound target questions – i.e. those items which have one or more counterpart scenarios with different or alternative conditions.

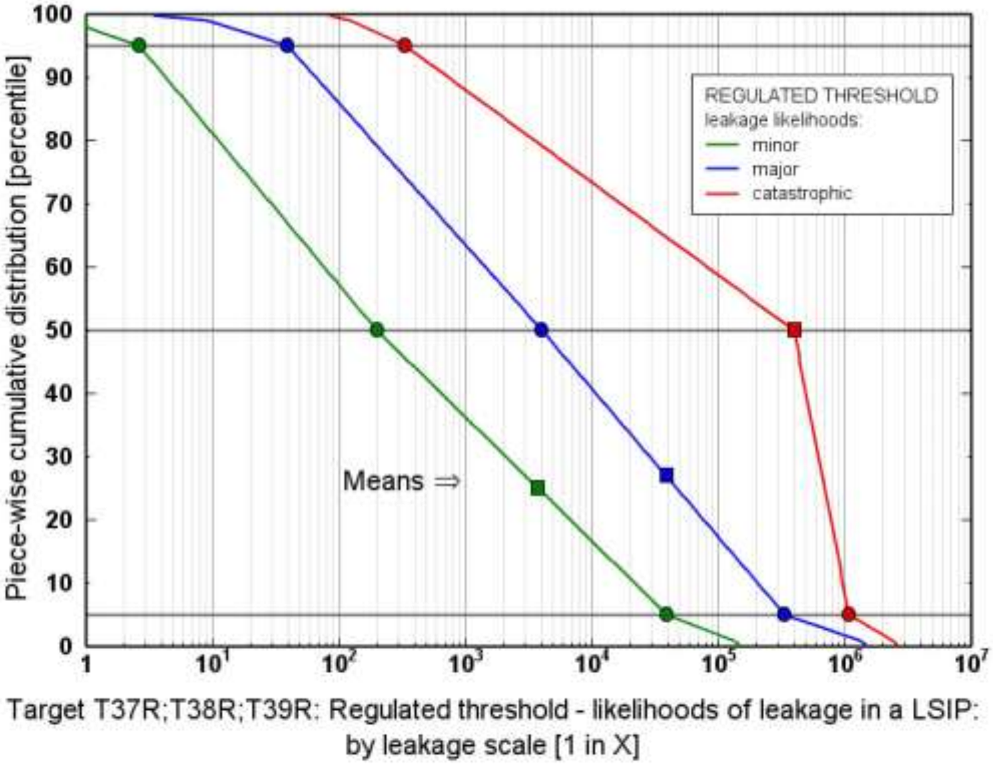
The piecewise distributions are ‘minimum information’ representations of uncertainty, simply defined by the three quantiles (i.e. 5th, 50th and 95th percentiles) derived by aggregating the weighted combination of experts’ judgements.

In risk assessment practice, standard distribution forms may be fitted as appropriate to the quantiles, e.g. normal, lognormal, beta, Weibull …..

T37-39Rev. What should be the regulated threshold for the likelihood of minor, major or catastrophic storage leakage in a LSIP sequestration project (1 in X, where X ≥1; for example, 1 in 100 would represent a 1% likelihood)?

a) Minor leakage *b) Major leakage* *c) Catastrophic leakage*

Leakage	Lower limit (5th percentile)	Mean	Central Value (median)	Upper limit (95th percentile)
[T37R] Minor	1 in 39,600 (1 in 11,600)	4000 (1020)	1 in 202 (1 in 27)	1 in 2.7 (1 in 1)
[T38R] Major	1 in 337,000 (1 in 71,400)	40,000 (7100)	1 in 4060 (1 in 340)	1 in 40 (1 in 27)
[T39R] Catastrophic	1 in 1.1 million (1 in 1 million)	378,000 (95,000)	1 in 399,000 (1 in 3160)	1 in 338 (1 in 276)



T43Rev: How long will a typical saline aquifer storage site remain safe, where safe means 95% or more facilities will not fail in the time periods you specify (years)?

T44Rev: How long will a typical saline aquifer storage site remain safe, where safe means 50% or more facilities will not fail in the time periods you specify (years)?

T45Rev: How long will a typical saline aquifer storage site remain safe, where safe means 5% or fewer facilities will not fail in the time periods you specify (years)?

Facilities that will not fail	Safe Storage Lifetime			
	Lower limit (5th percentile)	Mean	Central Value (median)	Upper limit (95th percentile)
[T43R] 95% or more facilities	8.6 million yrs (18 million yrs)	70,900 (994,000)	12,700 yrs (740 yrs)	166 yrs (7 yrs)
[T44R] 50% or more facilities	80 million yrs (166 million yrs)	6.7e+6 (8.8e+6)	125,000 yrs (4370 yrs)	5130 yrs (95 yrs)
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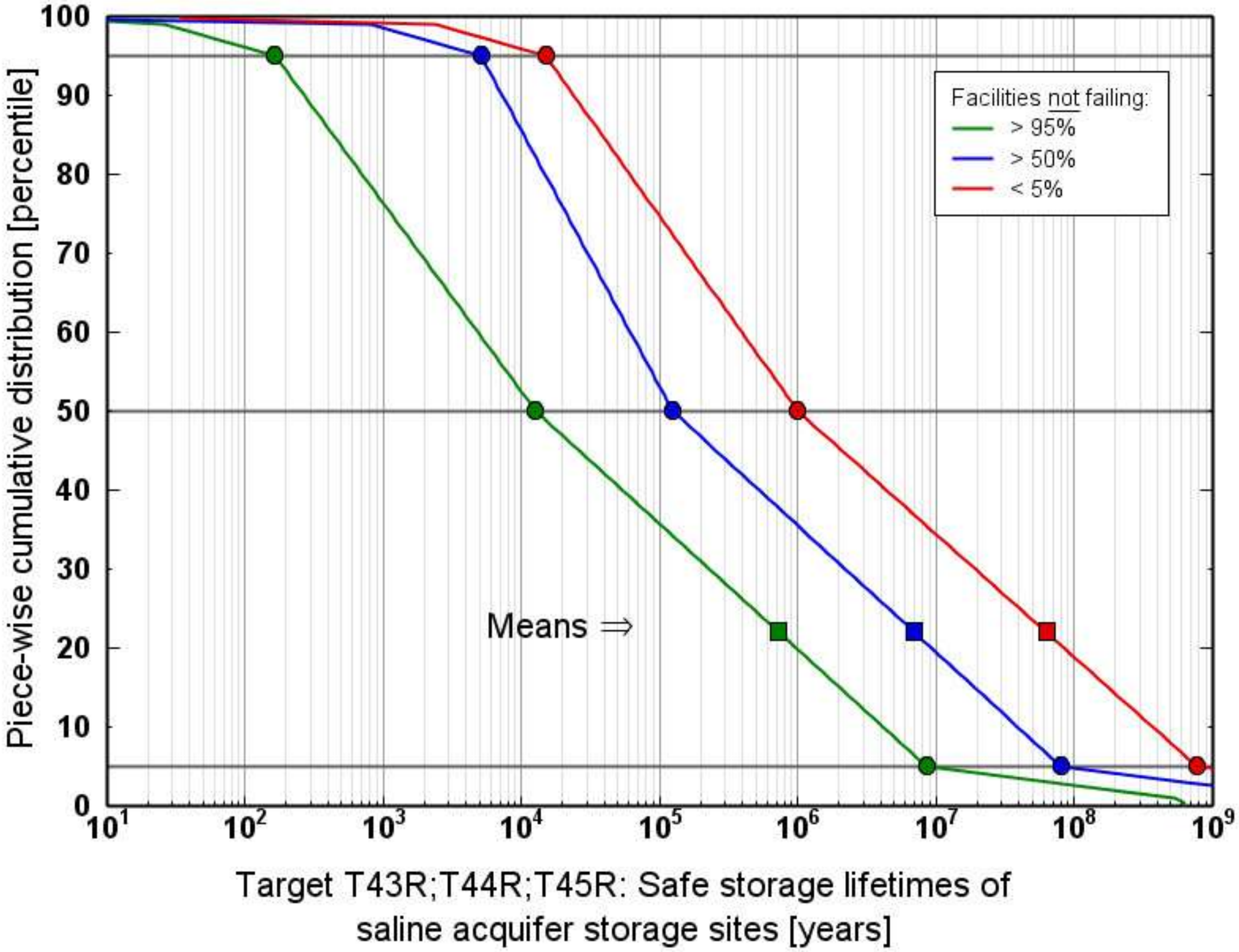
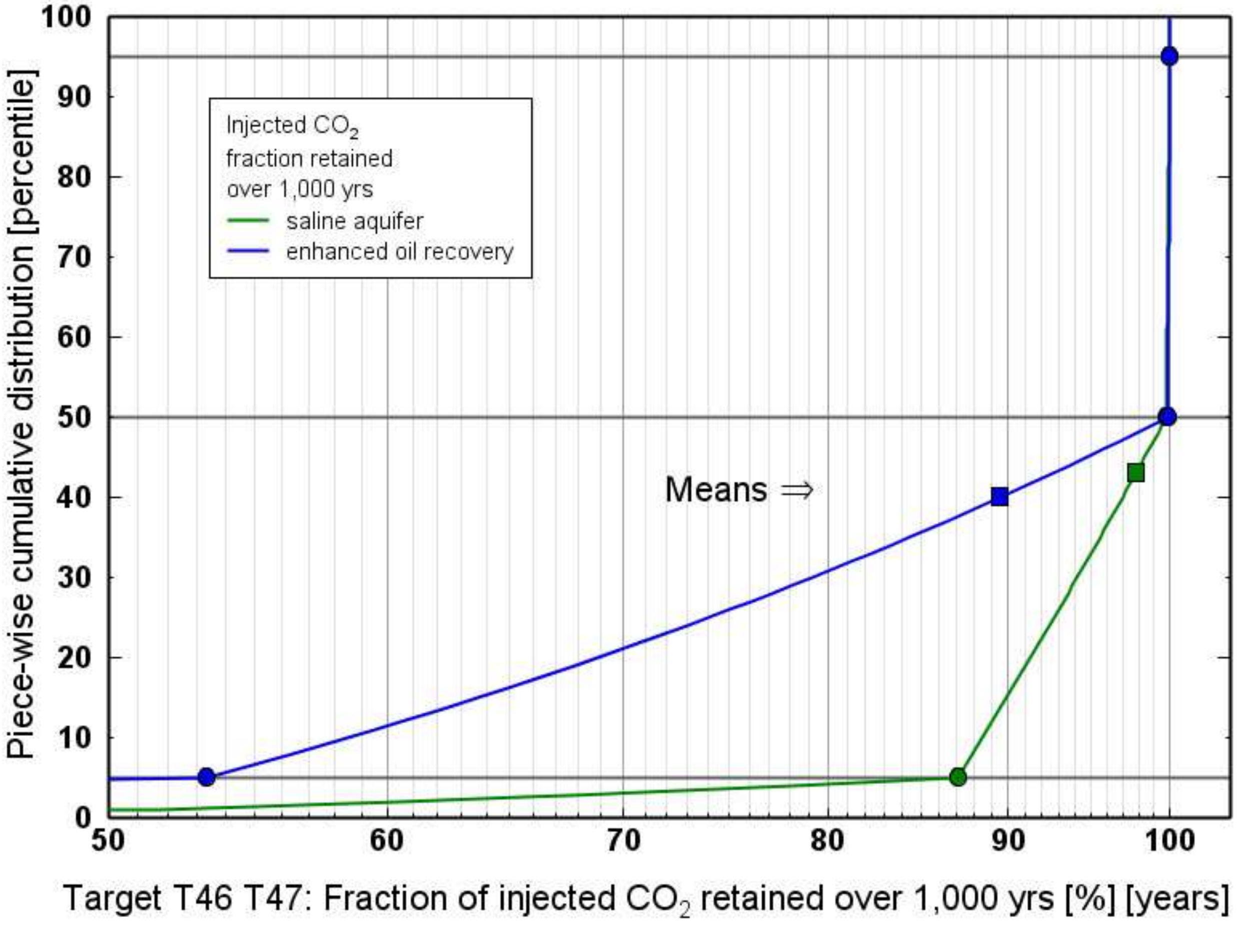
Piece-wise cumulative distribution [percentile]
100
90
80
70
60
50
40
30
20
10
0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
Facilities not failing:
> 95%
> 50%
< 5%
Means ⇒
Target T43R;T44R;T45R: Safe storage lifetimes of saline acquifer storage sites [years]

T46: In a typical large scale integrated *saline aquifer storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
87.% (63.8%)	97.7% (89%)	99.8% (94.2%)	100% (100%)

T47: In a typical large scale integrated *enhanced oil recovery storage* project, what fraction of injected CO_2 can be expected to be retained over a period of 1,000 years? (0-100%)

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
54% (35%)	89% (77%)	99.85% (85.8%)	100% (99.98%)

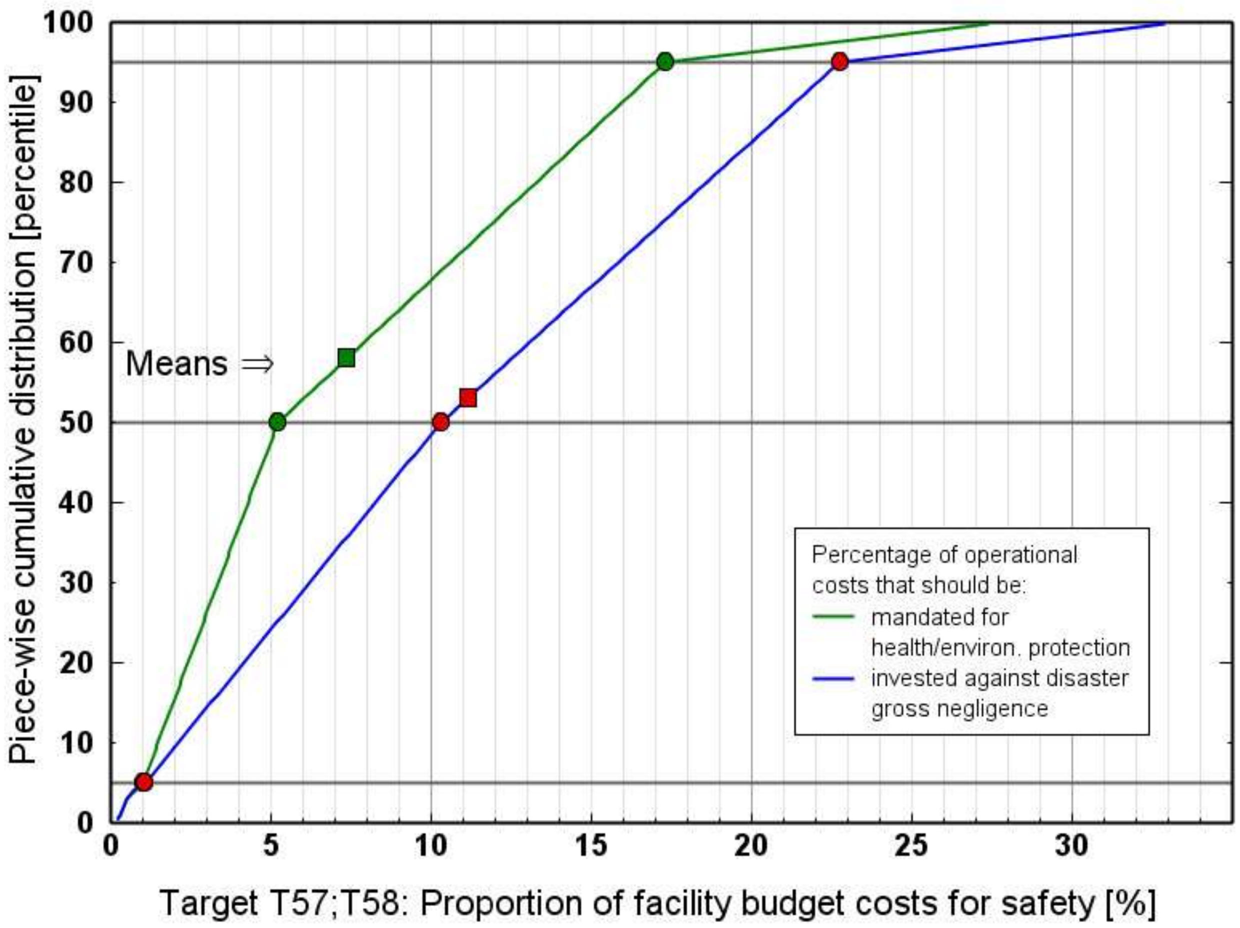


T57: On a project basis, what proportion of costs should be mandated by the leading regulatory agency to be spent on environmental and human health protection (%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (1.6%)	7.3% (10%)	5.5% (7.9%)	17% (23%)

T58: Assume there is an annual budget for the proponent to fund operational costs of a CCS storage facility. What percentage of this budget should be allocated to safety to ensure sufficient mitigation of environmental and human health impacts such that the company is reasonably secure against gross negligence claims in any post-failure litigation (%)?

Lower limit (5th percentile)	Mean	Median	Upper limit (95th percentile)
1.1% (1.8%)	11% (13%)	11% (11%)	25% (27%)



Section 3
Risk Management Options

Likert scale ratings and conversion to pairwise comparison
Risk Management Options

The final Section of the elicitation considered the effectiveness of risk management (RM) options for potential high impact low probability events: Catastrophic wellhead injection failure, Massive release of CO2 resulting in human fatalities, Caprock fracture, Induced seismic event >M4, and Large migration out of pore space. The risk management options were Site Selection, Well Integrity Studies, Emergency Response Plan (ERP), Automatic Emergency Shut Down System, and Training (operating procedures).

RM Option responses are illustrated as a mean score on a chart; a heat map matrix; as a graph for each event, with standard error; and by pairwise preference matrix (Part B).

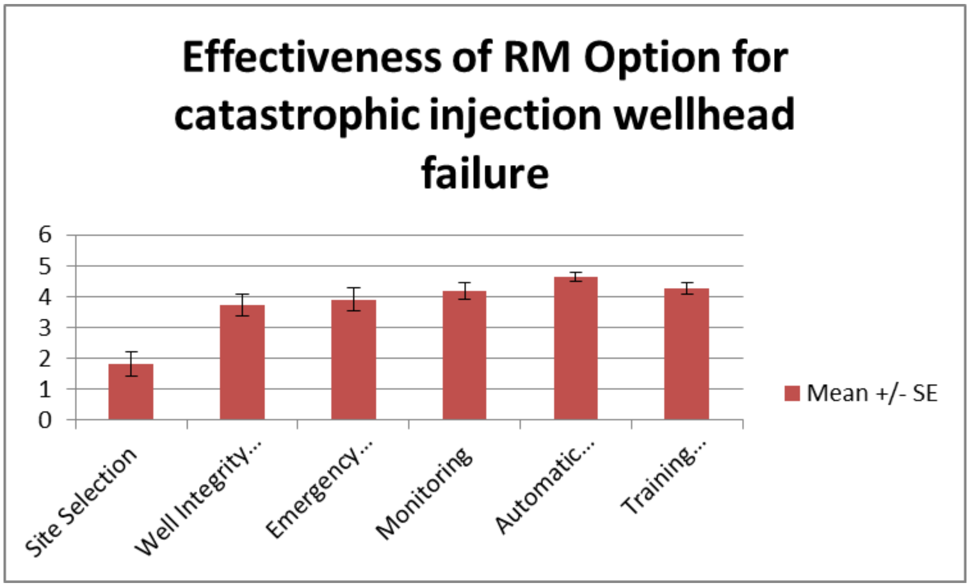
Part A: Likert scale findings

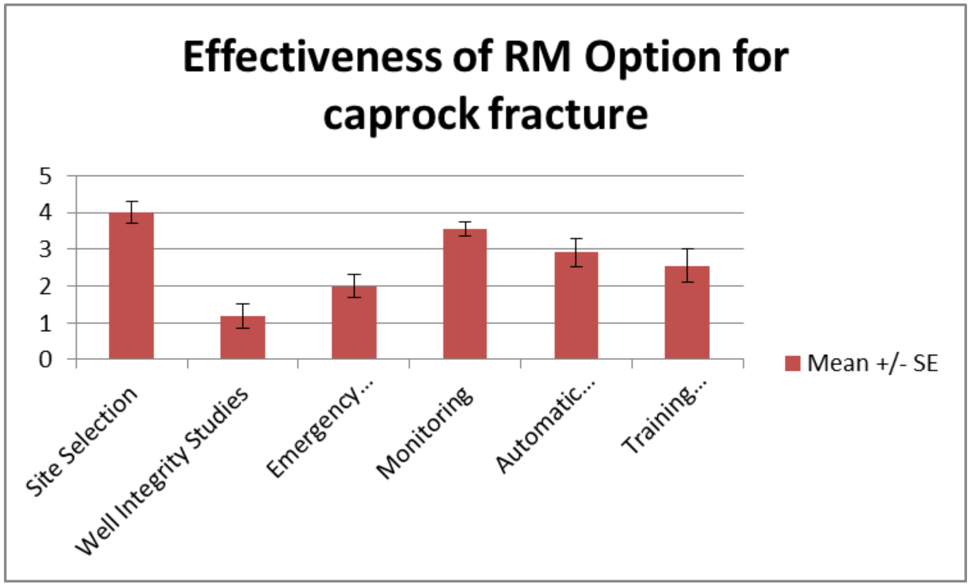
50. This question is focused on risk management of high impact low probability (HILP) (catastrophic) events. For questions related to leakage, please note that the nature of the leaked substance (eg CO_2, brine, or another contaminant) is not the focus of the question; rather, the question focuses on a leakage of any kind.

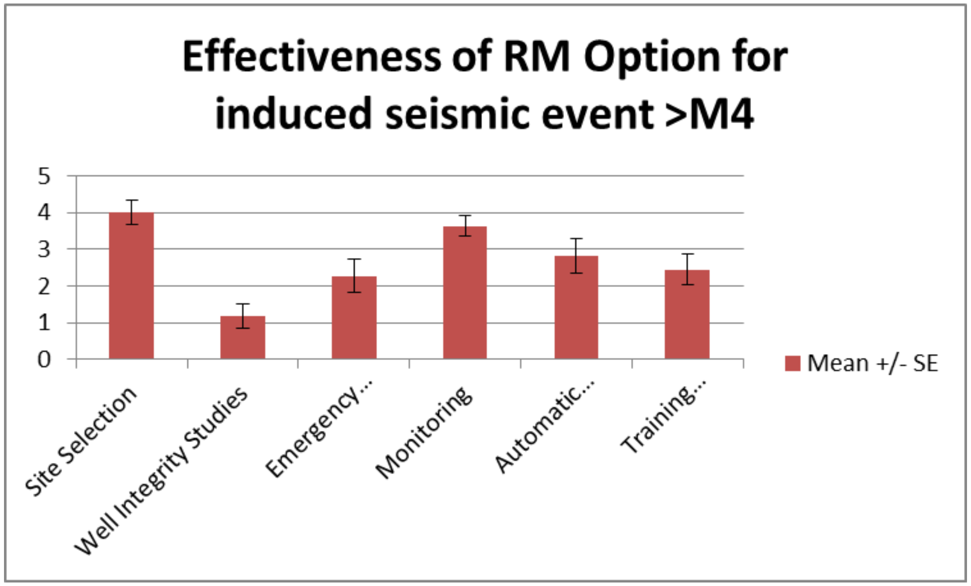
Please rate the effectiveness of each of the following methods to manage risk of high impact low probability (HILP) (catastrophic) events using the following 5-point Likert scale:

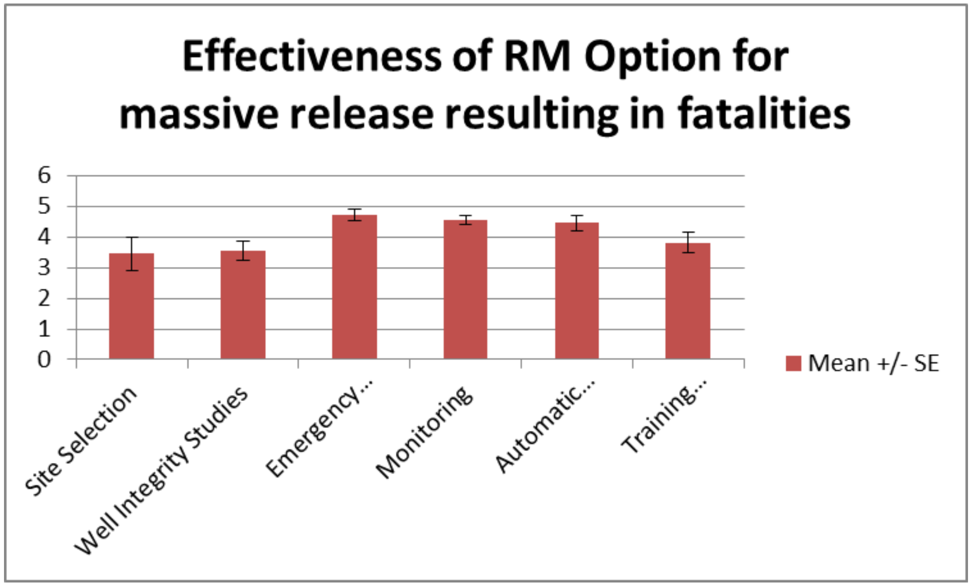
Not at all effective	1
Minimally effective	2
Moderately effective	3
Very effective	4
Extremely effective	5

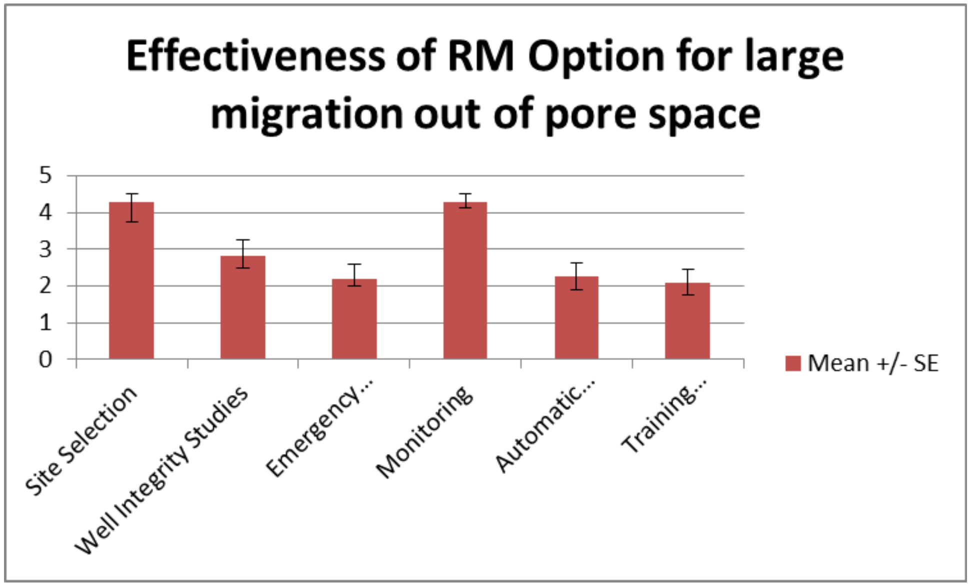
The five low probability high impact events are: large migration out of pore space; caprock fracture; induced seismic event >M4; massive release of CO_2 resulting in human fatalities; catastrophic injection wellhead failure. The mean effectiveness with standard error of each risk management option for each event is presented here.




Effectiveness of RM Option for caprock fracture


Effectiveness of RM Option for induced seismic event >M4


Effectiveness of RM Option for massive release resulting in fatalities


Effectiveness of RM Option for large migration out of pore space

Part B: Likert matrix for risk management options converted to equivalent Unibalance pairwise preference matrix form

In this subsection, the CCS Expert Group responses to the Likert matrix for risk management measures for five scenarios are converted to equivalent Unibalance pairwise preference matrix form, and analysed with the probabilistic inversion (PI) algorithm. The approach is marginally sub-optimal in Probabilistic Inversion terms because the Likert scale survey allows equality of two or more factors, which the pairwise elicitation seeks to avoid such as uninformative.

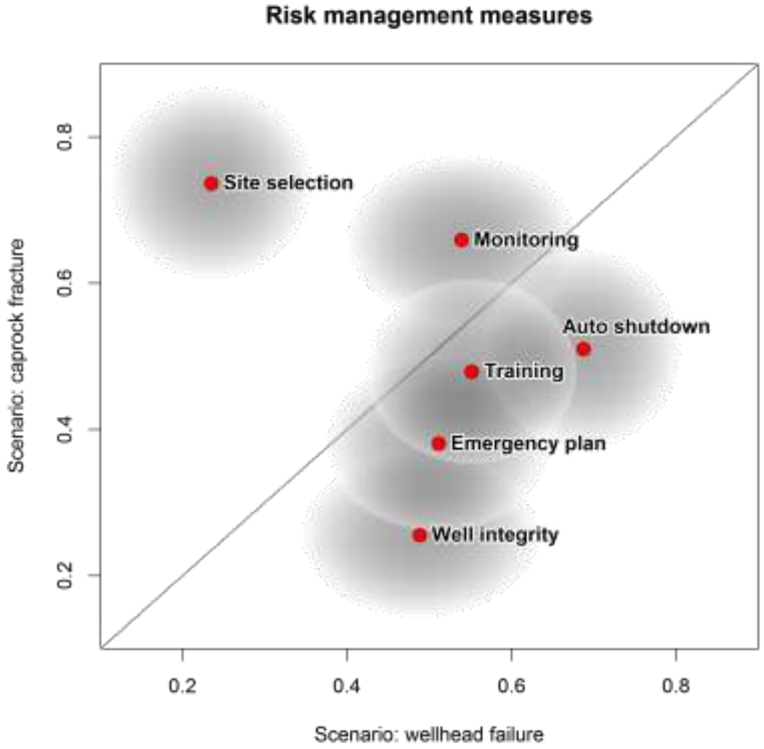
'Coeff of Agreement' measures how closely the patterns of individual experts' pairwise preferences are alike, while 'Coeff of Concordance' indicates how similar the corresponding rank orders are among the group. 'Random preferences p-value' is a test statistic for the strength of evidence that the hypothesis that the group's pairwise preferences are made at random can or cannot be rejected.

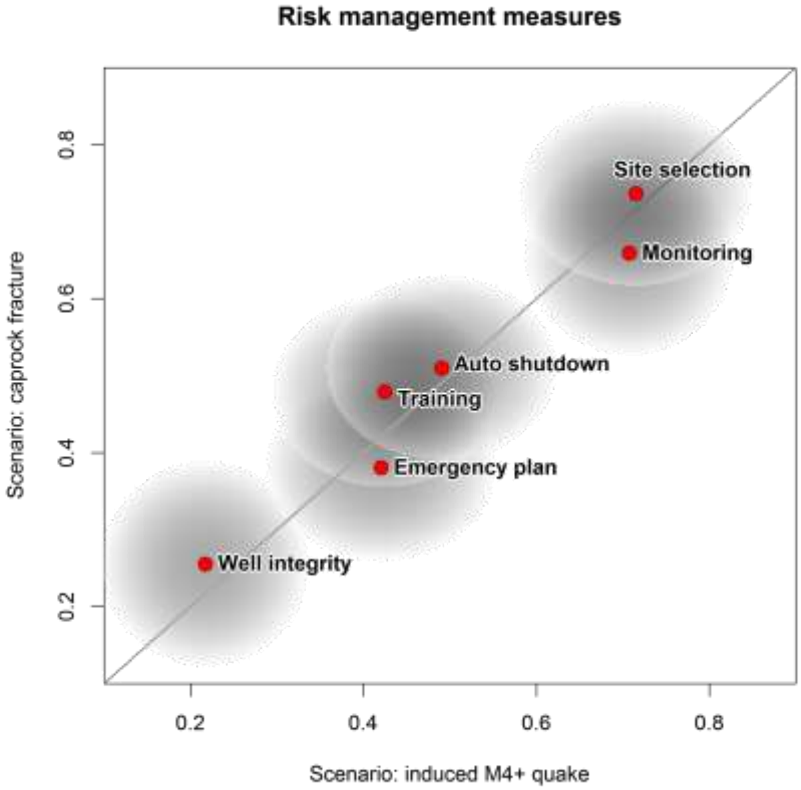
Ellipses depict 95% confidence areas for factor ranking scores from probabilistic inversion of experts' collective pairwise choices. For cases with alternative scenarios or options, horizontally extended ellipses indicate greater variance in ranking scores for the option on the x-axis option, relative to rankings for the y-axis option; vertically extended ellipses indicate greater variance vice versa.

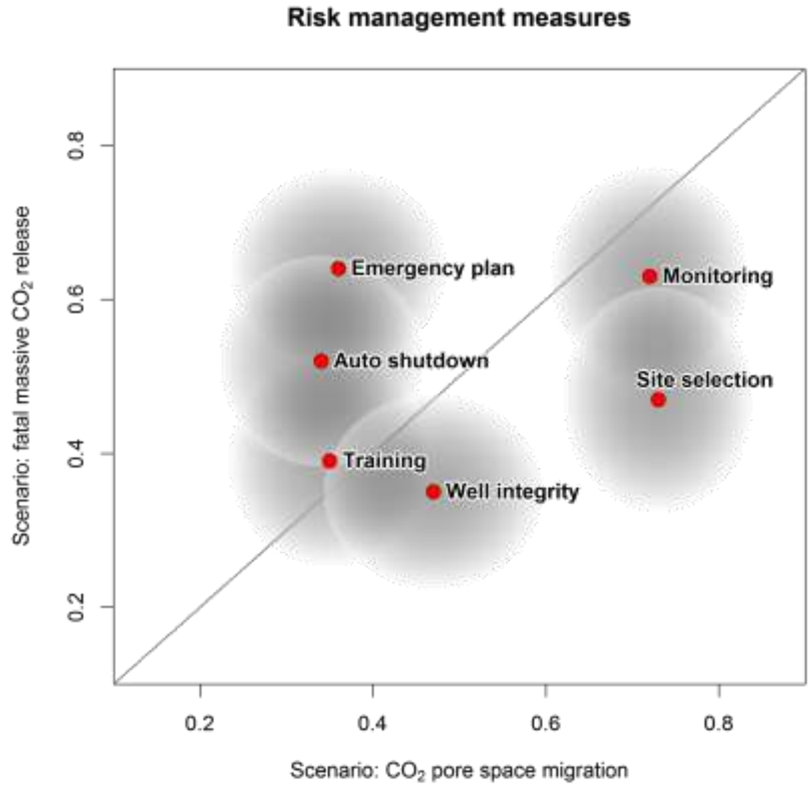
<u>Risk management measures for event scenarios</u>

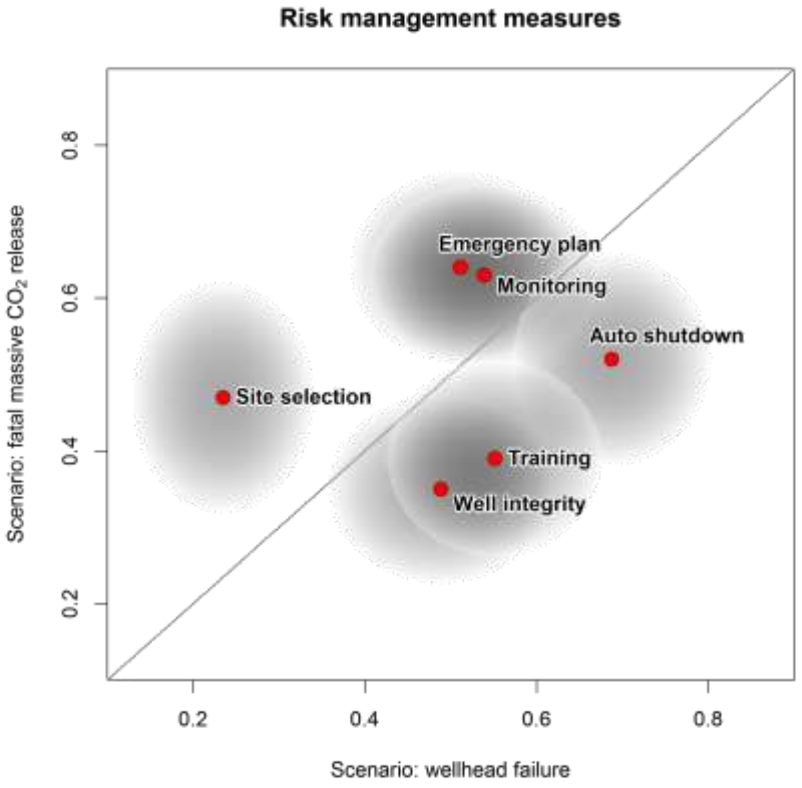
Rank scores and their variances from group probabilistic inversion:

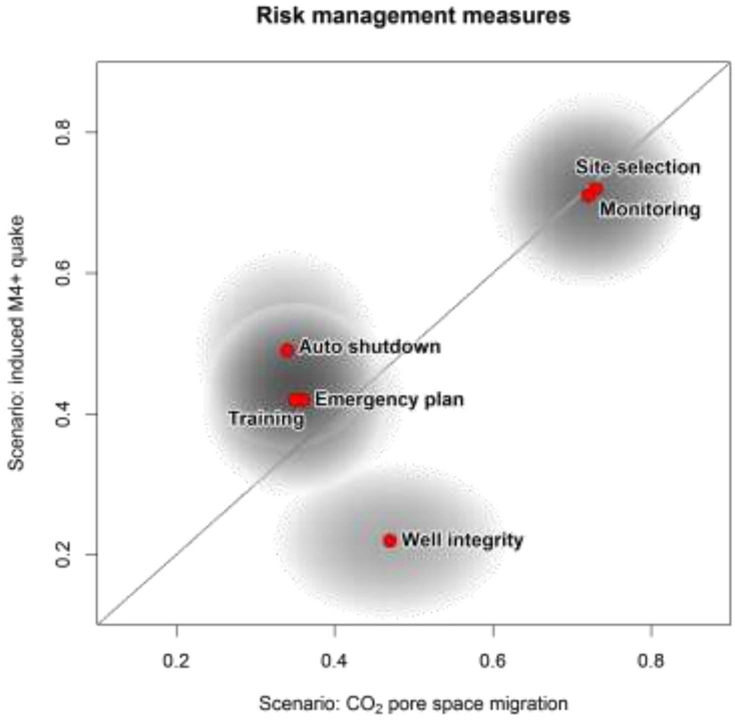
Scenario:	**Wellhead failure**		**Caprock fracture**		**Induced M4+ quake**		**Pore gas migration**		**Fatal massive CO_2 release**	
Risk measure	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**	**Score**	**St. dev.**
Site selection	0.23	0.20	0.74	0.21	0.72	0.24	0.73	0.21	0.47	0.28
Well integrity	0.49	0.26	0.26	0.21	0.22	0.19	0.47	0.25	0.35	0.25
Emergency plan	0.51	0.27	0.38	0.24	0.42	0.26	0.36	0.26	0.64	0.27
Monitoring	0.54	0.28	0.66	0.23	0.71	0.21	0.72	0.20	0.63	0.25
Auto shutdown	0.69	0.24	0.51	0.28	0.49	0.31	0.34	0.25	0.52	0.29
Training	0.55	0.26	0.48	0.26	0.42	0.27	0.35	0.23	0.39	0.27
	Stats									
Coeff agreement	0.06	very low	0.19	ok	0.19	ok	0.22	ok	0.0	none
Coeff concord.	0.30	ok	0.44	ok	0.38	ok	0.48	ok	0.20	ok
Random preferences p-value	0.05*	marginal reject	0.0001	reject	0.0000	reject	0.0000	reject	0.76**	cannot reject


Risk management measures
Site selection
Monitoring
Auto shutdown
Training
Emergency plan
Well integrity
Scenario: caprock fracture
Scenario: wellhead failure
0.2
0.4
0.6
0.8


Risk management measures
Site selection
Monitoring
Auto shutdown
Training
Emergency plan
Well integrity
Scenario: caprock fracture
Scenario: induced M4+ quake
0.2
0.4
0.6
0.8


Risk management measures
Scenario: fatal massive CO$_2$ release
Scenario: CO$_2$ pore space migration
0.2
0.4
0.6
0.8
Emergency plan
Monitoring
Auto shutdown
Site selection
Training
Well integrity


Risk management measures
Scenario: fatal massive CO$_2$ release
Scenario: wellhead failure
0.2
0.4
0.6
0.8
Emergency plan
Monitoring
Auto shutdown
Site selection
Training
Well integrity


Risk management measures
Site selection
Monitoring
Auto shutdown
Emergency plan
Training
Well integrity
0.8
0.6
0.4
0.2
Scenario: induced M4+ quake
0.2
0.4
0.6
0.8
Scenario: CO$_2$ pore space migration

Appendix E: Supplementary Material – Chapter 6

An Integrated Risk Management Framework for Carbon Capture and Storage
in the Canadian Context

Supplementary Material

Patricia Larkin[1], William Leiss[1], Joseph Arvai[2], Maurice Dusseault[3], Robert Gracie[3],
Mamadou Fall[1], Anthony Heyes[1], Daniel Krewski[1]

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Part A
Comparative Analysis of Activities Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage

Part B

[1]University of Ottawa
[2]University of Michigan
[3]University of Waterloo

Part A

Table A1: Comparative Analysis of Activities Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage in a Regulatory Context

Risk Assessment Activity	Framework									
	London Convention RAMF 2006	London Convention CO_2 Stream 2012	OSPAR 2007	EU CCS Directive 2009	EC CCS GD1 - Storage Lifecycle RM 2011	EC CCS - GD2 Storage, stream, monitoring, mitigation 2011	UNFCCC – CCS as CDM 2011	Australia – Injection and Storage regulation 2011	Australia – Environment regulation 2009	US EPA UIC Class VI Program Guidance[7]
Mandatory (M) or Voluntary (V)	V	V	M	M	V	V	M	M	M	V
CCS Chain[1]	S	C, I	I, S, PI	S	S	C, T, S, PI	C, T, S	I, S	T, I, S	I
Number of phases in project lifecycle	5		5		6		3			5
Waste prevention audit		X								
Link with other assessments[2]				X			X	X	X	X
CO_2 Stream characterisation		X				X		X		X
Problem Formulation	X		X	X				X		
Storage Site Selection and Characterization				X		X	X	X	X[3]	X
Hazard identification	X	X	X	X	X	X	X	X	X	X
Exposure assessment	X		X	Y	Y	X	X			
Effects assessment	X	X	X	X	X	X	X	X	X	
Risk characterization	X		X	X	X	X	X	X	X	
Risk Ranking					Y					X
Risk Management[8]	X	X	X	X	X	X	X	X	X	X

Note: X indicates the activity is clearly articulated in the framework; Y indicates the activity is acknowledged, but not necessarily elaborated upon.

[1] C – Capture; T – Transport; I – Injection; S – Storage; PI – Post injection; [2] eg Environmental Assessment, Strategic Environmental Assessment, emissions, waste, water use for CCS project; within country regulations; [3] Description of environment; [4] Identifying and describing all activities at an appropriate level of detail, particularly those activities relevant to environmental impact and risk; [5] Using a robust risk assessment method – in line with AS/NZS ISO 31000, Risk identification, Risk analysis, Risk evaluation, Risk treatment (RM); [6] On which to base focus of assessment; [7] Range of RA/RM issues discussed within six guidance documents; [8] See Table 1b for details of risk management activities

Table A2: Comparative Analysis of Risk Management Activities Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage in a Regulatory Context

Risk Management Activity		Framework									
		London Convention – RAMF	London Convention – Stream	OSPAR	EU CCS Directive	EC CCS - GD1 Storage Lifecycle RM	EC – GD2 Storage, stream, monitoring, mitigation	UNFCCC – CCS as CDM	Australia – Injection and Storage regulation	Australia – Environment regulation	US EPA UIC Class VI Program Guidance[1]
Mandatory (M) or Voluntary (V)		V	V	M	M	V	V	M	M	M	V
CCS Chain		I, S	I, S	I, S, PI	S	C, T, S, PI	C, T, S, PI	C, T, S, PI	I, S	T, I, S	I
Operations management and procedures						X	X	X	X	X	X
Preventive or corrective safeguards re escape		X		X		X	X				X
Monitoring (Plan) @ Operations Phase		X	X	X	X	X	X	X	X	X	M[2]
Monitoring – stream composition								X			
Monitoring – surrounding domains								X		X	X
Iterative process	Calibrate and update modelling					X	X	X	X	X	X
	Update monitoring plan				X	X	X	X			X
Mitigation Plans @ Operations Phase Corrective measures plans		X	X	X		X	X		X	X	M[2]
Contingency plan for large incidents								X		X	
Assessment of remedial measures								X		X	
Monitoring @ closure		X	X	X		X	X	X	X	X	M
Mitigation @ closure				X		X	X				X
Monitoring @ transfer							X				
Inspections						X	X				
Closure plan									X		X

[1] Range of RA/RM issues discussed within six guidance documents; [2] Required in USEPA Class VI Rule

Table A3: Comparative Analysis of Other Considerations Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage in a Regulatory Context

Other Considerations	Framework											
	London Convention RAMF	London Convention – CO$_2$ Stream	OSPAR	EU CCS Directive	EU Directive Pollution Prevention	EU Directive – Environment Plan	EC CCS GD1 Storage Lifecycle RM	EC CCS GD2 – Storage Stream Monitoring	UNFCCC CCS as CDM	Australia – Injection and Storage regulation	Australia – Environment regulation	US EPA UIC Class VI Program Guidance
Mandatory (M) or Voluntary (V)	V	V	M	M	M	M	V	V	M	M	M	V
Uncertainty	X		X	X					X			
Reporting	Y	Y	X	X						Y	X	X
Stakeholder Communication consultations		Rec'd	X		X				X[2]	X	X	
Improve knowledge, best practices			X[1]			X			X			
Inspections				X								
Transparency									X		X	

Note: X indicates the activity is clearly articulated in the framework; Y indicates the activity is acknowledged, but not necessarily elaborated upon.

[1] RM, Impact predictions; [2] EA and SEI assessments; [3] Greater effort for evaluation of impacts and risks of greater uncertainty or potential consequence; [4] Compliance and environmental performance

Table A4: Comparative Analysis of Risk Assessment Activities Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage in a Non-regulatory Context

Risk Assessment Activity		Framework											
			NETL			DNV GL							
		WRI CCS Guidelines	Monitoring, Verification, Accounting	Site Screening, Selection and Characterization[14]	Risk Analysis and simulation	CO2Qualstore[15]	Qualification for CO2 Capture Technology	Pipelines	CO2 Wells [1]	CO2RISKMAN	Geological Storage of carbon dioxide	CSA – Standard Z741	de.carbonise openCCS
CCS Chain[16]		C, T, S, PI	S, PI	C, T, S	S	S	C	T	I, S	C, T, I, S[17]	S	S	C, T, S
Number of phases in project lifecycle		4	4	4		6					7	5	6
Link with other assessment types[18]		X											
CO_2 Stream characterisation		X		X				X		X			
Problem Formulation				X		X	X		X		X		
Storage Site Selection and Characterization		X	X	X	X	X					X	X	X
Hazard identification		X			X	X	X	X	X	X	X	X	X
Exposure assessment	Risk Analysis				X					X	X	X	X
Effects assessment		X	X		X	X[19]		X	X	X		X	X
Risk characterization	Risk evaluation				X	X				X	X	X	X
Risk Ranking		X[20]		X		X	X		X	X		X	X
Risk Management[21]		X	X	X	X	X[5]	X	X	X	X	X	X	X

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[14] RA and RM activities mentioned but not elaborated

[15] CO_2Qualstore and CO_2Wells subsumed within "Geological Storage of carbon dioxide"

[16] C – Capture; T – Transport; I – Injection; S – Storage; PI – Post injection

[17] Short term storage only

[18] EA, SEA – assess emissions, waste, water use for CCS project

[19] Based on Technology Qualification

[20] Storage reservoirs, not risks

[21] See Table A5 for details

Table A5: Comparative Analysis Risk Management Activities Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage in a Non-regulatory Context

Risk Management Activity		Framework											
			NETL			DNV GL							
		WRI – CCS Guidelines	Monitoring, Verification, Accounting	Site Screening, Selection and Characterization[3]	Risk Analysis	CO2Qualstore	Capture	Pipelines	CO2Wells	CO2RISKMAN	Geological Storage of carbon dioxide	CSA – Z741	de.carbonise openCCS
CCS Chain		C,T, S, PI		C, T, S		S			I, S	C, T, I, S[4]	S	S	C, T, S
Operations management and procedures										X		X	
Preventive or corrective safeguards re escape		X			X	X		X	X	X	X		X
Monitoring (Plan) @ Operations Phase		X	X		X	X		X	X		X	X	
Monitoring – stream composition		X						X		X			
Monitoring – surrounding domains		X	X			X			X		X	X	
Inspections		X[1]	X				X	X					
Iterative process	Calibrate and update modelling		X	X	X	X			X	X	X	X	X
	Update monitoring plan		X			X	X		X	X	X	X	X
Mitigation Plans @ Operations Phase Corrective measures plans		X	X[2]		X	X		X	X	X	X	X	X
Contingency mitigation/remediation planning		X	X			X		X	X		X	X	
Assessment of remedial (mitigation) measures			X					X				X	
Monitoring @ closure		X	X			X					X		X
Mitigation of event @ closure													
Monitoring @ transfer													
Closure plan						X					X	X	

[1] In transport, including regulators; [2] Presented in case studies; [3] RA and RM activities mentioned but not elaborated; [4] Short term storage only

Table A6: Comparative Analysis of Other Considerations Included in Risk Assessment and Risk Management Frameworks for Carbon Capture and Storage in a Non-regulatory Context

Other Considerations	Framework												
		DOE NETL				DNV GL							
	WRI – CCS Guidelines	NETL – Monitoring, Verification, Accounting	Site Screening, Selection and Characterization[3]	Risk Analysis	Public Outreach	DNV - CO2 Qualstore Guideline, Guidance	Capture	Pipeline	CO2Wells	CO2RISKMAN	Geological Storage of carbon dioxide	CSA – Z741	de.carbonise openCCS
Uncertainty	X Genl	X	X	X		X	X		X		X	X	
Reporting (results)		X[1]			X	X			X			X	
Stakeholder Communication consultations	Y		X	X	X	X				X	X	X	X
Improve knowledge								X					X
Transparency as a goal		X			X	X	X				X	X	
Examples of best practices as they evolve						X							X
Unexpected outcomes						X							

Note: X indicates the activity is clearly articulated in the framework; Y indicates the activity is acknowledged, but not necessarily elaborated upon

[1] to Underground Injection Control regulator

Part B:

CCS Hazard Taxonomy and Risk Management Options

	Consideration of Risk Management Context[22] Risk management principles; Economic analysis; Socio-political considerations; Risk perception				
Hazard	Risk Management Options[23]				
	Regulatory	Economic	Advisory	Community-based	Technological
All Value Chain Activities					
Project basis	Environmental Assessment		Cross-industry learning and knowledge sharing Best management practices		Integrated hazard management
Capture Chain					
Air emissions Local, regional	• Emissions regulations • Monitoring requirements (NPRI) • Reporting requirements (NPRI) • Siting specifications (setbacks)	CEPA/Provincial Penalties/Fines	Notification process - exceedances local public health (or other agency)	Siting (position, features) Emergency response zone	• Process technologies and operations • Design specifications • Alarm and shut down • Monitoring
Amine/criteria contaminant deposition Local, regional	• Emissions regulations • Monitoring requirements • Reporting requirements • Alberta flagged amines RA uncertainty	CEPA/Prov Penalties/Fines	Notification process	Siting (position, features)	• Process technologies and operations • Design specifications • Monitoring

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[22] KREWSKI, D., WESTPHAL, M., ANDERSEN, M. E., PAOLI, G. M., CHIU, W. A., AL-ZOUGHOOL, M., CROTEAU, M. C., BURGOON, L. D. & COTE, I. (2014). A framework for the next generation of risk science. *Environ Health Perspect,* 122 (8)**,** 796-805. 10.1289/ehp.1307260

[23] Integrated framework for risk management and population health KREWSKI, D., HOGAN, V., TURNER, M. C., ZEMAN, P. L., MCDOWELL, I., EDWARDS, N. & LOSOS, J. (2007). An integrated framework for risk management and population health. *Human and Ecological Risk Assessment: An International Journal,* 13 (6)**,** 1288-1312. 10.1080/10807030701655798

	Risk Management Options				
Hazard	Regulatory	Economic	Advisory	Community-based	Technological
Transport Chain					
Pipeline failure Associated systems failure [CO_2 or CO_2 stream impurities] Inhalation occupational health and safety (OHS), public	Setbacks (AB CO2 pipeline class not required to identify Emergency Response Zone delineation) ERP/EPZ Shut down device interval Reporting Stream composition	Payments to municipal or provincial emergency response	Emergency response plan dissemination Training and qualifications ISO/CSA	Pipeline routing Emergency response plan development (inclusions) and implementation Site specific Emergency Response Zone Surveillance	Pipeline Integrity Management Plan • Design • Operations • Inspection • Monitoring • Maintenance Pressure control devices Alarm and shut down device/procedures
Injection Chain					
Injection wellhead or well casing failure CO_2 or CO_2 stream impurities Inhalation OHS	• Area of Review • Setbacks • Development plan • Permitted operational guidelines • Stream composition • Inspection, maintenance • Emergency Response Plan/EPZ • Drilling plan • Disposal plan (fluids) • Ignition plan (gases)		Emergency response plan dissemination Procedures Training	Siting Emergency response plan development (inclusions) and implementation	• Site characterization (subsurface hazardous substances in flowback) • Well design, development • Operating strategies • Responsive MMV programs • Pressure control, alarm, and shut down devices

	Risk Management Options				
Hazard	Regulatory	Economic	Advisory	Community-based	Technological
Injection Chain (con't)					
Induced seismicity	Permitted operational guidelines Performance-based guidelines for MMV Transparent reporting	Contingency fund	Emergency response plan dissemination	Emergency response plan development (inclusions) and implementation EPZ	Site characterization and selection Responsive MMV programs Pressure control, alarm, and shut down devices
Surface uplift	Permitted operational guidelines Performance-based guidelines for MMV[24]		Information and education for 3rd parties	Surveillance	Site characterization and selection Responsive MMV programs Pressure control, alarm, and shut down devices
Caprock Fracture	Permitted operational guidelines Performance-based guidelines for MMV		Safety procedures Training		Site characterization and selection Responsive MMV programs Pressure control, alarm, and shut down devices

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[24] Project specific operating conditions, a principle followed by the AER (Golder, 2011).

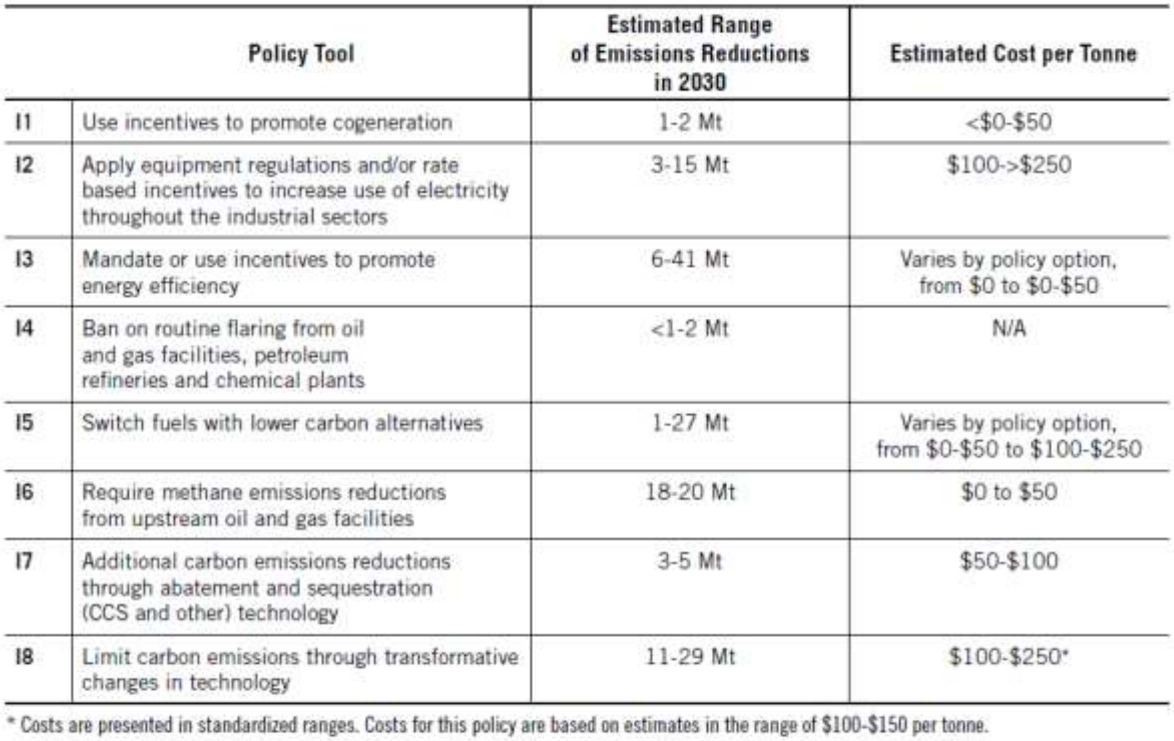
	Risk Management Options				
Hazard	Regulatory	Economic	Advisory	Community-based	Technological
Capture, Transport, Injection Chain					
Accidents, Malfunctions, Unplanned Events (AMUE) (Process Upsets)	• CO2 stream specification • mix of Mandatory and Voluntary requirements • Spill response plan • ERP/EPZ	CEPA/Provincial Penalties/Fines	• ERP dissemination • Off specifications notification • BMP – eg natural ventilation • Training	• Siting (position, features) • ERP development and implementation • Includes EPZ • 3rd party monitoring	• CO2 competency management system • Stream specifications • Operating strategies • Alarm and shut down device(s) • Monitoring
Injection or Storage Chain					
Near or far field	• Siting, separation • Stream specification • Design specifications (operating well – EPA UIC Class VI) • Inspection, maintenance • Performance-based guidelines for MMV • ERP/EPZ		Operations Training Information and education for 3rd parties	Siting Surveillance	Site characterization and selection Well development, design, materials Responsive MMV programs Pressure control, alarm and shut down devices
From direct, diffuse or lateral transport process Near or far field	• Site selection • Characterization of baseline conditions • Stream specification • Performance-based guidelines for MMV • ERP/EPZ • Reporting	Sampling, Inspection Contingency fund	Information and education for 3rd parties	Site characterization Emergency response plan development (inclusions) and implementation Surveillance monitoring	Site characterization and selection Integrity testing of known wells in vicinity Injection well development, design Biophysical environmental monitoring Responsive MMV programs

	Risk Management Options				
Hazard	Regulatory	Economic	Advisory	Community-based	Technological
Storage Chain					
Diffuse leakage Near or far field	Renewable permit process and monitoring requirements Performance-based guidelines for MMV				Site characterization and selection Responsive MMV programs
Lateral leakage Far field	Renewable permit process Performance-based guidelines for MMV Setbacks			ERP/EPZ	Site characterization and selection Responsive MMV programs
Direct free-phase CO_2 Near field Short or long term	• Setbacks • Development plan • Renewable permit process • Performance-based guidelines for MMV • Fit for purpose certification • Closure plan • Post closure plan	Payments into contingency fund Penalty structure	Reporting DNV 2012 storage: Specifications and performance requirements to be clearly defined, quantified and documented	ERP/EPZ	Site characterization and selection Responsive MMV programs

Appendix F: Supplementary Material – Chapter 7

This Appendix provides policy options to mitigate emissions for large industrial emitters and the electricity sector – tables excerpted from the report of the Specific Mitigation Opportunities Working Group (2016).

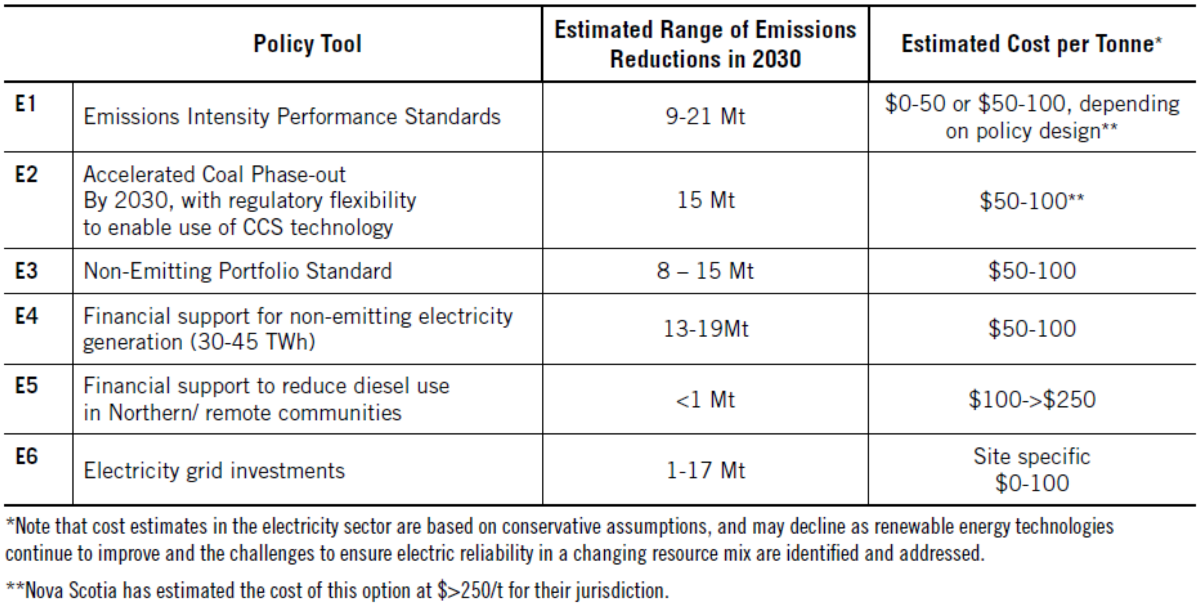
Policy Options for Large Industrial Emitters (Table 3)



Policy Tool		Estimated Range of Emissions Reductions in 2030	Estimated Cost per Tonne
I1	Use incentives to promote cogeneration	1-2 Mt	<$0-$50
I2	Apply equipment regulations and/or rate based incentives to increase use of electricity throughout the industrial sectors	3-15 Mt	$100->$250
I3	Mandate or use incentives to promote energy efficiency	6-41 Mt	Varies by policy option, from $0 to $0-$50
I4	Ban on routine flaring from oil and gas facilities, petroleum refineries and chemical plants	<1-2 Mt	N/A
I5	Switch fuels with lower carbon alternatives	1-27 Mt	Varies by policy option, from $0-$50 to $100-$250
I6	Require methane emissions reductions from upstream oil and gas facilities	18-20 Mt	$0 to $50
I7	Additional carbon emissions reductions through abatement and sequestration (CCS and other) technology	3-5 Mt	$50-$100
I8	Limit carbon emissions through transformative changes in technology	11-29 Mt	$100-$250*

* Costs are presented in standardized ranges. Costs for this policy are based on estimates in the range of $100-$150 per tonne.

Policy Options for Electricity Generation and Transmission (Table 6)



Policy Tool		Estimated Range of Emissions Reductions in 2030	Estimated Cost per Tonne*
E1	Emissions Intensity Performance Standards	9-21 Mt	$0-50 or $50-100, depending on policy design**
E2	Accelerated Coal Phase-out By 2030, with regulatory flexibility to enable use of CCS technology	15 Mt	$50-100**
E3	Non-Emitting Portfolio Standard	8 – 15 Mt	$50-100
E4	Financial support for non-emitting electricity generation (30-45 TWh)	13-19Mt	$50-100
E5	Financial support to reduce diesel use in Northern/ remote communities	<1 Mt	$100->$250
E6	Electricity grid investments	1-17 Mt	Site specific $0-100

*Note that cost estimates in the electricity sector are based on conservative assumptions, and may decline as renewable energy technologies continue to improve and the challenges to ensure electric reliability in a changing resource mix are identified and addressed.

**Nova Scotia has estimated the cost of this option at $>250/t for their jurisdiction.