



PHASE I FINAL REPORT FROM CSLF RISK ASSESSMENT TASK FORCE

Background

At its meeting in November 2006 in London, the CSLF Technical Group created a Task Force to Examine Risk Assessment Standards and Procedures. This Task Force is chaired by the United States with representation from Australia, Canada, France, India, Japan, Netherlands, Norway, the United Kingdom, the United States, and the IEA Greenhouse Gas R&D Programme. For its Phase I activities, the Task Force has focused primarily on risks that are unique to carbon capture and storage, i.e., those risks associated with the long-term storage of CO₂ as a reactive, mobile, and buoyant fluid in geologic reservoirs. This comprehensive Phase I Final Report is a summary of the Task Force's activities.

**CSLF Task Force to Examine Risk Assessment Standards and Procedures
Phase I Final Report**

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1. Introduction

1.1 Risk Assessment and Geologic Storage of CO₂

Geologic storage of CO₂ involves the injection and containment of a buoyant CO₂ fluid in the pore space within subsurface reservoirs. Both the injection and containment rely on prediction of the behavior of the CO₂ and the storage system over a range of time scales and conditions, which in turn relies on processes and attributes of the storage system that are not perfectly known or understood. Consequently, CO₂ storage at a particular site will inherently embody some uncertainty regarding the site's eventual performance (including its capacity, injectivity, ability to contain CO₂ and other fluids, etc.). Risk assessment is a process for the formal evaluation of these factors at a site, thereby enabling a sound decision based on the safety, effectiveness, and economics specific to the site.

Several international efforts are ongoing and developing related to various aspects of risk assessment for geologic storage of CO₂. These efforts are developing a broad experience base (including tools) in this area. They are also exploring a range of approaches to risk assessment (spanning from qualitative to quantitative, addressing some issues that are common to the efforts and some that are unique).

The potential scale of implementing CO₂ storage will require a multitude of sites, spanning a range of geologic environments, surface environments, and storage scenarios. Risk assessment methodologies must be able to accommodate this diversity while providing a common basis for comparing sites.

Thus there is a need to examine the various risk assessment efforts and approaches in the context of whether there is a common set of standards and procedures that is evolving. In particular, those aspects of risk assessment that are unique to CO₂ capture and storage (CCS) (*i.e.*, those associated with geologic storage) are evolving and must be examined.

1.2 Charter

At the joint meeting of the Technical and Policy Groups of the Carbon Sequestration Leadership Forum (CSLF) in London (14–15 November 2006), the Technical Group formed a task force to examine risk assessment standards and procedures.

This task force was formed to address a need identified in the CSLF strategic plan. Specifically, the Technical Group is responsible for developing recommendations for risk assessment standards and procedures.

In Phase I of its activities, the objective of the task force was to identify potential risks from CCS activities and to examine the risk assessment standards and procedures that can be used to place these risks in context based on their likelihood to occur and their potential impacts.

1.3 Membership

Membership of this task force is open to member countries and interested parties. Country representation includes Australia, Canada, France, India, Japan, Netherlands, Norway, United Kingdom, and United States. In addition, the International Energy Agency's Greenhouse Gas Programme is represented on the committee, providing coordination with its efforts in risk assessment for geologic storage of CO₂.

Task Force membership is shown in Table 1.1.

<i>Country</i>	<i>Original Representation</i>	<i>Changes to Representation by End of Phase I</i>
Australia	John Bradshaw	Clinton Foster
Australia	Bill Koppe	
Canada	Stefan Bachu	
France	Hubert Fabriol	
France	Mathieu Feraille	
France	Claudia Vivalda	
India	R. R. Sonde	
Japan	Makoto Akai	
Japan	Chiaki Shinohara	
Netherlands	Ton Wildenborg	
Norway	Odd Magne Mathiassen	
United Kingdom	Tim Dixon	
United States	Victor Der (Joe Giove)	
United States	Howard Herzog	(replaced by Guthrie)
United States	George Guthrie	
IEA-GHG	John Gale	Tim Dixon

1.4 Goals of Phase I Task Force Activities

Although geologic storage of CO₂ is coupled to a variety of above-ground activities (including the capture, transport, and injection of CO₂), the task force chose to focus primarily on risks that are unique to CCS, *i.e.*, those risks associated with the long-term storage of CO₂ as a reactive, mobile, and buoyant fluid in geologic reservoirs.

This report presents results of the task force's Phase I activities, including:

- an overview of risk assessment and related methodologies,
- a review of the existing literature on risk assessment for geologic storage of CO₂,
- a summary of ongoing risk-assessment activities in various countries,
- a highlight of critical issues, and,
- an identification of areas where additional information is needed.

1.5 Risk Assessment and Engineered Geologic Storage of CO₂

Many detailed definitions of *risk assessment* have been proposed, and it is not the intent of this effort to assess these. However, a few general observations can provide a context for the discussion of risk and CO₂ storage.

A recent report by the U.S. National Research Council notes that

“long-established concepts and practices have defined risk assessment as a process that involves hazard identification, hazard characterization or dose-response assessment, exposure assessment, and risk characterization” (NRC, 2007).

Evaluation (either qualitative or quantitative) of the potential impact(s) of the occurrence of an event is common to most definitions for risk analysis and/or risk assessment. Hence, at the core of risk analysis or assessment is the identification of potential consequences of concern and the ability to predict the probability of occurrence for these consequences based on the performance of the system of interest.

In the context of geological sequestration, risk assessment can be applied at any point in the process, from the capture and transport of CO₂ as part of various engineered systems to the injection and storage of CO₂ in a geologic reservoir. This task force has focused on the latter aspects, because the issues associated with capture and transport are not unique to sequestration and are relatively well understood in the context of other engineered and industrial processes.

Geologic storage relies on injecting CO₂ into the pore space within a permeable and porous reservoir that is contained vertically and (perhaps) horizontally by impermeable barriers to CO₂ flow. Placement of CO₂ requires drilling of wellbores through the impermeable caprock into the reservoir and then injecting CO₂, which displaces existing pore fluids and increases reservoir pore pressure. Risk assessment, then, must assess the performance of this engineered geologic system over time as the system responds to these new conditions.

The tools needed to predict of the performance of an engineered geologic system with respect to CO₂ storage can rely significantly on tools developed for a number of other similar challenges. CO₂ storage shares some aspects with industrial operations such as enhanced oil recovery (EOR) using CO₂, natural-gas storage and acid gas disposal. In each of these operations, large volumes of supercritical fluid or gas are injected into geologic reservoirs with the need to contain the injected fluid or gas within the zone of interest. Although the overall scale of these operations is small compared with the potential for CO₂ storage, the scale of operations at individual sites can be comparable to what might be anticipated for a CO₂ storage site. Hence, these operations provide important tools, observations, and experience that bear on risk assessment for CO₂ storage.

Nevertheless, there are unique aspects to CO₂ storage. For example, as noted, the potential scale of CO₂ storage may be significantly larger than existing industrial analogs, requiring new considerations with respect to risk assessment. The timescales of CO₂ storage also pose somewhat unique challenges: the fate of CO₂ and the reservoir must be predicted over decades to centuries, and some factors that control system performance will evolve over time, changing

the characteristics of the system. Finally, many potential storage systems under consideration (such as deep saline formations) represent geologic systems for which experience and data may be limited.

An overarching factor in risk assessment for engineered geologic systems is uncertainty. The heterogeneity of natural systems and our inability to characterize (or to define) them completely are among the many factors that contribute to uncertainty, even for very well characterized sites. Tools have been developed to address a variety of uncertainties, rendering many predictions probabilistic as opposed to absolute (deterministic).

1.5.1 Potential generalized impacts of geologic storage of CO₂

Risk assessment typically considers not only the probability of an event occurring but also the potential impact (or consequence) of that event. In the context of geologic storage of CO₂, potential events and impacts/consequences can occur throughout a storage operation as well as post-closure when injection has ceased. Discussion in the preceding section focused on understanding the behavior of the geologic storage site, which relates to predicting the occurrence of various events. The corresponding potential impacts/consequences are discussed in more detail in section 2.2.

Two general categories of risks can be defined: those relating to direct impacts of CO₂ leaked from the intended storage reservoir and those relating to indirect impacts due to the displacement of native fluids (e.g., brines, other gases such as methane) or propagation of a pressure front resulting from CO₂ injection.

Potential impacts may affect the geosphere (subsurface), biosphere, hydrosphere, and atmosphere and include the following (in ascending order from the storage unit to the atmosphere):

1. impingement on pore space not covered under deed or agreement (i.e., movement into pore space not associated with the intended storage reservoir), including impact on other (or future) CO₂ storage reservoirs
2. impingement on other subsurface resources (for example, oil/gas reservoirs, coal beds, coal-bed methane, mineral deposits, underground mines) (note that impingement can come from CO₂ mass moving onto pore spaces, or by displaced brine moving into the pore spaces)
3. change in local subsurface stress fields and geomechanical properties or conditions, possibly resulting in surface heaving.
4. impact on the groundwater and/or surface water
5. elevated soil-gas CO₂ in terrestrial ecosystems
6. accumulation of CO₂ in low lying areas subject to poor atmospheric circulation or poorly ventilated spaces

7. CO₂ or other displaced greenhouse gases (such as methane) return to the atmosphere (i.e., loss of CO₂ storage benefit)

The goal of risk assessment is to determine the likelihood (probability) and consequences of each of these potential impacts so that they can be minimized (and, in some cases, eliminated) through thorough effective risk management practices at a site.

1.6 Risk Assessment Methodologies

Risk assessment can focus on various levels of detail, ranging from general risk assessment to site-specific risk assessments, and ranging from qualitative to quantitative.

General risk assessments focus on the overall aggregated impacts, such as an assessment of the regional, national, or global risks of long-term CO₂ storage at a number of storage sites. In contrast, site-specific risk assessments focus on the unique aspects of a specific storage reservoir and are key steps in deciding whether the site is suitable for CO₂ storage and in identifying any necessary monitoring and remediation measures. Site-specific risk assessment can also provide the basis for general risk assessments. This document primarily considers issues associated with site-specific risk assessment for engineered geologic systems (*e.g.*, a CO₂ storage reservoir).

Several risk-assessment approaches for engineered geologic systems have been developed in the research and industrial communities. Many of these approaches are aimed at predicting the behavior of fluids in an engineered geologic system over time, which requires understanding the flow and reaction of fluids through the porous and potentially fractured geologic reservoir. The coupled behavior of flow, chemical reactions, temperature changes and mechanical response of the system makes the prediction challenging, which is further complicated by the heterogeneity of the natural system and the large range in scale from chemical reactions and flow (which occur at scales of less than a micrometer) to the various coupled systems that determine the behavior of the site (which occur at scales of meters to kilometers). These challenges preclude both a detailed characterization of the entire engineered geologic system as well as a detailed computational treatment of the entire system. Although parts of the engineered geologic system can be addressed in detail, other qualitative and quantitative tools are required to develop an integrated prediction as a basis for risk assessment.

1.6.1 Methodologies for industrial systems

A number of methods and tools have been developed to assess risks in industrial facilities. For example:

- the HAZOP approach (Hazard and Operability study). Designed for thermo-hydraulic systems, it intends to systematically identify possible deviations of the processes and their consequences. It constitutes the topic of the IEC 61882 (2001) standard.
- the FMECA (Failure Modes, Effects and Criticality Analysis), that looks into guide lists at the possible failure modes of a component within a system. It is described in the IEC 60812 (2006) standard.
- the SWIFT (Structured What-If Technique), systematic team brainstorming technique supported by check-lists to identify hazards at a system level.
- the Probabilistic Risk Assessment (PRA).

These various techniques are supported by tools such as fault/event trees, Bayesian belief networks, Markov graphs, Petri nets... These tools are of particular use to quantify probabilities for the occurrence of the risk scenarios. The last three are especially designed to take into account in the quantification process dependencies between events or dynamic aspects.

Quantification represents a major caveat in risk assessment. Guidelines for the entire process of quantitatively assessing risks due to dangerous substances published in the Netherlands (VROM, 2005a) are broadly consulted.

The methods used in industrial safety apply to systems for which the design is completely controlled and the interactions between parameters are largely known. The risks come from unexpected combinations of operating variables, and can be managed by acting on the design of the operations. In the case of CO₂ storage, however, the system parameters are poorly known and their interactions uncertain; moreover control is limited to a few operating variables and does not extend to all processes and events determining the behavior (Bos *et al.*, 2005). Alternative approaches have been developed to address the unique attributes of complex natural systems.

1.6.2 Features, Events, Processes (FEPs)

One approach to risk assessment for CO₂ storage is the use of a catalog of Features of an engineered geologic system that impact its behavior, discrete Events that can impact behavior, and other Processes that can influence its behavior (IAEA, 1981, 1983; Cranwell, *et al.*, 1982; Chapman *et al.*, 1995; Nirex, 1998; SKB, 2006).

There are several important applications of FEP lists and related FEP analyses, but major applications (based on NEA/OECD 2000) are:

- to stimulate broad discussions amongst the project team and independent experts during the identification of the relevant FEPs;
- to provide a source of information that can be used during scenario or model development activities;
- to provide a framework to record information about a FEP and whether or not the FEP is included in assessment models;
- to act as a tool for auditing the models used in an assessment with a view to ensuring that all important processes are included, or to assist in specifying further model developments or data acquisition.

A database of FEPs can aid in the site-specific description of the system and identification of site-specific issues, allowing comprehensive evaluation of each site's unique characteristics. Detailed lists of FEPs have evolved in the context of geologic systems for various environmental needs, and these have been adapted to a generic database for geologic storage of CO₂ by Quintessa (Savage *et al.*, 2004; Maul *et al.*, 2005). This master list (www.quintessa-online.com/fep.php) serves as a comprehensive set from which the FEPs relevant to a specific site can be drawn. Lewicki *et al.* (2007) also assess FEPs that pertain to CO₂ storage. This approach has been used in many of the initial CO₂ storage efforts, such as Sleipner in Norway (Torp and Gale, 2003), Weyburn in Canada (Stenhouse *et al.*, 2006a), In Salah in Algeria (Riddiford *et al.*, 2005), and the Decatur Project in the Illinois basin of the United States (Hnottavange-Telleen *et al.*, 2008).

1.6.3 Relational approaches with FEPs

There are a number of different ways in which the FEPs and the relationships between them can be developed to describe a site's behavior. In particular, three approaches have been used:

- A “top-down” approach. An example of this approach is the Master Directed Diagram (MDD) approach, which was developed by Nirex of the UK (Nirex, 1998). An MDD is a diagram with a tree-like structure that has some of the attributes of a network.
- The Process Influence Diagram (PID) approach, which identifies and represents all possible influences between all FEPs within a system.
- The interaction matrix approach. In this case, FEPs representing components of the system under consideration are placed on the leading diagonal elements (LDEs) of the matrix. Interactions between LDEs are then noted in the off-diagonal elements (ODEs).

1.6.4 Simulation and Risk Assessment

FEPs analysis (and the associated representation approaches) can be incorporated as part of a three step approach to integrate simulation and risk assessment for an engineered geologic system:

- development of site-specific conceptual models for critical scenarios (sometimes referred to as scenario analysis) (which typically relies on a prioritized set of FEPs for the site) followed by identification of FEPs interactions (by the PID approach, for example);
- development of mathematical descriptions for the critical scenarios, which can be based on empirical assessments of analogs, or deterministic simulations of the geologic system's response based on fundamental physical and chemical phenomena;
- assessment of potential consequences resulting from the critical scenarios, which can include various health/safety/environment (HSE) risks as well as various non-HSE risks (see below).

The first two steps are sometimes referred to as a site performance assessment; some usages also group the third step as part of performance assessment.

In the case of qualitative risk assessment, the second step is typically omitted, and the assessment of consequences is based on an assessment of FEPs.

In the case of quantitative risk assessment, computational models can range from the process level (such as related to the flow and reactivity of fluids in the reservoir) to the system level (such as related to the geologic system and its coupling to the other systems at the site). In process models, fundamental phenomena can be described from first principles at a range of scales. Due to the challenges in addressing the entire site at a process level (as noted above), several approaches can be employed to simplify the calculations.

One approach exploits simplified analytical expressions to describe various complex processes. Although these expressions can often represent processes fairly accurately, they are typically limited in applicability to a specific set of conditions. In addition, they are typically restricted in application to simplified descriptions of the engineered geologic system at the site.

Another approach exploits hybrid computational models, in which process models are coupled to a system-level model to allow generalized system-level behavior to be based on detailed simulations. Furthermore, detailed descriptions of the site can be employed when those data are available. Although hybrid approaches can more accurately represent the system, they typically are more time consuming to run than purely analytical models.

For both types of approaches, accurate quantification of the parameters that describe the engineered geologic system are fundamental to the quality of the simulation and prediction. Parameter quantification can rely on direct observations from an analogue system, laboratory measurements, theoretically derived values, and/or expert opinion. Regardless of the quantification method, uncertainty is frequently associated with parameters describing natural systems, resulting from both the difficulty (or inability) to quantify a parameter and the variability exhibited by many parameters. Sensitivity analysis can be used to provide insight into the impact of this uncertainty on the predictions, and many approaches utilize probability distributions to describe parameters.

1.6.5 Probabilistic risk assessment and uncertainty

As noted, a number of uncertainties complicate the prediction of the performance of natural systems, ranging from uncertainties in model parameters to uncertainties in the appropriate model for describing the system to uncertainties associated with natural heterogeneities. Probabilistic risk assessment allows ranking of issues and results through an integrative and quantitative approach including explicitly uncertainties. It typically requires a mix of objective and subjective data. Refsgaard, van der Sluijs, and coworkers (Refsgaard *et al.*, 2006, 2007; van der Sluijs, 2007) present detailed assessments of uncertainties and methodologies for natural systems.

2. Existing Literature on Risk Assessment for Geologic Storage of CO₂

2.1 CO₂ risk assessment literature review

2.1.1 Overarching frameworks

Several studies have explored the general framework for risk assessment for geologic storage of CO₂, stressing the need for the establishment of a common risk framework.

The IPCC Special Report on CCS (IPCC, 2005) sets the basis for assessing risks related to CO₂ storage activities. It indicates the main potential release pathways for CO₂ out of geological reservoirs and the kinds of hazards that could result from storage sites. It investigates the question of the probability of release according to various types of evidences, stating that “no existing studies systematically estimate the probability and magnitude of release across a sample of credible geological storage systems.” It identifies the main challenges posed by risk assessment for CO₂ geological storage, after having mentioned that in this new field, “no well-established methodology for assessing such risks exists.” It underlines the use for assessing risks of the FEP methodology, intended to provide a comprehensive catalogue of the risks and their mechanisms, of scenarios describing possible future evolutions of the storage sites and of models to represent these scenarios. It stresses the need to acquire more knowledge about long-term

well behavior, and to address uncertainties in the risk assessment models. Finally the potential to learn from natural and engineered analogues is emphasized.

Work undertaken to amend the conventions regulating injections under the sea-bed (*i.e.*, the London Convention/Protocol and the OSPAR Convention) have led to an agreement on a risk assessment framework (London Convention, 2006; OSPAR, 2007). It consists of six essential steps:

- a. Problem formulation: critical scoping step, describing the boundaries of the assessment;
- b. Site selection and characterization: collection of site-specific data;
- c. Exposure assessment: description of the movement of the CO₂ plume;
- d. Effects assessment: description of the response of receptors to CO₂ exposure;
- e. Risk characterization: integration of the exposure and effects information to estimate the likelihood of an adverse impact;
- f. Risk management: monitoring, planning, mitigation and remediation measures.

The development of a methodological framework for assessing risks associated with CO₂ storage operations is underway in the EC-funded project CO2ReMoVe. This framework is consistent with the guidelines established for offshore storage presented above (Korre and Durucan, unpubl.).

A study for the IEA Greenhouse Gas Programme examined the transposition of the usual Environmental Impact Assessment frameworks for use with CCS (IEA GHG, 2007a). It concluded that amendments are required to fit CCS activities, and that a single international guideline would be valuable. The current gaps detected hold to:

- The quantification of the impacts of a CO₂ release and the estimation of its probability, which are site-specific;
- The process of conducting a site performance assessment;
- The understanding of the health and environmental impacts of a release of CO₂ and impurities;
- The management of liability;
- The balance of positive climate change mitigation impacts against negative local impacts.

2.1.2 System-level modeling for risk assessment

Several studies have examined the general aspects of and methods for risk assessment, stressing the importance of addressing uncertainties and the need for the establishment of a common risk framework.

Stenhouse *et al.* (2006b) presents a briefing document based on a literature review and identified several methodologies for risk assessment:

- scenario analysis;
- fault/event tree analysis;
- expert judgment;
- screening-level analysis.

Stenhouse *et al.* (2006b) underscore the variety of analytical, semi-analytical or numerical models that can be used as well as the need to handle various kinds of uncertainties:

- parameter uncertainty;
- conceptual model uncertainty;
- modeling uncertainty;
- scenario/event uncertainty.

Stenhouse *et al.* (2006b) also underscore the value of establishing a technical standard for risk assessment.

A generic quantitative risk assessment for CCS was attempted by Vendrig *et al.* (2003). They do not focus exclusively on the underground part of the storage, considering also surface transport and injection facilities. As for the geological part, they identify major hazards through a “Structured What-If Technique” involving an expert panel. But they do not give quantitative estimates for the risk due to the considerable uncertainties that surround the various parameters and processes, concluding that risk levels “would be extremely site-specific.”

Bowden and Rigg (2004) propose in more detail the assessment methodology used by the GEODISC project: a systematic quantitative process based on the judgment of a panel of experts. Key risk events are identified in a list and evaluated in terms of likelihood, consequences and time scale of occurrence. Six key performance indicators are computed and compared against acceptability criteria. This method (entitled RISQUE) has been used for several sites in Australia.

Wildenborg *et al.* (2004) recommend a scenario approach based on a FEP database. The FEPs are screened and grouped then combined to form long-term evolution scenarios. Conceptual models are developed to represent these scenarios. Probabilistic simulations can then be run on numerical models to assess the risks. Such work is supported by the detailed FEP database constructed by TNO. Quintessa has also developed a FEPs database that can be used in a scenario approach (Maul *et al.*, 2005; Savage *et al.*, 2004). A FEPs database can be employed both in a “bottom-up” development of scenarios and models (as described by Wildenborg *et al.*, 2004) and in a “top-down” auditing of scenarios or models that are established by other means.

Viswanathan *et al.* (2008) and Stauffer *et al.* (2009) present a hybrid system-process model (CO₂-PENS) that is based on a PID-like approach to extending a FEPs analysis. The CO₂-PENS tool aims at integrating in a system-level model a number of process-level models representing:

- the storage reservoir;
- the cap rock;
- the potential release mechanisms;
- the transport of CO₂ from the reservoir;
- the release of CO₂ in surface.

The user chooses the processes he wants to take into account among a few items for each category. This constitutes sort of a graphical interface to the FEPs. The CO₂-PENS system model allows both a simplified analytical description of processes and the use of detailed process models (allowing coupling to a variety of process-level simulators). CO₂-PENS is being used in risk assessments for several of the field tests and demonstrations being conducted as part of the United States Department of Energy’s (US DOE’s) Regional Carbon Sequestration Partnership efforts.

Oldenburg and Bryant (2007) also decompose the system into process-level models. They focus on a simple certification framework. The storage complex is divided into compartments. The likelihood of a leak is evaluated by estimating the probability that a leakage pathway encounters the CO₂ plume on the one side, and a target on the other side. The CO₂ flux across the pathway is simulated through deterministic simplified models, and the impacts of the release compared to acceptable thresholds. A level of risk is obtained by the product of the values of the probability and the consequences. The Certification Framework is being used in risk assessments for several of the field tests and demonstrations being conducted as part of the US DOE's Regional Carbon Sequestration Partnership efforts.

2.1.3 Process level modeling for risk assessment

Risk assessment is necessarily supported by the use of a number of models. Gaus *et al.* (2008) review the use of geochemical and transport models for CO₂ storage, and in particular how they can be useful for assessing risks. Birkholzer *et al.* (2006) discuss the modeling needs in the light of the CO₂ release mechanisms shown by natural observations, putting the stress on CO₂ migration along a fault and hydraulic fracturing in the cap rock.

A number of studies have investigated methods to represent CO₂ leakage along wells. A quantitative methodology dedicated to the wells was developed by Gérard *et al.* (2006) to quantify risk levels. Risk levels are assigned based on the integrity of wells that penetrate the CO₂ reservoir, either during injection or abandonment phases. This method is being applied on several CCS storage sites (van der Beken *et al.*, 2006). The well is described as a combination of components. Each scenario—as defined by the properties of the different components—is assigned a probability. The severity of a scenario is evaluated based on the results of modeling fluid migration through the well to different target zones. For each scenario, the associated probability and the severity enable to quantify risk levels associated to well integrity. Nordbotten, Celia, and coworkers (Nordbotten *et al.*, 2004, 2005; Celia *et al.*, 2005, 2006) present analytical solutions for the extension of the CO₂ plume in the reservoir and the potential for leakage through wells. Frenette *et al.* (2006) present an assessment and decision support strategy, based on the evaluation of gas migrations through wells and components degradation, to evaluate well leakage, whereas Watson and Bachu (2007, 2008) present possible indicators for CO₂ leakage along wells.

The CO₂ behavior and impacts following a release constitute another point of interest for modeling. Duguid and Celia (2006) suggest analytical models for representing human exposure and estimating the level of risk to humans. Bogen *et al.* (2006) describe the coupled use of a dispersion model and a GIS system to detect potential areas where CO₂ accumulation could reach critical levels and provide an estimate of the risk.

Risks to the environment due to CO₂ releases are seldom treated in the literature, partly because of the limited understanding of the impacts on the ecosystems of CO₂ exposure (IEA GHG, 2007b).

2.1.4 Analog studies

Observations of natural analogs (*e.g.*, accumulations of CO₂ in geologic reservoirs and natural CO₂ vents) and industrial analogs (*e.g.*, experience from CO₂ enhanced oil recovery, storage of natural gas and acid gas disposal) are of utmost importance for risk assessment for CO₂ geological storage. Benson *et al.* (2002) draw lessons from natural analogs and from the performance of underground injection of liquid industrial waste, geologic disposal of radioactive waste and natural gas storage. IEA GHG (2006) compiles data from the latter sector to identify regulatory issues, site selection expectations and to infer incident frequencies from the feedback about natural gas storage.

Natural CO₂ atmospheric releases have been extensively studied. For instance, Beaubien *et al.* (2004) investigate the CO₂ fluxes, concentrations and effects on groundwater and humans in volcanic areas, with no significant human impacts being noticed. Yamamoto *et al.* (2006) examine CO₂ release mechanisms during seismic events in Japan. White *et al.* (2006) evaluate CO₂ fluxes above natural CO₂ reservoirs in Colorado and found the seals to be effective.

2.1.5 Field cases

Risk assessment activities have been carried out in a more or less thorough and structured way for several CCS pilot sites or projects. Most activities have relied heavily on FEPs analysis, and some have additionally conducted process-level simulations for predicted fate of CO₂ in the reservoir.

For Sleipner, Lindeberg, and Bergmo (2002) simulate the long-term fate of CO₂ at the site. They predicted that the CO₂ would be totally dissolved in the reservoir after 5000 years and that the maximum diffusion flux through the cap rock would be extremely low, only becoming significant ~100,000 years after injection.

Long-term behavior of the CO₂ and leakage risks at Weyburn were assessed within a methodological framework based on the FEPs, as described by Stenhouse *et al.* (2005). The Quintessa FEP database was initially developed for this application. A number of simulations were performed. Fully probabilistic calculations find a 95% probability that the cumulative amount of CO₂ released after 5000 years will be less than 1% of the total amount stored (Walton *et al.*, 2004). A deterministic model for transport in the reservoir with a probabilistic model for leakage through wells shows a maximum release of 0.14% of the total amount of CO₂ stored (Zhou *et al.*, 2004).

The GEODISC approach (Bowden and Rigg, 2004) has been used for several field cases in Australia, *e.g.* the Latrobe Valley (Hooper *et al.*, 2005) and the Otway Basin (Sharma and Cook, 2007). This semi-quantitative methodology relies on expert-panel analysis of a limited number of hazardous events, for which the likelihood, consequences, and timescale of occurrence of each is assessed. Comparably, a failure mode and effects workshop was organized for the Gorgon project (Chevron, 2005 and 2006); it discussed qualitatively the probability of the events, the safeguards and mitigation measures and the residual risk.

Risk assessments have been conducted for various sites within the CO₂STORE project. For the Valleys (Chadwick *et al.*, 2006) and Kalundborg (Larsen *et al.*, 2007) case studies, the

assessment was mainly qualitative and relied on the Quintessa FEP database. The process is comprised of an analysis of all relevant FEPs, the identification of the most important ones, and the development of a few scenarios involving these major FEPs. These scenarios were simulated using numerical reservoir models. For the Schwarze Pumpe case study, the Schweinrich structure was assessed according to the method recommended by Wildenborg *et al.* (2004) and Svensson *et al.* (2005). This assessment is more thorough than for the other two case studies; based on a systematic screening of the TNO FEP database and an evaluation of the interactions between the various events and processes, it results in the formation of safety scenarios that are then modeled. In these three cases, a major concern appears to come from long-term well integrity.

Four sites in consideration by the FutureGen project were submitted to a human health and environmental risk assessment as part of the Environmental Impact Statement (US DOE, 2007). Based on a comparison with natural and industrial analogs and on expert judgment, a semi-quantitative process was conducted to estimate potential CO₂ release risks, at a site screening level. The likelihood was assessed qualitatively, but the consequences of a release were quantitatively modeled.

Two sub-seabed formations below the Norwegian continental shelf have been the subject of a coarse risk assessment with the objective of ranking the sites in terms of risk and functionality (Eldevik *et al.*, 2007). The process was organized as an expert workshop and remained mainly qualitative. It consisted of the identification of the hazards using a brainstorming session (Structured What-If Technique), the selection of the three most relevant ones for each formation, and the discussion of their likelihood, possible consequences and mitigation measures. The exercise highlighted the lack of site representative data at this screening level as a barrier for risk assessment.

Another form of risk assessment was applied for investigating performance of the pilot site of the Mountaineer project (Ohio River Valley; Sminchak *et al.*, 2006). It exploited a qualitative rapid screening of the Quintessa FEPs database, designed to identify the potential critical events. Only a few items in the database were selected and analyzed in detail to identify recommendations for risk management.

The US DOE's Regional Carbon Sequestration Partnership (RCSP) initiative is conducting risk assessments as part of the Development Phase (Phase III) projects that were initiated in 2008. Nine large-volume tests are planned within the seven partnerships, with injections nominally on the order of ~1 million metric tons CO₂/year. Each of the partnerships is utilizing a slightly different approach to risk assessment, ranging from FEPs analysis to system-level modeling. The partnerships utilize a cross-cutting working group of scientists and engineers to compare approaches and models used in the process. In addition, US DOE has initiated a more comprehensive national risk-assessment activity within its Carbon Sequestration Program to support the effort within the RCSPs and other large scale demonstrations. This broad effort spans from development of simulation and risk-assessment tools to research on key fundamental phenomena (such as wellbore integrity). In addition, a group of researchers from several U.S. national laboratories—led by the National Energy Technology Laboratory—are helping to identify research paths to address any gaps in the risk assessment needs.

2.2 Key common risks and issues identified for engineered geological storage of CO₂

A common concern among many of the risk efforts is the presence of wellbores, which is believed to be an important factor in risk associated with leakage from the storage formation (Savage *et al.*, 2004). The risk may arise from wells active during the development and operation of the site, or through previously abandoned wells crossing the formation reservoir. Concerns include corrosion of casings and cements present in well completion and/or plugging and abandoning, as well as potentially poor initial completions. The analysis is complicated by a limited set of observations from cement exposed to CO₂+brine in an wellbore within an enhanced oil recovery operation (Carey *et al.*, 2007), which suggests that chemical reactions may cause the cement to equilibrate over time and, perhaps, cause precipitation in (closing of?) previously existing flow pathways. A detailed understanding is needed for wellbore integrity over time as a function of the variety of cement formulations under various potential reservoir conditions. IEA Greenhouse Gas Programme has a research network focused on this challenge.

The probability of a leakage through rock and faults is generally assumed to be lower in comparison with wellbores, provided the site selection and characterization is thorough. This assumption is based in part on studies from natural analogs, which suggest that the geological storage of CO₂ can be effective (Bradshaw *et al.*, 2005). In addition to the physical containment of CO₂ that is believed to dominate during early stages of most storage scenarios, a variety of additional trapping mechanisms (*e.g.*, mineralization and dissolution of CO₂ into brine) are believed to become important over decades (and longer), lowering the likelihood of CO₂ release with time (Damen *et al.*, 2003).

As noted, risk assessment typically relates both to potential events that could occur as well as to their potential impacts. There are two kinds of potential impacts (IPCC 2005):

- *Global impacts*—arising from the release of the CO₂ back to the atmosphere, which impacts the effectiveness of CO₂ storage.
- *Local and regional impacts*—relating to the direct or indirect impacts of CO₂ storage to humans or ecosystems, the environment, other resources, *etc.*

Direct impacts from exposure to CO₂ relate primarily to accumulation of CO₂ in poorly ventilated or confined areas. CO₂ is not toxic. There is no known health effect of chronic exposure to concentrations below 1%. The current average concentration of CO₂ in the atmosphere is ~0.038%. On the other hand, at concentrations above about 2%, CO₂ has a strong effect on respiratory physiology and at concentrations above 7–10%, it can cause unconsciousness and death (IPCC 2005). Consequently, the accumulation of CO₂ in a poorly ventilated area (*e.g.*, in confined outdoor environments, in caves, or in buildings) is a potential risk to humans and terrestrial ecosystems. Concentrations in surface air will be strongly influenced by surface topography and atmospheric conditions (Benson *et al.*, 2002). Because CO₂ is 50% denser than air, there is a potential risk of accumulation in confined spaces. The impact of a small leak on terrestrial and marine ecosystems is not well understood yet; still, some studies have highlighted this as a potential issue (Benson *et al.*, 2002; IEA-GHG 2007b).

Other potential impacts relate primarily to the movement of CO₂ (or other fluids) into other compartments in the geologic system. Migrating CO₂ can alter the chemistry of groundwater, either directly (by dissolving into the water and causing subsequent dissolution of other

inorganic and organic material into the water) or indirectly (by mobilizing and transporting components from another part of the geologic system into the groundwater). In the worst case, the impact may require water treatment prior to the use of groundwater for drinking or irrigation. Migration of CO₂ to other resource reservoirs in the subsurface is a potential risk associated with CO₂ leakage. An example might be the movement of CO₂ into a natural gas reservoir, which could impact the purity of the natural gas and, hence, require the separation of CO₂ following production of the gas. Finally, an additional potential impact relates to the displacement of brines (and potentially other fluids) by the injected CO₂, causing many of the same impact outlined for CO₂ movement.

Another class of potential impacts includes geomechanical and geophysical events. The injection of CO₂ at pressures higher than the formation pressure can induce fracturing, potentially creating new pathways for CO₂ migration. (However, it is expected that many regulatory agencies may require that pressures be maintained below the rock-fracturing pressure.) In addition, the injection of CO₂ raises reservoir fluid pressures, which in most cases is anticipated to dissipate over a large area. The change in stress state has the potential to induce seismic activity in the geologic system, which has been observed in a variety of reservoirs that have experienced large injection or production of fluids. Generally, these events are small in scale (posing no risk to surface structures) and can be used to map fluid movements through passive seismic monitoring.

2.3 Monitoring and mitigation options that support risk management for engineered geological storage of CO₂

2.3.1 Monitoring

Monitoring has a central role in the risk management: By coupling effectively with risk assessment, monitoring can reduce uncertainties in the predictions, can verify the predicted performance of the site, and can allow for early identification of issues that need to be mitigated. Another CSLF task force has focused on monitoring, so it is the intent here to provide a short discussion of monitoring in the context of risk assessment. The monitoring plan should be elaborated in the early stage of the project, once the initial risk assessment has been carried out. An effective monitoring plan is site specific and should take into account potential leakage pathways, potential magnitude of leakage events (flux rates), potential receptors and critical parameters affecting potential leakage as defined by risk assessment (Zakkour, 2007). Different methods can be used, individually or in combination. Monitoring should occur both during injection and post injection, and the data should be used in history matching to validate (and to improve) the predictive models that underpin the risk assessment. This, in turn, enables a continuous improvement of the geological model for the site, the risk assessment, and the monitoring plan. Monitoring has been widely addressed in many publications, among them: the IPCC 2005 Special Report, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Annex 1, Vol. 2, Chapter 5), the BERR Monitoring and Reporting Guidelines for Inclusion via Article 24 of the EU ETS Directive (Zakkour, 2007), the DTI Technology Status Report “Monitoring Technologies for the Geological Storage of CO₂ (DTI, 2005) etc. The IEA Greenhouse Gas Programme monitoring tool¹ enables a rapid selection of tools and methods as

¹ available at www.co2captureandstorage.info/co2monitoringtool

well as for additional sources of best practice. In addition, U.S. DOE has recently released a best-practices guide² to monitoring that has evolved out of the Regional Carbon Sequestration Partnerships' activities. However, technologies are likely to evolve rapidly in the forthcoming years with the increased demand and experience from large scale CCS operations, so best practices for monitoring must also remain dynamic.

2.3.2 Remediation

To date little work has been done in this matter. However, three main publications have done the preliminary researches and have outlined the situation.

Perry (2005) makes a list of some remediation techniques used by the natural gas storage industry (an industrial analog for the study of corrective actions in case of CO₂ leakage). The list is made upon ten reported incidents of leaks, divided into two categories: leaks through the well and cap rock leaks.

Leaks through the well can be handled by common oil and gas industry knowledge: well workovers, handling of wellbore leaks and blowouts, and eventually plugging and abandonment of the well.

Cap rock leaks are more difficult to handle, as there is far less experience than for well remediation. Perry (2005) lists three main leak mitigation techniques:

- *Shallow gas recycle*—This consists of producing the gas accumulated in a shallower reservoir and recycling it back into the storage reservoir.
- *Aquifer pressure control*—In order to prevent the gas from migrating out of the reservoir, pressure can be lowered by producing the formation water, or pressure in aquifers just above the storage reservoir can be increased by injecting water into it.
- *Caprock sealing*—This approach could rely on foams or cements, but the technique remains to be proven.

For control of potential leakage, Benson and Hepple (2005) list similar techniques to those of Perry (2005): pressure control for leaks from the storage reservoir, and standard well remediation techniques for leaks from active or abandoned wells. They also discuss remediation of the impacts of the leak. Options exist for remediation of leakage into shallow groundwater, leakage into the vadose zone and accumulation in soil gas, large releases to the atmosphere, indoor environments with chronic low level leakage, and accumulation in surface water. Mostly, common techniques used in environmental remediation can be adapted for CO₂.

A study on the feasibility of remediating CO₂ escaped into the vadose zone is presented in Zhang (2004). The successful treatment of the CO₂ saturated in stratified lake environments is described by Schmid *et al.* (2006).

IEA-GHG (2007c) is the last paper on the subject to date, and it mainly expands further the work initiated by Benson and Hepple (2005), particularly detailing remediation techniques for leakage through wells (including costs of possible prevention techniques and presumed costs of

² “Monitoring, Verification, and Accounting of CO₂ Stored in Deep Geologic Formations” (DOE/NETL-311/081508) can be found at: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf.

remediation). Economic issues will have to be studied a bit further as it will have an impact on the design of the project, and on the choice of the good remediation technique. Attention must be given to the time-scale of the intervention.

3. Ongoing and Emerging Activities on Risk Assessment for Engineered Geologic Storage of CO₂

3.1 *Risk assessment activities in various countries*

Several ongoing and developing efforts are investigating various aspects of risk assessment. Detailed summaries of these activities are provided in the appendix. Table 3.1 lists short descriptions of these activities.

Several common themes emerge from these efforts:

- FEPs analysis is widely exploited as part of both qualitative and quantitative assessments
- uncertainty plays a central role in many of the risk assessment approaches, requiring probabilistic approaches for various aspects of the assessment
- a variety of computational and mathematical tools have been developed, ranging from detailed reservoir models to system-level models to novel methods (such as Evidential Support Logic or ESL)
- risk assessments include not only the potential impact of CO₂ release to the surface but also subsurface impacts on groundwater, other resource reservoirs, mines, etc.

Table 3.1. Summary of international risk-assessment activities.

Country	Risk-Assessment Activity	Timing and Scale	Main Goals/Outcomes
Australia	GEODISC	ongoing	completion of a comprehensive and quantified risk assessment based on the RISQUE methodology; application of RISQUE to the Dongara, Petrel, Gippsland and Carnarvon areas
Australia	CO2CRC	completed	adaptation and development of the RISQUE methodology for application to CO2 storage
Australia	Latrobe Valley CO2 storage assessment (Monash Energy & CO2CRC)	completed 2005	assessment of viability, storage potential, uncertainties, and risks/impacts for an onshore storage site quantitative risk assessment using the GEODISC-RISQUE method recognized the potential risk of CO2 migration into oil production zones
Australia	Gorgon project (Chevron)	completed 2006	risk assessment performed in the context of an environmental impact assessment using a qualitative scoring system consistent with Australian/New Zealand standards on risk assessment

Table 3.1. Summary of international risk-assessment activities (cont'd.).

Country	Risk-Assessment Activity	Timing and Scale	Main Goals/Outcomes
Australia	ZeroGen		<p>implemented comprehensive risk assessment management system, including risk workshops, a risk register, and risk maps</p> <p>considered risks associated with power plant construction/operation (1.2 MtCO₂/year for 25 years) to pipeline to storage site</p>
Australia	Otway Basin pilot		<p>quantitative risk assessment using GEODISC-RISQUE method</p> <p>considered both engineered and natural systems</p> <p>natural CO₂ accumulations impact ability to identify injected CO₂ that is potentially released</p>
France–Germany	COSMOS-2		<p>developing novel scientific and technical guidelines for maximizing safe geological storage of CO₂ in saline formations using a field site at Ketzin (Germany)</p> <p>monitoring of CO₂ migration and wellbore integrity</p>
EU	MOVECBM	2006–2008	<p>improve understanding of CO₂ injected in coal, including associated migration of methane</p> <p>field tests in Poland (Kaniów) and Slovenia (Velenje)</p>

Table 3.1. Summary of international risk-assessment activities (cont'd.).

Country	Risk-Assessment Activity	Timing and Scale	Main Goals/Outcomes
EU	CO2ReMoVe	2006–2012	development of new risk assessment tools and a rigorous risk assessment methodology for a variety of sites
FP5 EU	CO2STORE	2003–2005	investigation of lessons learned from the other previous projects to provide sound, science-based methods for assessment
France	Lacq Project	2006–2014	After a preliminary phase of hazard identification, 11 scenarios were identified by expert judgment. Probability of occurrence was assessed based on field studies, experience from the natural gas production (well and reservoir knowledge), and numerical simulations (including geomechanical, geochemical coupled with transport)
Japan	JGC Corporation	2005–2007	determination of the applicability and effectiveness of proposed safety assessment method based on evidential support logic (ESL) and exploiting the IEA FEP database and an expert panel
Japan	Mitsubishi Research Institute, Inc.	2006–2007	goal of developing international standards of safety assessment methodology confidence building with ESL tool

Table 3.1. Summary of international risk-assessment activities (cont'd.).

Country	Risk-Assessment Activity	Timing and Scale	Main Goals/Outcomes
Japan	Research Institute of Innovative Technology for the Earth (RITE)	2006–	evaluation of fracture permeability in seals
Japan	Ministry of the Environment	2008–2011	investigation of the Environmental Management System for the sub-seabed geological storage of CO ₂
United States	Regional Partnership program (consisting of 7 multi-organizational partnerships)	ongoing	<p>phase I included high level capacity assessment and development of a national storage site database</p> <p>phase II includes small scale (10² to 10⁴ ton) injections of CO₂ into a variety of geologic environments as well as preliminary risk assessments (mostly based on analysis of FEPs)</p> <p>phase III includes large scale injections (nominally ~1 million tons CO₂ per year) and the development of more rigorous site-specific risk assessments (ranging from FEPs to reservoir simulations)</p>

Table 3.1. Summary of international risk-assessment activities (cont'd.).

Country	Risk-Assessment Activity	Timing and Scale	Main Goals/Outcomes
United States	Carbon Sequestration Program (Office of Fossil Energy in the Department of Energy)—Regional Carbon Sequestration Partnership Program and Core R&D Program	ongoing	<p>several small, focused risk assessment studies at various national laboratories</p> <p>development of detailed reservoir simulation capabilities (primarily continuum-scale reactive transport)</p> <p>assessment of long-term integrity of hydrodynamic seals, including a large focus on physics/chemistry of integrity of cemented wellbores</p> <p>detailed experiments on fluid-rock interactions to predict long-term CO₂ fate and impact</p> <p>development of system models for assessing site performance and risk (e.g., Certification Framework and CO₂-PENS)</p>
United States	Carbon Sequestration Program (Office of Fossil Energy in the Department of Energy)—National Risk Assessment Program	ongoing	<p>multiple US DOE national labs integrating efforts from across the US DOE program with results from other efforts (both from within the US and internationally) as well as conducting additional coordinated and collaborative research to cover key remaining gaps</p> <p>products will include development and validation of new tools and technology as well as findings based on assessments of critical issues</p>

Table 3.1. Summary of international risk-assessment activities (cont'd.).

Country	Risk-Assessment Activity	Timing and Scale	Main Goals/Outcomes
United States	Center for Zero Emission Research and Technology	ongoing	fundamental science on fluid-rock interactions and monitoring methods and tools
International Energy Agency Greenhouse Gas Program	International Risk Assessment Network	2005–	coordination of international research efforts on risk assessment addressing the expectations of regulators with respect to risk assessment
International Energy Agency Greenhouse Gas Program	Wellbore Integrity Network		coordination of international research efforts on wellbore integrity and its impact on long-term CO ₂ storage
International Energy Agency Greenhouse Gas Program			assessment of what is known about the impacts of CO ₂ leakage onshore, to clarify issues related to surface impacts

4. Proposed next steps for CSLF risk assessment task force

4.1 Recommendations to consider passing to the Policy Group

The task force noted several aspects of risk assessment that it believes the Technical Group should pass to the Policy Group for further consideration by individual members:

- *The link between risk assessment and liability should be recognized and considered.* Risk assessment is the process by which potential impacts of, and risks posed by, a CCS operation can be evaluated. Consequently, responsibilities and liabilities can be defined and assigned. The identification of potential impacts and mitigation needs raises the issue of defining liabilities up front such that sound business decisions can be made.
- *Establish acceptable risk levels – Storage-integrity goals for sites should be discussed.* As noted, risk assessment is a process by which potential impacts and their likelihood can be identified and quantified, but it does not determine which potential impacts or likelihoods are acceptable goals. Storage-integrity goals are the measure by which decisions can be made based on the results of a risk assessment, and they are necessary to define the accuracy and precision of monitoring needs. Often, performance goals (such as storage-integrity goals) underpin regulatory frameworks.
- *The use of risk assessment to ensure successful storage at sites should be considered in the context of stakeholder outreach and communication.* When well structured, risk assessment can be an effective communication tool for demonstrating that the potential consequences of storing CO₂ have been considered carefully and thoroughly, thereby demonstrating the commitment to ensuring public safety and environmental protection.

4.2 Recommendations for next steps for consideration by Technical Group

The task force identified the following issues requiring further attention:

- *A gap assessment to identify CCS-specific tools and methodologies that will be needed to support risk assessment.* This analysis should be considered by the PIRT as they identify research areas that the CSLF should encourage.
- *The feasibility of developing general technical guidelines for risk assessment practices that could be adapted to specific sites and local needs, and subsequently development of such guidelines.* The need for a common framework was stressed in many of the articles reviewed by the task force. In discussing this, the task force concluded that a standardized framework on which to base risk assessments would be difficult to achieve given the wide variation both in site-specific attributes and in country-specific needs/approaches. However, generalized approaches exist that could be adapted or modified for CCS applications. Those approaches can contribute to technical guidelines that might lead to a more common approach for risk assessment at various sites.

In the task force's assessment, accomplishing this will require significant resources to complete, which will require consideration before timelines and goals are set.

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Appendix: Detailed summaries of risk assessment activities in various countries

A.1 Risk Assessment Activities in Australia

A.1.1 Introduction

Several projects have carried out risk assessment activities with respect to geological storage of carbon dioxide in Australia. Carbon dioxide storage risk assessment was first applied in Australia during the Australian Petroleum Cooperative Research Centre's (APCRC) GEODISC³ research program. Recent examples of Australian CO₂-storage risk assessment activities include those related to current or planned carbon dioxide storage projects, including the Monash Energy / CO2CRC Latrobe Valley CO₂ storage assessment, Chevron's Gorgon project, the ZeroGen project and the CO2CRC's Otway Basin pilot project.

A.1.2 Existing risk management guidelines

In terms of standards or guidelines with respect to risk and uncertainty assessment and management, the 2004 Australia and New Zealand Risk Management Standard provides "a generic framework for establishing the context, identifying, analyzing, evaluating, treating, monitoring and communicating risk".⁴ Existing environmental risk management / environmental management system standards are also applicable.^{5,15} However, no formal standards or universally accepted and / or practiced methodologies exist for risk assessment/management of geological storage of carbon dioxide in Australia.

A.1.3 Risk assessment and Australian CO₂ storage projects

Examples of where risk assessment has been applied in some form to CO₂ storage activities in Australia include the GEODISC project, the joint Monash Energy-CO2CRC Latrobe Valley CO₂ Storage Assessment project, Chevron's Gorgon project, the ZeroGen project and CO2CRC's Otway Basin pilot project.

A.1.4 GEODISC Project

One requirement of the GEODISC research program (continuing in the APCRC's follow-on program, CO2CRC) was the completion of a comprehensive and quantified risk assessment to assess technical, social and economic risks associated with geological storage of CO₂ in Australia⁶. In order to do this, an appropriate risk assessment methodology (RISQUE) was developed jointly with Business Risk Strategies (URS). Several papers describe in detail the risk

³ GEOlogical DISposal of Carbon dioxide

⁴ Standards Australia and Standards New Zealand. 2004. Australian / New Zealand Standard Risk Management, AS/NZS 4360:2004. (preface, p. iii)

⁵ Standards Australia. 2004. Handbook - Environmental risk management - Principles and process, HB 203:2006.

assessment methodology and results of the GEODISC research project^{6,7,8,9,10} (see especially Bowden and Rigg⁶, 2004 and summarized here).

The RISQUE method of risk assessment has been applied both in GEODISC and the CO2CRC⁶. This approach uses quantitative techniques to characterize risk in terms of likelihood of risk events occurring and their consequences (risk quotient = likelihood × consequence) through best practice risk assessment methods and information provided by an expert panel, and is consistent with the Australian risk management standard⁴. The method generates quantitative expressions of risk, risk profiles and benefit-cost relationships resulting from a staged process of risk assessment (establishing the context, risk identification, risk analysis, development of a risk management strategy, and implementation of the strategy).

The key aims of the assessment were to assess the risk of leakage, the effectiveness of the intended reservoir, and adverse consequences to aid in comparing alternative sites. Less easily quantifiable community and environmental issues were also included. For GEODISC, the method was applied to four conceptual CO₂ injection projects - the Dongara, Petrel, Gippsland and Carnarvon areas. The risk assessment carried out for these four sites enabled ranking of the projects and a comparison between them to choose the most suitable injection site.

Potential risk and uncertainty factors proposed and considered include:

- Containment - leakage through permeable zones in seal, faults, wells, seal, and at the facility;
- Regional and local scale over-pressurization;
- Capacity - exceeding spill point, over-filling, lack of capacity;
- Reduced injectivity;
- Earthquake induced fracturing;
- Rock fabric failure;
- Migration direction;
- Infrastructure failure – well head, pipeline, compressor, platform or decommissioning failure and facility environmental damage;
- Stakeholder and public perception;
- Inadequate source;
- Groundwater displacement;
- Regulatory change and legal claims (licensing, ownership, liability);

⁶ Bowden, A.R. and Rigg, A. 2004 (1). Assessing risk in CO₂ storage projects. The APPEA Journal, 2004, pp.677-702. <http://www.co2crc.com.au/PUBFILES/GEODISC/15BowdenRigg.pdf>

⁷ Bowden, A.R. and Rigg, A. 2004 (2). Assessing reservoir performance risk in CO₂ storage projects. GHGT7 Proceedings. http://www.co2crc.com.au/PUBFILES/STOR0405/GHGT7Bowden_Rigg_AssessRisk.pdf

⁸ Bradshaw, J., Bradshaw, B., Allinson, G., Rigg, A., Nguyen, V., Spencer, L. 2002. The potential for geological sequestration on CO₂ in Australia: preliminary findings and implications for new gas field development. The APPEA Journal, 2002, pp.25-46.

http://www.co2crc.com.au/PUBFILES/GEODISC/03Bradshaws_AusPotential.PDF

⁹ Rigg, A., Allinson, G., Bradshaw, J., Ennis-King, J., Gibson-Poole, C., Hillis, R., Lang, S., Streit, J. 2001. [The search for sites for geological sequestration of CO₂ in Australia: a progress report on GEODISC](http://www.co2crc.com.au/PUBFILES/GEODISC/02_RiggSiteSearch.PDF). The APPEA Journal, 2001, pp.711-725. http://www.co2crc.com.au/PUBFILES/GEODISC/02_RiggSiteSearch.PDF

¹⁰ Streit, J., Watson, M. 2004. Estimating rates of potential CO₂ loss from geological storage sites for risk and uncertainty analysis. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies.

- Contamination (surface water and groundwater, soils, petroleum resources) and subsurface biological concerns;
- Injection engineering conditions;
- Project costs (viability).

Key performance indicators developed to address the risk assessment aims for each site were:

- Reservoir performance – containment and effectiveness;
- Greenhouse benefits – project viability and macro level greenhouse benefits;
- Community impacts – community safety, and amenity and environment.

Derived outputs of the risk assessment, at both broad (whole site) and detailed levels (e.g. identifying key contributors to risk at a given site), needed to:

- Address key performance indicators;
- Enable comparison of sites;
- Include technical, economic, and community risk events;
- Assist in communication of risk to stakeholders;
- Be able to be incorporated into risk management design of injection projects;
- Help to identify areas of future research.

A.1.5 Latrobe Valley CO₂ Storage Assessment Project

The Latrobe Valley CO₂ Storage Assessment (LVCSA) project considered the viability and potential to store CO₂ emissions from Victoria's Latrobe Valley in the offshore Gippsland Basin, an early assessment of the risks and uncertainties of a major infrastructure development¹¹. The Latrobe Valley, located within the onshore Gippsland Basin, is rich in brown coal and the area is responsible for large volumes of CO₂ emissions (per unit of electricity). The offshore Gippsland Basin is a major petroleum province and contains significant mature petroleum fields, which, when depleted, could potentially store CO₂ emissions from onshore emission locations. Risk assessment activities in relation to CO₂ storage are summarized and extracted from the LVCSA Final Report (2005)¹¹.

With respect to risk assessment, this project addressed issues such as storage assurance, that is, the potential risks and uncertainties of geological storage in the target area; potential impacts, risks, and uncertainties of infrastructure development and operation; and interaction with petroleum producers in the region, since target areas for CO₂ storage are also target areas for petroleum exploration and production. Risk assessments were performed on the infrastructure (preliminary and quantitative assessments) and geological storage integrity components of the project. The preliminary risk assessment identified potential impacts, risks and uncertainties, and proposed mitigation actions. The more detailed quantitative risk assessment and risk modeling identified hazards associated with compression and transport of CO₂ and pipeline leaks. Both found that the risks associated with infrastructure are low and manageable by industry. A quantitative risk assessment was also applied to the geological storage component using the GEODISC method (see previous section), and suggested that CO₂ could be contained to an acceptable level.

¹¹ Hooper, B., Murray, L., Gibson-Poole, C. (eds). 2005. Latrobe Valley CO₂ storage assessment, final report. CO2CRC Report no. RPT05-0108. http://www.co2crc.com.au/PUBFILES/OTHER05/LVCSA_FinalReport.pdf

Possible adverse impacts on oil production from CO₂ injection. A recognized but unevaluated risk is that CCS activities could compromise adjacent oil and gas production. Current production facilities in the area are not equipped to process / separate high concentrations of CO₂ from oil and gas, and there is a possibility that, due to geological uncertainties, CO₂ injected adjacent to producing fields could migrate at a much faster rate than expected potentially causing problems in production.

The quantitative risk assessment (QRA) carried out for the geological storage (containment) aspect of the project used the GEODISC method⁶, relying on the assessment of a panel of researchers from various disciplines. The context of the QRA for the studied site(s) was defined, including injection timeframes, locations, and amounts; reservoirs and expected plume migration (including to existing wells and faults); and eventual traps.

Containment risk. Components of containment risk (risk of leakage) assessed for each area include:

- Permeable zones in seal;
- Leakage from faults (through seals);
- Leakage from wells (exploration, production and injection);
- Regional and local over-pressurization;
- Exceeding spill point (insufficient capacity);
- Earthquake induced fractures;
- Migration detection (*e.g.* incorrect prediction of migration direction);
- Compressor, platform, pipeline and well head failure.

A.1.6 Gorgon Project

The Chevron-Shell-ExxonMobil Gorgon Project will store CO₂ resulting from the production of natural gas in the Greater Gorgon area fields (North West Shelf), located off the coast of Western Australia. The separated CO₂ will be injected into the Dupuy Formation beneath Barrow Island¹². Prior to the project's approval, Chevron was required to complete and submit an environmental impact assessment of the proposed Gorgon Project. This included a risk assessment of the CO₂ storage aspects of the project. In September 2005 Chevron submitted a draft Environmental Impact Statement / Environmental Review and Management Programme for the Gorgon Development¹³, and the Final Environmental Impact Statement / Response to Submissions on the Environmental Review and Management Programme for the Proposed Gorgon Development was completed in May 2006¹⁴. The EIS details the risk assessment process used as well as its results, some of which are summarized here.

The environmental risk assessment process (for detailed description see chapters 9 and 13 of the EIS¹³) evaluated the likelihood (using a qualitative scoring system) and consequences of adverse

¹² Malek, R., Bartlett, R., Evans, B. 2004. A technical appraisal of storage of Gorgon CO₂ at Barrow Island, North West Shelf. APPEA Journal 2004, pp.639-646.

¹³ Chevron, 2005. Draft Environmental Impact Statement / Environmental Review and Management Programme for the Gorgon Development. 2005. September 2005. http://www.gorgon.com.au/03moe_eis.html

¹⁴ Chevron, 2006. Final Environmental Impact Statement / Response to Submissions on the Environmental Review and Management Programme for the Proposed Gorgon Development. May 2006. http://www.epa.wa.gov.au/docs/gorgon/EIS_Gorgon_ERMP.pdf

environmental impacts occurring as a result of some stress. The assessment was completed in accordance with standards including the Australian/New Zealand standards on Risk Assessment, Risk Analysis of Technological Systems¹⁵, and the handbook on Environmental Risk Management. Potential risks and environmental consequences were identified by technical experts in a broad range of fields through a series of workshops. Some deterministic “what if” scenarios as well as a probabilistic approach were taken with respect to managing uncertainties associated with CO₂ storage, including identifying, evaluating, and generating options for managing subsurface risks.

Extensive monitoring activities (including seismic, monitoring wells, geochemistry of water and soils) are planned to manage and reduce uncertainty associated with CO₂ injection / storage activities. A CO₂ Injection Operations Management Plan has been proposed to manage events such as unpredicted migration of the CO₂, unacceptable formation pressures, corrosion of pipelines and wells, and others. However, the probability of CO₂ migrating to the surface has been determined to be remote. Studies of the area have determined that the containment risk (risk of containment failure) is extremely low, and unacceptable risk associated with CO₂ storage at any point would likely result in venting of the CO₂ to the atmosphere. Risk and uncertainty factors for injection and storage include:

- Risk to existing assets including producing oil / gas fields;
- Distance from CO₂ source to sink (this addresses risks associated with transportation);
- Risk of migration out of the reservoir (*e.g.* into overlying formations) and risk of unexpected or faster than predicted migration (*e.g.* through high permeability layers or due to unexpected pressure gradients);
- Risk of leakage through faults (which resulted in a choice of injection sites and migration paths away from faults, as well as acceptable reservoir pressures to prevent migration through faults);
- Risk of leakage through existing wells;
- Risk of inadequate top seal;
- Structural uncertainty;
- Risk of lower than predicted/required injectivity rate due to: low permeability or permeability heterogeneity, reduced pore volume / distribution, reservoir compartmentalization, residual oil saturation, or mineralization near the injection well;
- Risk of insufficient capacity;
- Microseismicity (fracturing or fault reactivation due to injection);
- Ability to image / monitor CO₂ (once injected);
- Health and safety risks to people;
- Environmental risks to Barrow Island;
- In addition, risks associated with CO₂ injection infrastructure leading to CO₂ leakage into the atmosphere or groundwater reservoirs were considered (*e.g.* mechanical failure of equipment, pipeline, well casing).

Potential impacts on the project were evaluated in terms of: health, safety, and environmental issues; containment; monitoring and verification; injectivity; capacity; risk to hydrocarbon /

¹⁵ Standards Australia and Standards New Zealand. Risk Analysis of Technological Systems – application guide. AS/NZS 3931:1998.

other assets; cost. Responses to these potential impacts (such as using relief wells, if necessary, to release formation pressure and mitigate the risk of migration along faults or fractures) were developed and are described in the EIS.

The risk assessment on Gorgon was extended in 2008 to reflect a proposed increase in the scale of the project from 10 million tonnes per year of LNG to 15 million tonnes per year, with a commensurate increase in the rate of CO₂ injection. This extended assessment process included an update of the CO₂ injection failure modes and effects work. The EIA document containing this work can be found at: http://www.gorgon.com.au/03moe_environmentalreview.html.

A.1.7 ZeroGen Project

ZeroGen Pty Ltd (ZPL) is planning to build and operate a commercial-scale demonstration power station which will integrate coal gasification with capture and storage of CO₂. In December 2007, ZPL was advised of a strong sentiment within the project funders to “steepen the risk curve” and accelerate the development of a commercial-scale IGCC with CCS plant by 2020. In response to this request, in March 2008 the project was reconfigured into a larger two-staged approach. This involved the deployment of a 120MW gross capacity IGCC with CCS plant (Stage 1), and a 450MW gross capacity IGCC with CCS plant in 2017 (Stage 2).

During the development of Stage 1, however, discussions and funding exploration initiatives in Japan presented a new opportunity from which an accelerated pathway for the development of a commercial-scale IGCC with CCS plant might be achieved, whilst addressing the principal technical integration risks. The current proposal consists of an IGCC plant with a gross capacity of approximately 550MW with CO₂ capture, without the need to construct the smaller Stage 1 plant.

In relation to CO₂ storage, ZPL has been actively investigating the Denison Trough as a potential CO₂ storage site for a demonstration project since 2006. Based on current information, the Denison Trough indicates a P₁₀ storage potential of 100 million tonnes if the adjacent depleting gas fields are also available for storage. Further work will be required to delineate the field to improve the probability of storage from P₁₀ to P₈₀. This additional work commenced in early 2009 and has already identified promising possibilities.

A comprehensive risk assessment management system was implemented for the project (as is applied to all new projects). This consisted of a series of risk assessment workshops which identified and assessed all potential risks in all activities and tasks for each phase of the project, and proposed appropriate control measures. This information was used to develop a preliminary risk register and risk maps, which will be developed further as the project advances and control measures are implemented in order to minimize risk.

Studies with respect the storage of CO₂ have shown that the northern Denison Trough is potentially suitable for the injection and storage of up to 2MtCO₂/year for 30 years. The containment risk (risk of leakage) for the saline reservoirs of interest was assessed as very low for the chosen location. For the containment risk analysis, factors considered were the geological configuration of the basin, the absence of present day seismic activity, and the placement of wells away from sites that could act as future leakage points. Other issues include interaction

with landowners and holders of petroleum and mining leases. An exploration program is currently underway to confirm the capacity and costs of the storage.

A.1.8 Otway Basin Pilot Project

The CO2CRC's Otway Basin Pilot Project (OBPP) is located in Victoria, and will initially involve injection of 100,000t of CO₂ into a depleted gas field^{16,17,18}. Risk areas have been identified through the project's risk assessment process and an extensive monitoring and verification scheme has been proposed to address some of these issues.

A Quantitative Risk Assessment was performed using the RISQUE method (see GEODISC section) for the Otway Basin project. This process involves the use of expert panels to provide input into a quantitative risk analysis and management framework. Both the engineered system (wells, processing plant and the gathering line) and the natural system (site geology, reservoir formation, overlying and underlying formations and groundwater flow regimes) were considered. The QRA will be modified as new data becomes available - further work is underway to evaluate the containment risk assessment, using information from a recently drilled well. Factors under review include permeable zones in the seal, leakage through faults, regional and local scale over-pressurization and migration direction as well as impacts on water resources and surface land use. Uncertainties related to monitoring include the presence of natural accumulations of CO₂ in the area, making it difficult to distinguish the injected CO₂ in the subsurface.

Other uncertainties addressed for this project include public perception of geological storage as well as uncertainties regarding the regulatory and legal environment (given the current general lack of CO₂-storage appropriate legislation and regulatory framework at state and federal levels). Research and community consultation activities have/will attempt to address some of the public perception issues surrounding CCS.

A.2 Ongoing "Risk-Assessment Related" Activities in France

There are nine entities in France involved in risk assessment studies for geological storage of CO₂:

- Public Institutes: BRGM (Bureau de Recherches Géologiques et Minières), IFP (Institut Français du Pétrole), INERIS (Institut national de recherches sur l'environnement et les risques industriels), and CEA (Centre d'Études Atomiques)
- Research laboratories: LAEGO-INPL (Institut National Polytechnique de Lorraine)

¹⁶ Dodds, K., Etheridge, D., de Vries, D., Sharma, S. 2006. Developing a monitoring and verification scheme for a pilot project, Otway Basin, Australia. Abstract, Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies.

¹⁷ Sharma, S., Cook, P., Robinson, S., Anderson, C. 2007. Regulatory challenges and managing public perception in planning a geological storage pilot project in Australia. International Journal of Greenhouse Gas Control, I (2007), pp.247-252.

¹⁸ Etheridge, D., Leuning, R., Luhar, A., Spencer, D., Coram, S., Steele, L.P., van der Schoot, M., Zegelin, S., Allison, C., Fraser, P., Porter, L., Meyer, C.P., Krummel, P. 2007. Atmospheric monitoring and verification of geosequestration at the CO2CRC Otway Project. CO2CRC Report No. RPT07-0735.

- Private companies: GDF-Suez, Schlumberger, Oxand and GEOGREEN.

A.2.1 *COSMOS 2*

COSMOS-2 is a transnational German-French project supported by the Eurogia program (EUREKA Cluster) and related to the COSMOS German project, in turn centered on the CO₂ injection site of Ketzin (Germany).

COSMOS-2 aims at developing novel scientific and technical guidelines for maximizing safe geological storage of carbon dioxide (CO₂) in deep saline aquifer formations. Its particular focus is on technologies for monitoring and modeling CO₂ displacement and storage containment.

This will be achieved by verifying CO₂ injection and migration processes, while assessing and mitigating the risk of storage leakage through the cap rock or wells. The three main components of COSMOS-2 project are:

- The monitoring of the CO₂ migration in the reservoir using electrical imaging technology, and the development of measurement interpretation techniques for a quantitative analysis of these measurements.
- The monitoring of wellbore integrity using cased-hole logging techniques, and the integration of the measures with a simulator of completion degradation processes to assess quantitatively the risk of leakage through the wells.
- The modeling and monitoring of the cap rock integrity during the injection phase.

COSMOS-2 follows a similar transnational project (COSMOS-1) whose particular focus is on the development of novel materials and monitoring technologies for CO₂ injection projects.

A.2.2 *CO2ReMoVe*

CO2ReMoVe is a consortium of industrial, research and service organizations with experience in CO₂ geological storage. The consortium proposes a range of monitoring techniques, applied over an integrated portfolio of storage sites, which will develop:

- 1) Methods for base-line site evaluation
- 2) New tools to monitor storage and possible well and surface leakage
- 3) New tools to predict and model long term storage behavior and risks
- 4) A rigorous risk assessment methodology for a variety of sites and time-scales
- 5) Guidelines for best practice for the industry, policy makers and regulators

BRGM, IFP and Schlumberger are partners of CO₂ReMoVe. IFP is the coordinator of the Subproject 2 (SP2), Performance assessment and mitigation.

A.2.3 *CO2GeoNeT*

CO₂GeoNeT is a Network of excellence (NoE), which includes 13 institutes and contains a critical mass of research activity in the area of underground carbon dioxide storage. Its main objective is to form a durable and complementary partnership comprising of a critical mass of key European research centers whose expertise and capability becomes increasingly mutually interdependent. The initial partnership will be between 13 institutes, most of whom have a long and established history of research in geological sequestration. Some new players are also

included, either because they are expected to have significant national strategic profile in future CO₂ storage projects, or have capabilities which can be realigned to strengthen the network, or even bring uniqueness. BRGM and IFP are partners of CO₂GeoNet. BRGM is presently the Network manager.

A.2.4 CO2STORE

CO2STORE is a research project involving 19 participants from industry and research institutes. The project aims at preparing the ground for widespread underground storage of CO₂ in aquifers, investigating how lessons learned from the other previous projects on this matter (like SACS, GESTCO, NASCENT) can be implemented on other aquifers in Europe, not only offshore, but also onshore. Through careful evaluation and application of both existing and novel approaches, the project will provide sound, scientifically-based methodologies for the assessment, planning, and long-term monitoring of underground CO₂ storage.

More specifically, CO2STORE main goals are to:

- Investigate the feasibility of alternative and smaller CO₂ reservoirs
- Investigate the final fate of CO₂ injected into the Utsira reservoir near the Sleipner field
- Investigate alternative cost-effective monitoring techniques
- Update documentation needed for dissemination of the technology

BRGM, IFP and Schlumberger are partners of the project.

A.2.5 MOVECBM

MOVECBM is a research project partially funded by the European Commission involving around 20 partners. The objective of the MOVECBM project is to improve the current understanding of CO₂ injected in coal and, hence, the migration of methane thus ensuring a long-term reliable and safe storage. In the MOVECBM project modeling and laboratory work are performed that will be based on parameters of the previously investigated test site in Kaniów, Poland by the EC RECOPOŁ project.

In addition to the field production test in Kaniów, a small scale combined injection and production experiment will be carried out in the Velenje coal mine in Slovenia. Horizontal injection and production wells in the coal are used to investigate adsorption desorption and migration processes for local coal conditions. The results from the mine are expected to provide the missing information between the larger scale field experiment in Kaniów and the laboratory work. The above mentioned experiments will allow testing optimal storage and production regimes, but also the corresponding optimal monitoring methodology.

OXAND and Schlumberger are partners of the project.

A.2.6 Lacq CO₂ Capture and Geologic Storage Pilot Project**Project Title:**Lacq CO₂ Capture and Geological Storage Pilot Project (France)**Lead Organization(s) and Point(s) of Contact (w/e-mail):**

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Duration:*State and completion dates (if applicable):*

Ongoing (the project started in 2006). Injection should start in 2009 and the project should end 5 years later (2014)

Injection and monitoring dates (if applicable):

2 years of injection followed by 3 years of observations (5 years in total)

Dates & short description of key risk assessment milestones:

Risk assessment was performed for the licensing process (still ongoing) during 2008. This included an Environmental Impact Study and a "Danger assessment". The latter includes a description of the different risk scenarios (especially leakage scenarios), the monitoring plan and the possibility of intervention and gas extraction in case of leakage ».

The application was surveyed by BRGM (June 2008) and a public consultation was carried out during 2 months, from 21/07/2008 to 22/09/2008. Results of the public consultation were published in October 2008 and the licensing process should be finished in April 2009.

Scale of Injection (if applicable):100 000 tons of CO₂ in 2 years**Risk Assessment Methodology:**

After a preliminary phase of hazard identification, 11 scenarios were identified by expert judgment. Probability of occurrence was assessed based on field studies, experience from the natural gas production (well and reservoir knowledge), and numerical simulations (including geomechanical, geochemical coupled with transport). The likelihood was found negligible for all 11 scenarios. The consequences of the most unfavorable scenario were studied more in depth: the eruptive well. They were found very limited.

The long term risks were not taken into account in the preliminary studies but all the gas should be extracted in case of any problem. Some researches are planned to continue during the exploitation phase.

Brief Summary:

The main objectives of the Lacq-Rousse project are to demonstrate the feasibility of the whole CCS chain, capture, transport and storage and to validate the injection and reservoir monitoring techniques.

The capture plant will be installed on a natural gas processing plant in Lacq. The capture technology used will be oxy-combustion.

The CO₂ will be injected in the depleted Natural Gas reservoir of Rousse, 30km away from Lacq (SW of France)

[The page on the institutional website](http://www.total.com/fr/responsabilite-societale-environnementale/dossiers/captage/COE-engagement-Total/CO2-pilote-Lacq_11347.htm) : http://www.total.com/fr/responsabilite-societale-environnementale/dossiers/captage/COE-engagement-Total/CO2-pilote-Lacq_11347.htm

Key Risk Assessment Findings (if applicable)

In the 11 scenarios studied, all the risks, considering the prevention measures taken and the monitoring plan chosen, are retained as acceptable.

The events are :

- Leakage through the caprock
- Leakage through existing faults
- Lateral gas leakage
- Leakage through the well into an aquifer situated above the reservoir
- Leakage along the wellbore to the surface
- Mechanical troubles due to geochemical reactions in the reservoir
- Mechanical troubles due to gas injection
- Mechanical trouble of the rocks in case of an earthquake
- Effect of an earthquake on the well
- Subsequent drilling of a perforating well
- Eruptive well

A.3 Risk assessment related activities in Japan

#1
Project Title: Study on safety assessment approaches for a proposed CCS project
Duration: 2005 to 2007
Conducted by: JGC Corporation
Brief Summary: <p>As part of the feasibility study for a proposed CCS project, safety assessment approaches have been examined. The purpose of this examination includes determining the applicability and effectiveness of the proposed safety assessment method, which aims at confidence building in stakeholders.</p> <p>The proposed method is based on Evidential Support Logic (ESL). ESL is a generic mathematical concept to evaluate the confidence in a decision on the basis of the evidence theory, and it utilizes interval probability theory. The degree of confidence in a proposition can be evaluated with this method. In this study, the proposition is a leakage scenario.</p> <p>The proposed method was applied to a site and the confidence in the following three leakage scenarios was evaluated:</p> <ul style="list-style-type: none"> - High permeable structures in the cap rock - Development of preferential leakage pathways due to the reaction of carbonate with CO₂-saturated formation water - Degradation of well sealant due to cement deterioration <p>These scenarios were constructed using the IEA FEP list and natural gas analogy, as well as after discussions among the expert panel.</p>

#2
Project Title: Development of international collaboration for building confidence in CCS
Duration: 2006 to 2007
Conducted by: Mitsubishi Research Institute, Inc.
Brief Summary: <p>With the aim of developing international standards of safety assessment methodologies, confidence building methods were studied. First, the project reviewed the arguments related to the effectiveness of CCS technology. The arguments discussed here are based on natural and industrial analogs, geological knowledge, reservoir simulation, and monitoring data. Second, the project discussed the management of uncertainty with reference to the case of nuclear reactors and radioactive waste disposal. Methodologies to structure uncertainty by “ignorance” were presented.</p> <p>Finally, guidelines for confidence building were developed. The key messages of the guidelines are:</p> <ul style="list-style-type: none"> - Share the different viewpoints of different stakeholders - Utilize various arguments from different phases of the CCS project, from both scientific and engineering aspects - Support project planning by figuring out the degree of confidence at every point of the process - Share the confidence not only in technical reports but also in other media. <p>The project also presented an example of confidence building using the ESL tool.</p>

#3
Project Title: A study on fracture permeability of seal formations
Duration: April,2006 to present
Conducted by: Research Institute of Innovative Technology for the Earth (RITE)
Brief Summary: <p>Evaluation of fracture permeability of seal formations is necessary to assess CO₂ storage risks. It is assumed that small faults and fractures occur in deeply seated seal formations. Upper Tertiary mudstones from Hokkaido and Chiba areas in Japan were cored out, cut and fractured for the laboratory test. As the permeability measurement, the oscillation method and the steady-state flow method were applied to these intact mudstones, precut mudstones and fractured mudstones. Measurements were carried out under confining pressures until effective pressures reached to the pressure of equivalent to 1,500 meters in depth.</p> <p>Results were as follows:</p> <p>The intact mudstone showed very low permeability under the every effective pressure. The fractured and precut mudstones indicated that they were high permeable under the low effective pressures and were very low permeable under the effective pressures of over ca.25 MPa. From the experiments, these fractures were inferred to be almost closed under the effective pressure of 25 MPa and more, which was equivalent to 1,000 meters in depth.</p> <p>From now on, we will continue the same laboratory tests with different samples and add data to estimate the fracture permeability of seal formations.</p>

#4
Project Title: Investigation of the Environmental Management System for the Sub-Seabed Geological Storage of CO ₂
Duration: 2008 to 2011
Conducted by: Ministry of the Environment, Japan
Brief Summary: <p>In line with the amendments to Annex I to the London Protocol 1996, Japan has amended the Marine Pollution Prevention Law in order to manage and implement the sub-seabed geological storage of CO₂ (offshore CCS) in an appropriate manner, and since then, the Ministry of the Environment (MOE) has been making efforts to establish a detailed regulatory framework for offshore CCS.</p> <p>Offshore CCS is now subject to the permits issued by the Minister of the Environment, with applicants being required to prove that their activities do not have any adverse effects on the marine environment. The documents required for the permit application include the environmental impact assessment (EIA) report and monitoring plan.</p> <p>As the responsible authority, the MOE has recognized the necessity for sufficient knowledge/resources to examine the permit applications, and has begun the investigations for the development and further improvement of the methodologies of EIA and monitoring for offshore CCS. This project continues for 3 years and will be completed in 2011.</p> <p>The following is a description of the project with respect to the risk assessment:</p> <ul style="list-style-type: none"> - This project has intends to characterize the general risks and potential impacts of CO₂ leakage. For this purpose, the representative site conditions in Japan are used as a model case. - The project used scientific and technical knowledge including natural/industrial analogs and the FEP database to identify the possible leak scenarios. On the basis of these leak scenarios, the conditions of possible seepage into the ocean will be predicted using the geological models and extrapolated into the newly developed ocean model. Given the nature of the law, this project focuses on the impact on marine environment. - In parallel with the above activities, the project has been monitoring the CO₂ at a natural analog site with a view to developing and verifying the appropriate monitoring techniques: these data will be used to validate the above models.

A.4 United States

The US DOE's Regional Carbon Sequestration Partnership (RCSPs) initiative is conducting risk assessments as part of the Development Phase (Phase III) projects that were initiated in 2008. Nine large-volume tests are planned within the seven partnerships, with injections nominally on the order of ~1 million metric tons CO₂/year. Each of the partnerships is utilizing a slightly different approach to risk assessment, ranging from FEPs analysis to system-level modeling. The partnerships utilize a cross-cutting working group of scientists and engineers to compare approaches and models used in the process.

The US DOE Sequestration program as a number of projects targeted at developing the science base and tools necessary to ensure the success of large scale CCS projects. Two areas of research emphasis within the US DOE core R&D program address this, including Simulation and Risk Assessment (which includes the development of predictive tools for the performance of storage systems) and Monitoring, Verification, and Accounting (which includes the development of tools and protocols for verifying that storage goals are met). Another area of research emphasis (Geologic Carbon Storage) is developing the understanding of geological systems, including as necessary to assess risk.

In addition, US DOE has initiated a more comprehensive risk-assessment activity within its Sequestration Program to support the effort within the RCSPs and other large scale demonstrations. This broad effort spans from development of simulation and risk-assessment tools to targeted research on key fundamental phenomena (such as wellbore integrity). The National Risk Assessment Program was initiated in 2009 as an effort to build a broad base for integration of risk-related R&D activities. Researchers from several U.S. national laboratories—led by the National Energy Technology Laboratory—are helping to identify research paths to address any gaps in the risk assessment needs. The group is additionally conducting coordinated and collaborative research to cover these key remaining gaps. Products from this effort will include development and validation of new tools and technology as well as findings based on assessments of critical issues.

A.5 IEA GHG Risk Assessment Activities

The IEA GHG has been working on the topic of risk assessment for a number of years now. From early discussions on the topic, the key message was that to gain public acceptance of CO₂ capture and storage, two key areas will need to be demonstrated: that the technology is safe and that its environmental impact is limited. Safety can be demonstrated to some extent through monitoring programs at CO₂ injection operations that are currently underway. However, whilst early results from these injection operations indicate leakage is not occurring, such programs do not necessarily provide confidence in the long-term *i.e.* 1000's years after injection has ceased.

The IEA GHG felt that risk assessment studies can assist the development of monitoring programs for injection sites, relying on predictions of the long-term fate of the injected CO₂ and assessing the potential for leakage in both the short and long-term. To gain public acceptance of CO₂ capture and storage (CCS) the regulators and public will also need to have confidence in the predictions made by the risk assessment studies. To gain such confidence it will be necessary to understand the different approaches being used and the assumptions underlying the results. The results should be produced in an open and transparent manner, so that the results are understood and the implications for ecosystems and human health can be fully appreciated.

The cornerstone of the IEA GHG Programme's risk assessment work is the IEA GHG International Risk Assessment Network. The Network was formally launched in 2005 in the Netherlands after two preliminary meetings in the UK in 2004 and in Canada in 2005.

The purpose of the network is to bring together the key groups working on risk assessment for CO₂ storage from around the world and to address what the regulators are expecting in regard to CCS assurance and whether risk assessment can provide the answers they require.

The outcome of the launch meeting was the agreement that the research network should aim to address what the regulators are expecting and whether risk assessment can provide the answers they require. The scope of the Risk Assessment Network was divided into a number of smaller and more specific subject areas, Data Management and Risk Analysis, Regulatory Engagement and Environmental Impacts. To continue to promote the progress of the network, working groups were created that focused on these more specific areas and run alongside the operation of the network. The working groups direct their own work, reporting back to the network at the annual meeting. The working groups are diverse in topic but allow participants in the network with special interest to focus on specific areas.

The establishment of the working groups also helped to highlight interest groups such as Regulatory bodies, NGO's and scientific specialists that are missing from current risk assessment discussions and those who should be encouraged or approached to join in the future.

The 2nd meeting of the Risk Assessment Network was held in the USA in 2006 and follows on from the developments of the Launch Meeting held in 2005.

The workshop aimed to provide:

- Overviews of other relevant international research network activities that impact on the risk assessment network, in particular the well bore integrity network.

- Provide feedback from the working groups on key topics that had been set up from the previous meeting.
- A review of the current status of risk assessment using case studies
- Assess the role of risk assessment in a the framework of risk management
- Assess how best to communicate the results of risk assessment studies.

The specific outcomes of the program covered a number of aspects of CCS risk assessment activity including risk assessment in a risk management framework, site characterization, use of natural analogues, risk assessment communication, and the risk assessment review of four case studies.

Risk assessment was identified as part of a larger risk management framework. Risk assessment was defined as the means of identifying, estimating or calculating and evaluating potential risks of CO₂ storage to human health and safety, the environment and assets. Risk assessment can be considered as problem oriented. Risk management on the other hand deals with assessing, monitoring and remediating risks to conform to risk acceptance levels. Risk management is therefore solution oriented. When the results of risk assessments in relation to CCS are looked at, more emphasis should put on the 'solution' instead of the 'problem', especially when we communicate the risks involved.

Following discussions on site characterization, it was agreed that site characterization would need to be a step wise process, with initial pre-screening an important aspect which would allow poor sites to be screened out early, allowing efforts to be concentrated on those sites that have the best potential. Risk assessment was identified as one tool that can be used in the early screening of storage sites. It was highlighted that risk assessment and site characterization both work in an iterative manner, and are involved over different project stages from preliminary screening to permitting to implementation. It was also noted that there will be increasing data requirements as you proceed to each stage.

Natural analogues were discussed and were identified as a method that could be used to build confidence in CCS. There are several ways that natural analogues could be used in this way which include:

- Helping geologists to understanding the leakage and trapping mechanisms,
- Verification of numerical models and risk assessment procedures,
- Interpretation and risk management,
- Helping to communicate the safety of CO₂ storage sites.

By building up a database of events from natural and industrial analogues comparable to those that could occur from a CO₂ storage reservoir you can build a risk matrix that allows you to compare and communicate the risks of CCS in a way that is readily understandable.

Risk assessment studies were discussed and were seen to be able to provide guidance on likely seepage rates from storage sites but they cannot define the impacts of leakage. Environmental Impact Assessments (EIA) can provide the framework for assessing the long term impacts of leakage. However, it was shown that at the time there was little research work underway that is addressing specifically the effects of CO₂ leaks and their potential impacts that could allow an EIA to be compiled. This research gap is now being addressed.

There was a clear feeling that risk assessment is only part of the message that needs to be given to regulators; remediation is another important issue as well. Also, we need to get the message over that we are not promoting innovatory technology, to avoid over regulation.

A major component of the second risk assessment network meeting was the review of four risk assessment cases studies. Three of the case studies were based on aquifers and one on an oil field operation. It should be emphasized that several of these cases were not complete risk assessment studies but were rather scoping studies. The results of such studies should therefore be treated with some care when communicated outside of the technical community. The aquifer based assessments generally suffered from a lack of data, which resulted in a lot of assumptions needing to be made. The oil field case was much better characterized which allowed a more detailed risk assessment process to be undertaken. All the assessments used expert panels which involve a degree of subjective analysis. Expert panels need to be drawn from as wide a group of individuals as possible whereas the groups involved in these assessments tended to be drawn internally from the research organizations involved. The oil field study gives us some confidence that CO₂ can be retained in that formation for 1000's of years but the same degree of confidence cannot be drawn from the aquifer studies. The studies have, however, contributed significantly to the learning process for undertaking such studies which will be of benefit in the future and help to allow us to better define the data requirements needed to complete a good robust risk assessment. More risk assessment studies are needed to help develop confidence in the techniques and models used as well in the results they generate.

The 3rd and most recent meeting of the Risk Assessment Network took place in the UK in 2007. The key topics up for discussion at the meeting were whether to use quantitative, qualitative, or simple analytical methods to analyze CCS risk, risk assessment terminology, site characterization and the feature, event, process (FEP) risk assessment method. The meeting also included representatives from the Wellbore Integrity Network, who provided the meeting with an overview of the status and lessons learned in the network and how they may apply to the risk assessment process. The Wellbore Integrity network was born out of the Risk Assessment Network to address the more technical issues surrounding the long-term integrity of wellbore seals.

In the conclusion of the 3rd meeting a number of issues were identified that will steer the agenda for the next meeting of the Risk Assessment Network. In regard to risk assessment technology, Imperial College performing a study that tries to identify and define key terms that are integral to CCS risk assessment communication. The terms identified are drawn from CCS literature and associated industries. The next step in this work is to circulate a questionnaire to people within the industry to try and build consensus on the terms to use and their definition. One suggestion was to set up a *Wikipedia* style website to act as a forum to build an agreed pool of terms.

A key discussion from this workshop was around the process of site characterization. This is a common theme running throughout the Risk Assessment Networks and was explored in this meeting but not resolved. The issue remaining is determining how much site characterization is enough to satisfy all the stake holders involved in a CCS project.

There was a lot of discussion in this network about whether to use quantitative, qualitative, or simple analytical methods to analyze CCS risk. The debate seemed to conclude that it would be

ideal to have a fully quantitative risk assessment process but currently it would not be possible for anything more than a semi-quantitative or predominantly qualitative process to be used. This led to a discussion on the use of expert panels in risk assessment which was seen as a process that needs formalization.

Following the session on the FEP risk assessment process it was found that this process is just one tool of many and the general feeling was that it was better suited as an auditing tool rather than the primary tool for risk assessment.

There were also a number of additional issues/questions raised over the course of the network that need to be addressed. These include:

- Risk assessment guidelines? – are they required and if so, what is the best way of formulating them?
- How confident are we in the modeling results we are generating for CCS projects?
- How long do we need to monitor for after the cessation of CO₂ injection?
- What use is the accident/worst case scenario risk assessment approach to the overall risk assessment process?

On top of the work done by the risk assessment network members themselves, the network also identified a need to begin a dialog with the regulatory bodies on what their needs and expectations are for risk assessment as part of a regulatory process for CCS. This led to a study with the aim of to begin that dialog process with the regulatory bodies. The study was carried out by Monitor Scientific Inc. of the USA and was completed in early 2007.

The study involved first the development of a briefing document and questionnaire on risk assessment for geological CO₂ storage projects. The briefing document reviewed the status of risk assessment for CCS and served as a reference document for future actions.

The questionnaires were used as a means of determining the ability of existing or planned legislation in different countries, to enable the authorization of CCS projects.

Both documents were sent to regulators and implementers of CCS projects in different countries to form the basis for dialog concerning their individual roles in their respective CCS projects. Regulators and implementers from a total of ten countries were consulted and participated in the study. The countries concerned were; Australia, Canada, France, Germany, Japan, Netherlands, New Zealand, Norway, U.K., and U.S.A. The countries selected were considered to give a comprehensive coverage of those countries currently most active in this area of CCS implementation.

The issues related to and the results of this dialog process have proved useful in a two way education exchange. As a result of the dialog IEA GHG could conclude that regulators, in particular, were better informed on the current status of risk assessment when applied to CCS projects. Whilst risk assessment is not a new tool, its application to CCS is new and requires considerable more development before we can be confident in the results that risk assessment studies will produce.

The study highlighted that there are a number of key areas that need to be addressed such as; the estimation of possible fluxes to the surface and their impact on the surface environment. In the flux case we need to correlate information from monitoring activities with geological/geochemical/hydrological modeling to allow us to gain confidence that predicted fluxes from risk assessment analyses can be justified scientifically. On the issue of surface impacts IEA GHG has recently undertaken a study to assess what is known about the impacts of CO₂ leakage on shore, which should help to begin to clarify issues related to surface impacts.

For the future developments of risk assessment, demonstration projects will undoubtedly be a significant source of information that can be drawn upon to help develop confidence in results. It should be noted however that when developing demonstration projects we need to consider the developmental needs for risk assessment as part of the activity to ensure that we do not leave any gaps that might result in the confidence of the scientific community and the general public in the predictions of risk assessment to be undermined. Demonstration projects will naturally take a time to produce the required results; in the mean time we should look to natural and industrial analogues as sources of information that can be used to generate confidence in geological storage of CO₂ as a safe and environmentally acceptable mitigation option.