PCOR PARTNERSHIP BEST PRACTICES MANUAL FOR SUBSURFACE TECHNICAL RISK ASSESSMENT OF GEOLOGIC CO₂ STORAGE PROJECTS

Plains CO₂ Reduction Partnership Phase III
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GLOSSARY OF RISK MANAGEMENT TERMS FOR GEOLOGIC STORAGE OF CO₂*

Containment	Vertical and lateral retention of CO_2 and affected fluids within a storage complex
Event	A material occurrence of change in a particular set of circumstances
Geologic Storage	The long-term isolation of CO_2 streams in subsurface geologic formations
Impact	The adverse effect of a risk on a particular project attribute, for example, cost, schedule, scope, or quality
Induced Seismicity	Refers to typically minor earthquakes and tremors that are caused by subsurface injection of fluids that alters the stresses and strains on Earth's crust
Injectivity	The rate and pressure at which CO_2 can be pumped into the storage unit without fracturing the formation
Likelihood	A chance of something happening, described by specifying a probability or frequency over a given period
Primary Seal (cap rock)	The low-permeability, continuous geologic unit (known in reservoir engineering as cap rock and in hydrogeology as aquitard or aquiclude) that confines a storage unit immediately above or below it and that constitutes an effective barrier to the leakage of fluids from the storage unit
Risk	The combination of the severity of consequences (negative impacts) of an event and the associated likelihood of its occurrence
Risk Analysis	A process for understanding the nature and level of risk
Risk Assessment	The overall process of risk identification, risk analysis, and risk evaluation
Risk Controls	Measures whose purpose is to reduce risk
Risk Evaluation	The process of comparing the results of a risk analysis with threshold criteria to determine whether 1) the risk, its magnitude, or both are acceptable or tolerable or 2) treatment is required to reduce the risk
Risk Identification	The process of finding, recognizing, and describing risks
Risk Management Process	A scheme that specifies the approach, components, and resources to be applied for the management of risks
Risk Register	A list of individual risks that have been identified for a storage project based upon a review of the project by representatives of the project developer and subject matter experts
Risk Treatment	A process to modify risk through the implementation of risk controls
Significant Risk	A risk that has been evaluated to require the implementation of an appropriate risk treatment.
Storage Capacity	The mass of CO_2 that can be stored within a particular storage complex
Storage Complex	A subsurface geologic system comprising a storage unit and primary and, possibly, secondary seal(s), extending laterally to the defined limits of the CO_2 storage operation or operations
Storage Project	A component of a CO_2 capture and storage operation that includes site selection and characterization, baseline data collection, permitting, design and construction of site facilities (e.g., site pipelines, compression, etc.), well drilling, delivery of CO_2 to the storage site and CO_2 injection during the active injection phase, site closure (including well and facilities abandonment), and postclosure, also includes testing and monitoring during all project phases
Storage Facility	An area on the ground surface, defined by the operator and/or regulatory agency, where CO_2 injection facilities are developed and storage activities (including monitoring) take place
Storage Site	Comprises the storage facility and the storage complex
Storage Unit	A geologic unit into which CO_2 is injected (e.g., depleted oil or gas reservoir or deep saline reservoir)
Threshold Criteria	Terms of reference against which the significance of risk is evaluated

* These definitions are consistent with the definitions of Canadian Standards Association (CSA) Group Standard Z741-12, a joint Canada–U.S. initiative (Canadian Standards Association, 2012); the Project Management Institute Body of Knowledge (Project Management Institute, 2008); and the International Organization for Standardization 31000, an international standard for risk management (International Organization for Standardization, 2009).

**PCOR PARTNERSHIP BEST PRACTICES MANUAL FOR SUBSURFACE
TECHNICAL RISK ASSESSMENT OF GEOLOGIC CO₂ STORAGE PROJECTS**

EXECUTIVE SUMMARY

In 2003, the U.S. Department of Energy established the Regional Carbon Sequestration Partnerships (RCSP) Initiative to help develop technology, infrastructure, and regulations needed to facilitate large-scale carbon dioxide (CO_2) geologic storage (herein "storage") and support deployment of commercial carbon capture and storage projects. The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is one of seven partnerships created by this program. The PCOR Partnership is publishing a series of best practices manuals for each of the four PCOR Partnership-defined primary technical elements of a storage site: site characterization; modeling and simulation; risk assessment; and monitoring, verification, and accounting. This document describes the risk assessment process for evaluating subsurface technical risks associated with a CO_2 storage project.

Risk assessment is the iterative process of identifying, analyzing, and evaluating individual project risks. In the context of a CO_2 storage project, risk is the combination of the severity of consequences (negative impacts) of an event and the associated likelihood of its occurrence. Risks can affect the operational performance and long-term safety of CO_2 storage. The focus of this document is on establishing the context of the risk assessment and conducting a risk assessment through identification, analysis, and evaluation. Risk treatment, communication, and monitoring are outside the scope of this document and are not included.

The PCOR Partnership has conducted a series of risk assessments as part of its RCSP activities. This experience includes two Phase III demonstration projects (large-scale projects with a target of storing 1 million metric tons or more total CO_2) involving dedicated CO_2 storage in a deep-saline formation and associated CO_2 storage incidental to CO_2 enhanced oil recovery (CO_2 EOR). Additional subsurface technical risk assessments were also conducted for other storage projects within the PCOR Partnership region. In addition to the Phase III demonstration projects, there are many completed and ongoing carbon capture and storage-related projects within the PCOR Partnership region. Collectively, this experience was used to develop a best practice for conducting risk assessments for implementing CO_2 storage projects, with a focus on subsurface technical risks related to injection into a storage complex.

This best practices manual identifies the key elements comprising a risk assessment for a CO_2 storage complex and defines important risk management terminology and technical factors that are unique to the geologic storage of CO_2. It also provides best practices for implementing a risk assessment based on lessons learned from conducting risk assessments for storage complexes within the PCOR Partnership region (Figure ES-1). Case studies of these real-world examples, which highlight key aspects of applying the risk assessment process to storage projects, are provided to support the proposed best practices.

The development of a best practice requires the execution of multiple projects where the knowledge gained and lessons learned are accumulated over time and integrated to yield a best practice. This development progression is an adaptive management process whereby best practices constantly evolve over time in response to knowledge gained and lessons learned. This document encompasses the current body-of-knowledge and best practices for applying a standardized risk assessment approach within risk management for storage projects. Application of these best practices will provide reliable and consistent standards for identifying project-related risks, analyzing the probabilities and potential impacts of these risks, evaluating which risks require treatment, and determining priority for treatment implementation. These best practices will continue to evolve and be refined over time as commercialization of the CO_2 storage industry proceeds.

Establish the Context
- Define the storage system and boundaries.
- Define the risk criteria, including probability and impact scoring tables.

Risk Identification
- Conduct elicitation of internal and external stakeholders and subject matter experts.
- Use an independent risk management expert to facilitate the process.
- Aggregate all available site characterization, geologic modeling, and reservoir simulation results to assist in the process.
- Generate a functional model of the storage site, including system components or subsystems, functions of each component, and system interactors.
- Ensure that the following four technical risk categories are considered, as these are common among storage projects: 1) storage capacity; 2) injectivity; 3) lateral and vertical containment of CO_2 or formation fluids, including oil for CO_2 EOR sites; and 4) induced seismicity.
- If this is a risk assessment update and the team is beginning with a prior risk register, then modifications to the risk register should be thoroughly documented for future reference. Moreover, the original risk register entry numbers should be retained for consistency over the project life cycle. New risks should be appended to the end of the original risk register list.

Risk Analysis
- Develop a set of quantifiable physical consequences and a means to link these physical consequences to project impacts.
- Consult predictive simulations to estimate probabilities associated with risks related to injectivity, storage capacity, and lateral and vertical containment of CO_2 and other fluids.
- Use an electronic template to capture risk scores from the respondents.
- Prior to finalizing a set of risk scores, verify outlying scores (extremely low or high scores relative to the group of scores) with individual experts.
- Quantify the uncertainty in the risk scores using either visual tools such as heat maps or statistical measures such as the expected value and standard deviation.

Risk Evaluation
- Plot each individual risk onto a risk map, which plots the risk probability score against the risk impact score.
- To evaluate uncertainty in the risk scores, generate risk maps for both the expected value and maximum risk scores.
- If a more quantitative risk evaluation is needed, employ probabilistic methods such as Monte Carlo simulation.
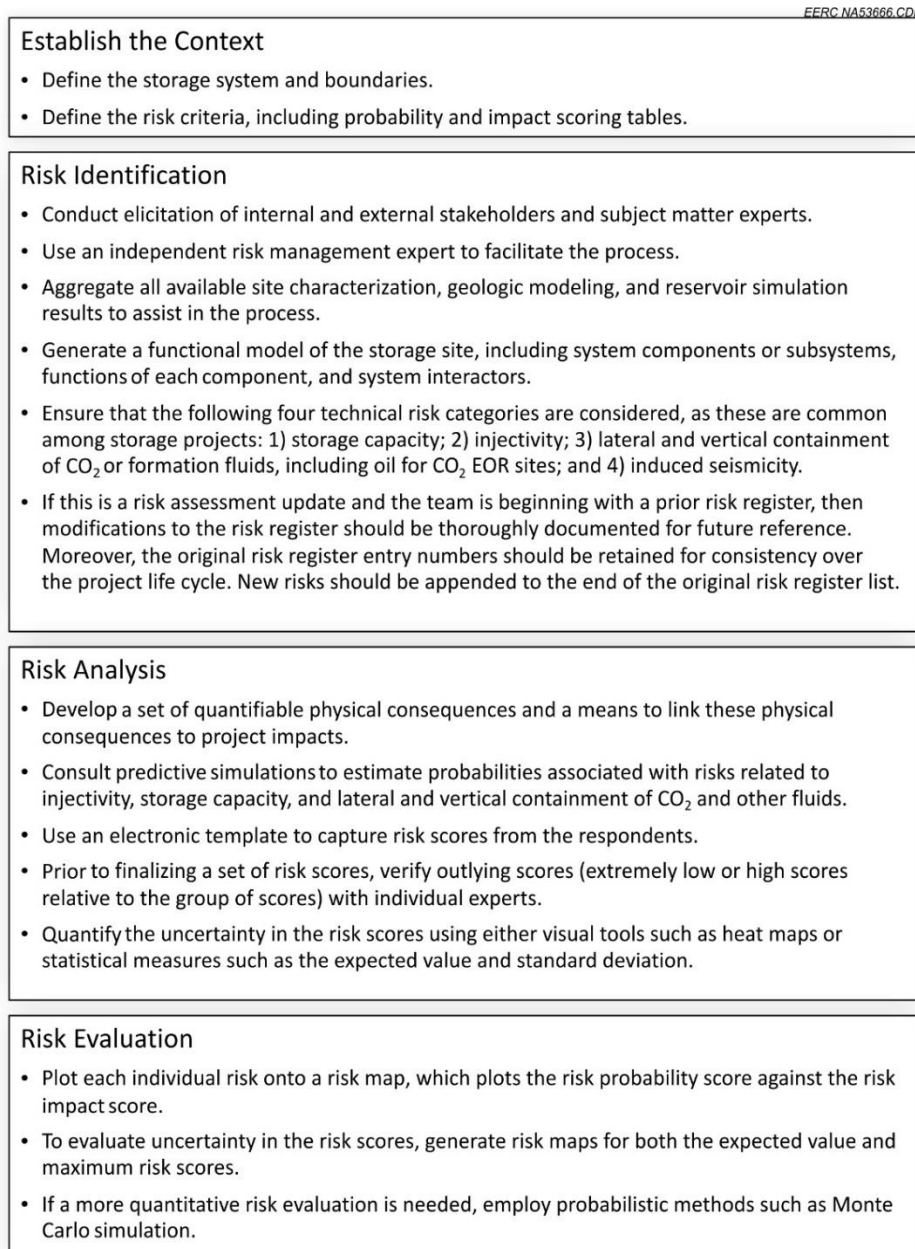
Figure ES-1. A best practice workflow for conducting risk assessments for storage projects.

PCOR PARTNERSHIP BEST PRACTICES MANUAL FOR SUBSURFACE TECHNICAL RISK ASSESSMENT OF GEOLOGIC CO₂ STORAGE PROJECTS

1.0   INTRODUCTION

In 2003, the U.S. Department of Energy (DOE) established the Regional Carbon Sequestration Partnerships (RCSP) Initiative to help develop technology, infrastructure, and regulations needed to facilitate large-scale carbon dioxide (CO_2) geologic storage (herein "storage") and support deployment of commercial carbon capture and storage (CCS) projects. The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is one of seven partnerships created by this initiative. The PCOR Partnership includes over 120 public and private sector stakeholders and covers an area of over 1.4 million square miles (3.6 million square kilometers) in the central interior of North America, including portions of Canada and the United States (Figure 1).

Figure 1. Map showing the PCOR Partnership region (Ayash and others, 2016).

A series of best practices manuals (BPMs) is being published for each of the four PCOR Partnership-defined primary technical elements of a storage site:

- Site characterization
- Modeling and simulation
- Risk assessment
- Monitoring, verification, and accounting (MVA)

These BPMs are derived from extensive PCOR Partnership regional characterization and field demonstration experience acquired via activities conducted throughout the PCOR Partnership region. An additional BPM has also been developed that encompasses best practices for integrating these technical elements into an iterative, fit-for-purpose adaptive management approach (AMA) for commercial storage project deployment. The AMA BPM is intended to provide guidance to project developers, regulators, and others interested in evaluating and developing CO_2 storage opportunities and serve as a useful reference for CO_2 storage technical specialists.

This BPM describes the risk assessment process that can be applied throughout the five PCOR Partnership AMA-defined life cycle phases of a storage project:

- Site screening
- Feasibility assessment
- Design
- Construction/operation
- Closure/postclosure

The focus of this document is on establishing the context of and conducting a risk assessment through identification, analysis, and evaluation.

The technical terms used in this document are in general agreement with the definitions of Canadian Standards Association (CSA) Group Standard Z741-12, a joint Canada–U.S. initiative (Canadian Standards Association, 2012); the Project Management Institute Body of Knowledge (Project Management Institute, 2008), and International Organization for Standardization (ISO) 31000, an international standard for risk management (International Organization for Standardization, 2009).

2.0   GEOLOGIC STORAGE

Storage projects can be broadly divided into two types: dedicated storage and associated storage. Dedicated storage involves the underground injection of anthropogenic CO_2 solely for the purpose of greenhouse gas (GHG) mitigation. The Sleipner project in the Norwegian North Sea has been injecting approximately 1 million tonnes of CO_2 per year since 1995 into a deep saline formation (DSF), and several other dedicated storage projects are now operating at a similar large-scale around the world (Global CCS Institute, 2017). Associated storage occurs as a result of CO_2 injection for other purposes, most commonly CO_2 enhanced oil recovery (EOR). CO_2 EOR was first undertaken in Texas in the 1970s, and over 100 CO_2 EOR sites are now operational in the

United States (Oil & Gas Journal, 2014). The technology is also being deployed in other countries, including Canada, Brazil, Mexico, and Saudi Arabia (Global CCS Institute, 2017).

Although predominantly linked to CO_2 EOR, associated storage could also result from enhanced coalbed methane (ECBM) or enhanced gas recovery (EGR) operations; however, these scenarios remain unproven at commercial scale. Despite associated storage being a direct result of CO_2 EOR, in many cases, operators of such sites might not seek recognition of GHG mitigation benefits because of various economic, regulatory, or legal considerations. CO_2 EOR projects are driven by the economic benefit of producing oil that may otherwise not be recoverable by primary or secondary production methods. Storage of CO_2 is a consequence of the EOR process, rather than a process goal. During EOR operations, a significant portion of injected CO_2 is produced along with oil, separated and purified as needed, and reinjected for additional oil recovery. As a result of the separation and recycle operations applied at EOR sites, CO_2 storage accounting may be more complex than in dedicated storage scenarios. Nevertheless, in standard commercial practice, essentially all of the CO_2 purchased is ultimately stored through CO_2 EOR operations.

The PCOR Partnership region encompasses significant CO_2 storage resource potential with large-scale operational CCS projects including both dedicated and associated storage (Peck and others, 2016). Extensive regional and site characterization activities for both storage scenarios have been undertaken by the PCOR Partnership, and this experience has informed the writing of this BPM. While the best practices described herein have been drawn from lessons learned in the PCOR Partnership region, many of the recommendations are applicable to other storage environments and scenarios, including offshore projects.

3.0   PCOR PARTNERSHIP ADAPTIVE MANAGEMENT APPROACH

The PCOR Partnership has formalized and implemented an AMA for the assessment, development, and deployment of commercial storage projects (Ayash and others, 2016). The AMA represents a fit-for-purpose approach that can be tailored to the needs of each project, ensuring that the necessary technical elements are appropriately and cost-effectively applied to generate the knowledge needed to enable project implementation. The AMA architecture is shown in Figure 2. The core of the AMA consists of four key technical elements (Table 1), conducted with varying scopes and levels of intensity as a project moves through each of the five life cycle phases of commercial development (Table 2).

As shown in Figure 2, multiple go/no-go decision points along the development pathway illustrate where the developer may review project status and confirm that progress is adequate to advance to the next phase. The goal of the AMA is to efficiently deploy and integrate the four technical elements as needed throughout a storage project to cost-effectively meet the technical, economic, and regulatory objectives and requirements of each phase, thereby maximizing potential for successful project implementation. Summary descriptions of the five project phases are presented in Table 2, and additional information can be found in Ayash and others (2016).
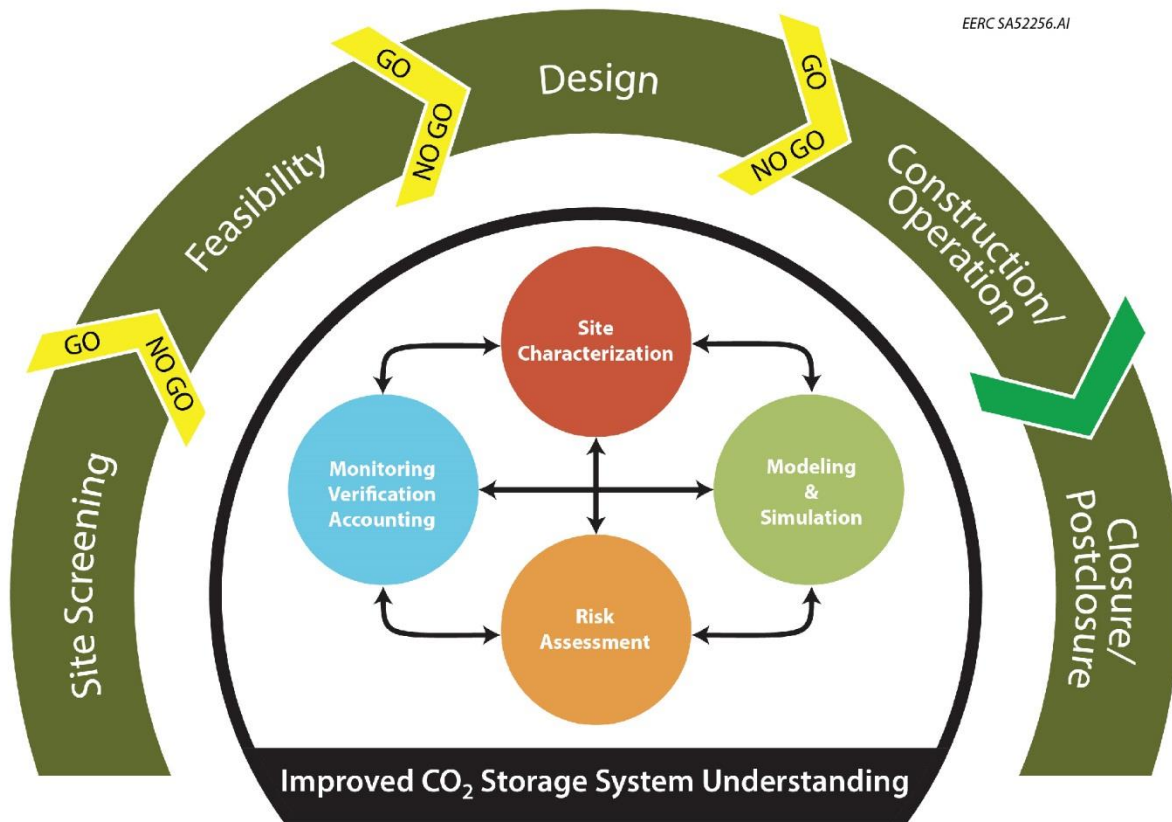
Figure 2. PCOR Partnership AMA for CO_2 storage project development (Ayash and others, 2016).

Table 1. AMA Technical Element Summary

Technical Element	Goal/Purpose	Example Methods
Site Characterization	Develop an understanding of surface and subsurface environment properties and characteristics relevant for storage project.	Collect, analyze, and interpret existing data, and acquire field data (e.g., logs) and/or samples (e.g., cores, fluids) for analysis or experimentation.
Modeling and Simulation	Model key subsurface features, and predict movement and behavior of injected CO_2.	3-D geologic base models can be developed to support numerical flow models for various injection scenarios.
Risk Assessment	Identify, monitor, and manage project risks.	Risks can be assessed and prioritized using qualitative or semiquantitative frameworks based on expert panel judgment.
MVA	Track behavior of injected CO_2, and monitor for potential changes in surface/subsurface environments.	Seismic surveys, pulsed-neutron logs, production data, pressure monitoring, and groundwater sampling.

Table 2. AMA Project Phase Summary

Project Phase	Goal/Purpose	Typical Technical Activities
Site Screening	Identify one or more candidate storage project sites.	Primarily site characterization, informed and supported by modeling/simulation and risk assessment as appropriate.
Feasibility	Assess technical/economic viability of candidate storage sites; identify viable site(s) for advancement to design.	Site characterization, modeling/simulation, and risk assessment.
Design	Complete detailed design to derive definitive project cost and time line estimates, secure required permits, and make go/no-go decision on construction.	Detailed modeling/simulation, risk assessment, and MVA design to support regulatory permit applications and investment decisions.
Construction/Operation	Build and operate facilities to achieve project CO_2 injection and storage objectives.	MVA plan implementation including baseline data collection prior to injection, routine history-matching of MVA data with simulation results, and regular review of risk assessment.
Closure/Postclosure	Cease CO_2 injection, and demonstrate CO_2 containment in the storage complex.	MVA program continuance (in line with simulation and risk models) to demonstrate compliance with regulatory requirements prior to permit surrender.

4.0   PROJECT DEFINITION

Prior to initiating a site-specific risk assessment for an envisioned or proposed storage project, the project should be adequately defined. The following are examples of key project elements to define:

- Overall goal
  - What is the desired project outcome?

- Scope
  - What are the key project objectives and steps/procedures to be utilized in achieving the objectives?

- CO_2 source
  - How much CO_2 is being produced and captured?
  - What is the CO_2 stream composition?
  - Will the CO_2 amount and composition be relatively consistent throughout the anticipated project duration or subject to significant fluctuation?

- Storage target
  - What storage capacity is required?

–   Is the project team interested in dedicated or associated storage, or is a combination a viable option?
–   If associated storage (i.e., CO_2 EOR) is a viable option, can the project handle fluctuating demand from the partner oil company?

- Finances
    –   What level of financial commitment is available?
    –   Is the project trying to get credit for stored CO_2?
    –   Who are the partners contributing financially to the project?
    –   Are the sources of income stable in the short and long term?

- Time line
    –   Are there key regulatory requirement deadlines that need to be met?
    –   If targeting associated storage, when is the partner company expecting CO_2 to be available for delivery?

5.0   RISK ASSESSMENT FOR A CO_2 STORAGE PROJECT

This section describes the risk assessment process for evaluating subsurface technical risks associated with implementing a CO_2 storage project, with a focus on risks related to injection into a storage complex. A CO_2 **storage complex** refers to the storage unit and seal formation(s) extending laterally to the defined limits of the CO_2 storage operation. A CO_2 **storage facility** is an area on the ground surface, defined by the operator and/or regulatory agency, where CO_2 injection facilities are developed and storage activities (including monitoring) take place. The storage complex and storage facility together make up the CO_2 **storage site** (Canadian Standards Association, 2012). While the processes described herein are applicable to conducting risk assessments for a CO_2 storage facility, the case studies and specific examples provided in this section are specific to subsurface technical risks associated with a storage complex.

Risk is the combination of the severity of consequences (negative impacts) of an event and the associated likelihood of its occurrence (Canadian Standards Association, 2012). In the context of a storage complex, a risk is an uncertain event that can negatively affect the operational performance and long-term safety of geologic CO_2 storage. While the risk assessment principles presented in this section are equally applicable to both technical and nontechnical risks (e.g., external-, organizational-, and project management-related risks), only details related to subsurface technical risk assessments are presented and discussed.

Quantifying risk involves determining both the likelihood of an event occurring and the potential impact(s) to the project should that event occur. Conducting risk assessments for a CO_2 storage complex therefore entails 1) identifying potential risks that could affect the performance and long-term safety of CO_2 storage at that location, 2) estimating their likelihood, and 3) quantifying the potential impacts associated with these risks. In its most general form, the overall project risk to a storage complex is the cumulative effect of the adverse impacts of the individual risks. The ranking of a particular risk is a function of both its likelihood and its impact.

For example, a risk that is unlikely to occur and will result in a negligible impact has a lower ranking than one with a greater likelihood of occurring and a significant impact to the project.

Risk assessment, in the context of this BPM, is defined as the iterative process of identifying, analyzing, and evaluating individual project risks. When applied to a storage complex, the risk assessment process enables project developers to proactively plan and implement mitigation strategies to address unacceptable risks. Because of the long-term nature of CO_2 storage projects, which may operate from 20 to 50 years or longer, risk assessment for these types of projects is most effective when it is repeated over time. This iterative process enables the evaluation of potential risks that may evolve from changing site conditions, changing site plans or designs, evolving operational activities, and/or policy and regulatory developments. Thus the risk assessment process is one that is repeated from project inception through the project closure/postclosure phases.

The PCOR Partnership has conducted a series of both programmatic and subsurface technical risk assessments as part of its Phase III RCSP activities. The former focused on the PCOR Partnership program in general, while the latter focused on specific Phase III demonstration projects (large-scale projects with a target of storing 1 million metric tons of CO_2). The PCOR Partnership has supported two Phase III demonstration projects: one involving dedicated CO_2 storage in a DSF (Fort Nelson, British Columbia, Canada) and the other focused on associated CO_2 storage incidental to CO_2 EOR (Bell Creek, Montana, United States). In addition to the Phase III demonstration projects, there are many completed and ongoing CCS-related projects within the PCOR Partnership region (Figure 3).

Figure 3. Map of the PCOR Partnership region showing the locations of completed and ongoing CO_2 storage projects.

The remainder of this section provides an overview of the risk management process. It identifies the key elements that comprise a risk assessment for a CO_2 storage project, defines important risk management terminology, and presents technical considerations unique to the geologic storage of CO_2. It also provides best practices for implementing a risk assessment based on lessons learned from risk assessment efforts within the PCOR Partnership Region. These risk assessments were performed as part of the PCOR Partnership Program, as well as additional CO_2 storage-related projects occurring in the region. Case studies of real-world examples, which highlight key aspects of applying the risk assessment process to CO_2 storage projects, are provided to support the presented best practices.

5.1   Overview of the General Risk Management Process

Figure 4 illustrates the overarching risk management process used by the PCOR Partnership for managing the subsurface technical risks of a storage project. This process is consistent with ISO 31000, an international standard for risk management (International Organization for Standardization, 2009).
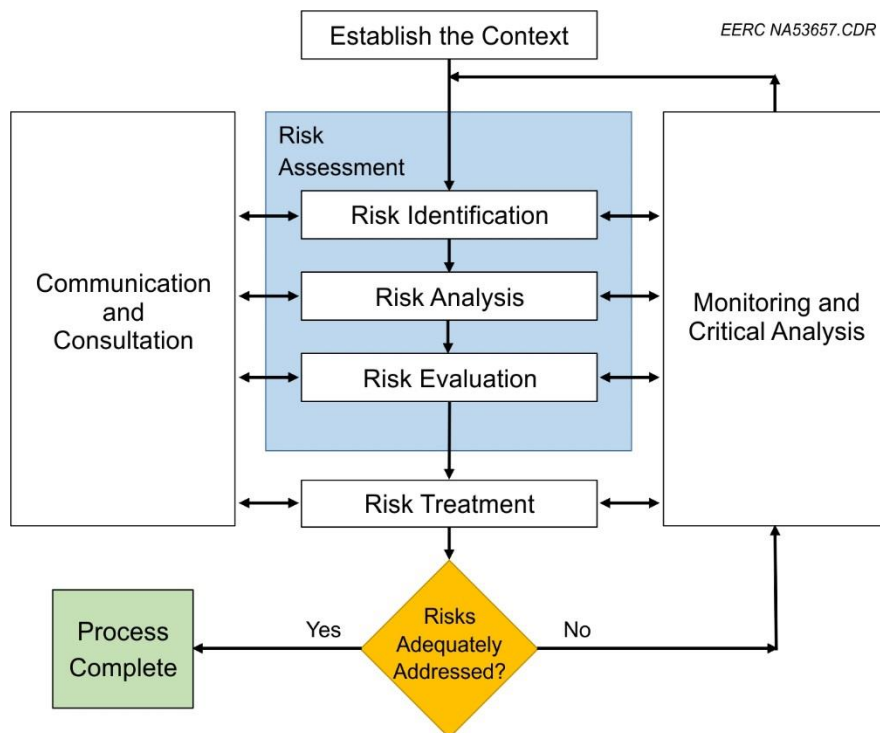

Figure 4. Risk management process adapted from the ISO 31000 (2009) standard.

An effective risk management framework comprises five primary elements: 1) establish the context, 2) risk assessment, 3) risk treatment, 4) communication, and 5) monitoring. Establishing the context generally consists of defining the scope of the risk management framework and outlining the risk criteria that will be used to evaluate the individual project risks. **Risk assessment** refers to the overall process comprising three components: risk identification, risk analysis, and

risk evaluation (blue box in Figure 4). **Risk identification** entails identifying the relevant site-specific risks and compiling those risks into a project risk register. **Risk analysis** involves quantifying, or scoring, the risks in the risk register by estimating their **likelihood** (i.e., the probability that the risk may occur) and their **impact** on a number of different project attributes should the risk occur (e.g., impacts to environment, health and safety, finance, public perception, and/or legal and regulatory compliance). Lastly, **risk evaluation** uses the probability and impact scores for each individual risk to rank and classify the risks from lower- to higher-ranking.

After completing the risk assessment process, those risks deemed unacceptable (based on risk criteria defined during the "establish the context" step) must be managed using one of four risk treatment options: 1) acceptance, 2) transference, 3) avoidance, or 4) mitigation. Finally, the risks are monitored to ensure lower-ranking risks do not increase to unacceptable levels over time and that higher-ranking risks have been successfully reduced to acceptable levels. A risk-based monitoring plan, informed by the results of the risk assessment, confirms the project is safe by monitoring the site-specific risks. Additionally, communication about risk with both internal and external stakeholders is an essential part of gaining confidence and trust in a project. Communication takes place during all stages of the risk management process.

While the ISO 31000 framework shown in Figure 4 represents the best practice for implementing the risk management process, several unique characteristics of CO_2 storage projects influence the application of this process. Thus the focus of this document is on establishing the context for a CO_2 storage complex risk assessment and conducting the risk assessment through risk identification, analysis, and evaluation. This document does not discuss risk treatment, communication and consultation, and monitoring and critical analysis. These topics are discussed in PMI (2008), ISO (2009), and CSA (2012). Prior to discussing the specific aspects of the risk assessment process; however, it is worth discussing some of the key differences between dedicated and associated storage as they relate to risk assessment, as well as implications for applying the process across the phases of the AMA.

5.2 Applying the Risk Assessment Process to Dedicated Versus Associated Storage Sites

There are several fundamental differences between dedicated and associated CO_2 storage projects. As described below, these differences affect the type of information that will be available for the risk assessment, as well as the potential risks related to the long-term performance of the storage complex.

5.2.1 Limited Site-Specific Subsurface Characterization Data for Dedicated Storage Sites

The availability of site-specific data to inform the risk assessment process is generally different for dedicated and associated storage projects. Typically, a dedicated storage project targets a greenfield site for which there may be limited prior site-specific subsurface characterization data. In addition, there are few publicly available data sets from which to draw inferences because of the relative lack of commercial, dedicated storage projects globally. This lack of data and experience forces dedicated storage projects to rely heavily on available generic

information in the literature and other public sources to inform the early phases of the risk assessment process before site-specific data are collected (e.g., drilling characterization wells). In contrast, associated storage will likely occur in oil fields that have decades of production history; therefore, many aspects of the subsurface conditions of an associated storage site are well characterized and will likely result in significant available data to support the risk assessment process. In addition, there is extensive industry experience with associated storage, with over 40 years of commercial CO_2 EOR operations in the United States, and the knowledge gained through these projects is available to inform the risk assessment.

5.2.2   Existing Geologic Models and Predictive Simulations for Associated Storage Sites

Risk assessment is, by definition, future-focused. Consequently, geologic modeling and simulation-based predictions are an invaluable component of the risk assessment process for evaluating the long-term performance of a storage complex. Similar modeling and simulation efforts are required for both dedicated and associated storage sites since the activities both focus on predicting the migration of the injected CO_2 and other affected fluids in the subsurface. However, in the case of associated storage projects, established subsurface models likely already exist from prior oilfield development activities. In addition, operational data from the field's oil production allow the simulation model to be calibrated, or history-matched, to known performance data. Having existing, history-matched subsurface models available at associated storage sites will yield improved predictions of fluid movement in the subsurface, which will reduce the uncertainty in the risk analyses associated with their migration (Pekot and others, 2017). At a dedicated storage site, models likely do not exist prior to the site screening and feasibility phases of the project, which requires constructing new models from limited site characterization data, yielding larger uncertainties in the model predictions and commensurately larger uncertainties in the risk assessment.

5.2.3   Potential Leakage Pathways

Since both dedicated and associated storage have the goal of long-term subsurface containment of the injected CO_2, the potential leakage of the stored CO_2 from the storage complex into overlying domains of concern (e.g., underground sources of drinking water [USDW], surface waters, atmosphere) represents a risk common to all storage projects. However, the likely causes of leakage may differ between dedicated and associated storage projects. For example, associated storage sites will have numerous existing wellbores that penetrate the geologic strata from the surface into the storage unit; therefore, wellbore integrity represents a primary concern for potential leakage. At the same time, the history of the associated storage site as a source of oil and gas suggests that the primary seal, or cap rock, overlying the storage unit is capable of containing fluids under pressure for millennia. Alternatively, most dedicated storage sites will likely contain few, if any, existing wellbores that penetrate the entire length of the geologic strata. Consequently, wellbore integrity may be less of a concern at a dedicated storage site. Instead, primary concerns for potential leakage may be the integrity of the primary seal that overlies the storage unit and its ability to contain the pressure and fluids over long timescales because it is untested.

5.2.4   Regulatory Paradigms

Lastly, the regulatory paradigms and corresponding monitoring activities for associated storage projects may also be different in scope than those implemented for dedicated storage projects, potentially resulting in different types and levels of data available to inform updates to the risk assessment. While both storage approaches will be generally focused on tracking the migration of CO_2 in the subsurface and documenting containment in the storage complex, there may be differences in the extent and duration of monitoring performed at the sites because of potential differences both in the goals of the site operators as well as in the regulatory environments in which they operate. For example, it may not be necessary to monitor CO_2 EOR projects in accordance with the recent U.S. Environmental Protection Agency (EPA) requirements for CCS sites (i.e., "Subpart RR – Geologic Sequestration of Carbon Dioxide" 40 CFR Part 98.440) if the site operator is not seeking monetization of, or credits for, the stored CO_2. Furthermore, it may not be necessary to extend monitoring at these sites beyond the period of CO_2 injection, as it may be possible to terminate all monitoring at the time operations cease. These differences will be largely site-specific in nature and will be driven by the applicable regulatory requirements as well as the operating and management goals of the site operator. At the same time, documenting associated CO_2 storage may also be complicated because of the number of injection wells and the recycling and processing of the gas that accompanies the oil recovered through the CO_2 EOR process.

5.3   Adaptive Management Approach to the Risk Assessment Process

Consistent with its AMA approach to deploying storage projects, the PCOR Partnership uses an iterative approach to risk assessment. This strategy integrates site characterization, modeling and simulation, and MVA measurements into risk assessment efforts over the development phases of the project (Figure 2). This process ensures that the risk assessment uses the most current site data and up-to-date understanding of the CO_2 storage complex. The risk assessment process does not change with the project phase; however, what is different is the quantity and quality of information that are available to perform each of these steps.

Risk assessment is an active process, and the relevant risks can change for a specific storage project as it matures and moves from one phase to the next (e.g., from site screening, to feasibility, to operation). With each phase of project development, additional data become available and the uncertainty associated with the risk assessment decreases over time. Consequently, the project phase affects the nature of available information and the degree of stakeholder knowledge about the potential project risks. Each iteration through the risk assessment process shown in Figure 4 will enhance the detail in the attendant risk assessment until each of the identified risks are adequately assessed.

For example, initial risk assessments conducted during the early stages of a storage project will typically be informed by high-level, regional characterization data. These initial risk assessments, while only qualitative or semiquantitative in nature, will aid the development of the project by focusing future project phases on the generation of the critical data needed to both quantify the risks and reduce the uncertainty associated with their assessment. Subsequent risk assessments will incorporate new site-specific characterization and monitoring data and updated modeling and simulation results, which act to reduce uncertainty in the risk analysis.

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5.4 Application of the Risk Assessment Process to Storage Projects

As shown in Figure 4, the PCOR Partnership's implementation of subsurface technical risk assessments began with establishing the context, followed by risk identification, risk analysis, and risk evaluation. The process was repeated over time, updating the risk assessment as additional site-specific data became available. The case studies and best practices presented in this BPM were derived from the methods employed and lessons learned while applying the risk assessment process to each project. Thus this BPM highlights specific risk assessment activities unique to the PCOR Partnership's application of the risk assessment process to CO_2 storage projects, including the following:

- Risk identification
  - The use of a functional model of the storage complex combined with a failure modes and effects analysis (FMEA) to identify risks
  - The discretization of the risk register into multiple risk permutations and subsequent consolidation to a reduced number of higher-order risks based on new site data collected over time

- Risk analysis
  - The incorporation of physical consequence tables into the assessment of risk impact scores
  - The use of geologic models and predictive simulations to analyze the likelihood of risks related to CO_2 containment
  - The use of a visual tool to assess uncertainty in the risk scoring across a large number of respondents

- Risk evaluation
  - The application of risk maps and Monte Carlo simulations to evaluate project risks

The remainder of Section 5 presents a description of the best practices that developed from these risk assessment activities.

5.5 Establish the Context

An essential first step in setting up a risk management system for a CO_2 storage project (Figure 4) and preparing for the first risk assessment is to establish the context of the risk assessment. Several questions must be answered during this stage, such as, "What is the scope of the risk management framework being established?" and "How is the storage system defined?" The answers to these questions form the basis for the subsequent risk assessment. Two important

aspects of establishing the context include the development of a functional model of the storage complex and the definition of the risk criteria.

5.5.1 *Developing a Functional Model of the CO₂ Storage Complex*

The development of a conceptual "functional model" of the storage complex is paramount to the risk assessment process. This step includes defining the storage system boundaries, the system components that will be evaluated in the risk assessment, and the functions of these components. The simplified nature of the functional model allows the project team to reduce the complexity of the geologic storage complex into a set of components about which the experts can formulate opinions about the likelihood of different failure modes and causes. Therefore, like the various physical models that are commonly created to describe the details of the storage system as accurately as possible, e.g., geologic, reservoir, geochemical, etc., a functional model is also important to establish the context for a risk assessment.

Case Study 1 presents this step as completed for a dedicated storage project in a DSF. This particular storage site was located near commercial gas fields; thus the subsurface technical risks included potential impacts to these gas fields. Accordingly, the functional model included these gas reservoirs as subsystems within the model.

5.5.2 *Defining the Risk Criteria*

A risk management policy is also developed for the project during this stage of the risk management framework. A key component of the risk management policy is the definition of the risk criteria, which establish the thresholds for acceptable risks. The main components of the risk criteria include the probability and impact tables that will be used during the risk assessment. The **probability scores** estimate the **likelihood** of the risk occurring, described by specifying a frequency over a given period. The **impact scores** quantify the adverse impact(s) of the risk on at least one project objective and reflect the specific risk tolerances of the project developer. The function of the risk criteria is to provide a common basis for assessing the probability and impacts of individual project risks.

Risk probability refers to the likelihood of a risk occurring, often described by specifying a frequency over a given period. For CO₂ storage projects, probability scores are generally assigned through expert opinion since the availability of direct measures of the long-term failure rates or similar quantitative measures for storage projects are limited because of the relative lack of a commercial operating storage industry. Table 3 provides an example five-point scale for discrete probability ranges that have been used successfully in several risk assessments for storage projects.

Table 3. Example Table of Risk Probability Scores and Definitions Used for Several Storage Projects

Probability Score	Definition
5	Very high
4	High
3	Moderate
2	Low
1	Very low

Case Study 1. Definition of a Functional Model of the Storage Complex

Figure CS1-1 presents a functional model of a DSF that was evaluated as part of a CO_2 storage complex for a dedicated storage project. Key features of a functional model for the storage complex included the following:

- **Components or subsystems:** Examples include storage unit (CO_2 reservoirs), seal formations (cap rocks and aquitards), wells, and overlying geologic units.

- **Functions of each component:** For example, the function of the cap rock is to prevent vertical migration of the stored CO_2 out of the storage unit.

- **System interactors:** Interactors are those things that are outside of the system that will interact with the components of the system, e.g., formation fluids.
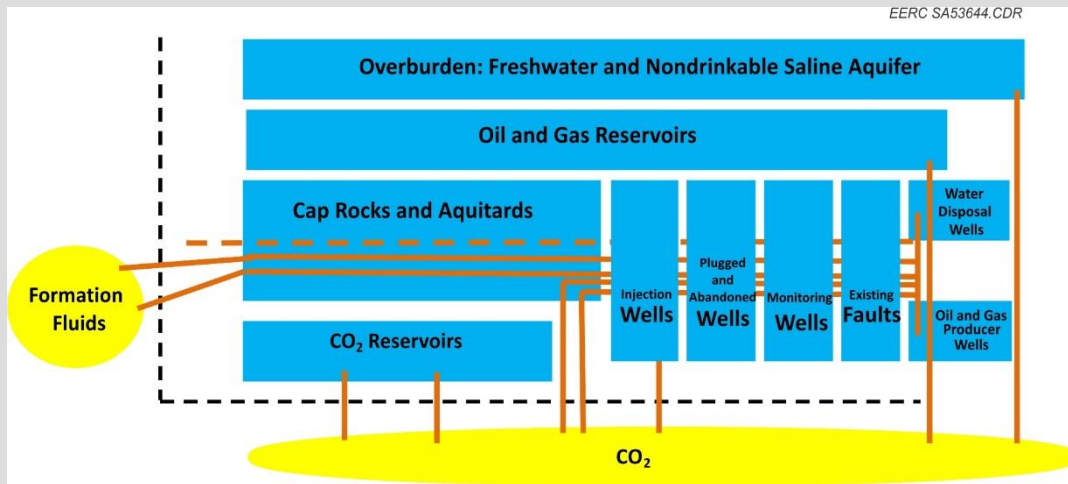
Figure CS1-1. Functional model of a DSF for a dedicated storage project.

The blue blocks in Figure CS1-1 represent key system components for the storage reservoir, cap rocks, neighboring natural gas pools, and overburden. Potential leakage pathways between the storage reservoir and these system components are also shown (orange lines), including injection wells, plugged and abandoned (P&A) wells, monitoring wells, existing faults, water disposal wells, and oil and gas producer wells. This functional model was used during the risk assessment to help identify the failure modes (where the storage system might fail) and failure causes (how the storage system might fail), which together led to a set of potential project-specific risks.

Recommended Best Practice – Define a functional model of the storage complex.
A functional model of the geologic storage complex is an important tool for establishing the context for a risk assessment. The simplified nature of the functional model allows the project team to define the boundaries of the storage system and to reduce the intricacy of the CO_2 storage complex by defining a set of components for which the likelihood of various failure modes and causes can more easily be evaluated.

Adaptations of the five-point scale shown in Table 3 may also be used: for example, a three-point scale (low, medium, or high) or a more detailed scale with greater than five risk probability scores.

Analogous to the risk probability scores, a common approach for estimating the project impact(s) of a particular risk should it occur is with a five-point scale from "very low" to "very high." These qualitative descriptions provide a range from insignificant or barely noticeable impacts (very low) to significant impacts that jeopardize the storage project (very high). Like the probability scales, the impact scales are also project-specific. Table 4 provides an example of the type of general categories that have been used successfully to permit an assessment of four project attributes: 1) cost, 2) schedule, 3) scope, and 4) quality. Adaptations of this five-point scale may also be used, for example, a three-point scale (low, medium, or high) or a more detailed scale with greater than five risk impact scores. In addition, impacts for other project attributes can also be included. For example, impact categories such as environment, health and safety, public acceptance, and corporate image may also be used as risk impact criteria.

Table 4. Example Table of Risk Impact Criteria for Different Project Attributes

Project Impact	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Cost	Insignificant cost increase	<10% cost increase	10%–20% cost increase	20%–40% cost increase	>40% cost increase
Schedule	Insignificant time increase	<5% time increase	5%–10% time increase	10%–20% time increase	>20% time increase
Scope	Barely noticeable scope change	Minor areas of scope affected	Major areas of scope affected	Scope change unacceptable to sponsor	Project objectives cannot be met
Quality	Barely noticeable quality degradation	Only very demanding applications are affected	Quality reduction requires sponsor approval	Quality reduction unacceptable to sponsor	Project end item is effectively useless

While establishing these risk criteria is required for any type of risk assessment, their definition is dependent upon the internal management policies and risk tolerances of the project developer. CO_2 storage project operators can base the risk criteria on previous risk assessments they have conducted, or they may choose to develop new risk criteria based on project-specific

considerations. New risk criteria are developed by interviewing both internal and external project stakeholders and combining the individual concerns and risk tolerance levels of these stakeholders with those of the storage project developer.

An important aspect of developing risk criteria is that the probability and impact tables are site-specific. The development of appropriate scales and discretization of these scales should reflect the nature of the potential risks and the availability of sufficient data to discern differences in their probability of occurrence and subsequent impacts. Moreover, the project impacts should reflect interviews with both internal and external project stakeholders and combine the stakeholder's individual concerns and risk tolerance levels with any existing risk assessment criteria of the storage project developer.

Recommended Best Practice – Define risk criteria for probability and impact scores.
To provide a common basis for assessing the probability and impacts of individual project risks, standardized criteria should be defined as part of establishing the context for the risk assessment. The development of appropriate scales should reflect the nature of CO_2 storage-specific risks to the project and the availability of sufficient data to discern differences in their probabilities and subsequent impacts. Moreover, impacts to the CO_2 storage project should reflect interviews with both internal and external stakeholders and combine the stakeholders' individual concerns and risk tolerance levels with any existing risk assessment criteria of the storage project developer.

5.6   Risk Assessment

This section outlines the risk assessment steps of identification, analysis, and evaluation. It describes the outcome of each step, how the project phase affects the process, and case studies and best practices highlighting PCOR Partnership experience with conducting risk assessments for storage complexes.

5.6.1   Risk Identification

The outcome of the risk identification step is a **risk register** or list of potential project risks that could negatively affect the operational performance and long-term safety of the storage complex.

Risk identification for CO_2 storage projects is accomplished through elicitation of internal and external subject matter experts and relevant stakeholders together into workgroup sessions. If possible, it is helpful if these workgroup sessions are facilitated by an independent risk management expert. Facilitation by an independent risk management expert helps the group adhere to the risk assessment process and to stimulate dialogue among the subject matter experts.

During the baseline risk assessment phase at the initiation of the storage project, the risk identification process begins with a preliminary list of potential storage-related risks assembled from a basic understanding of the storage site combined with an existing open-access database of

potential risks associated with the geological storage of CO_2 (e.g., Quintessa, 2014). The internal and external stakeholders use this preliminary list in conjunction with a functional model of the storage complex to identify potential risks.

Recommended Best Practice – Identify risks through elicitation of stakeholders and experts.
Because of the relatively small number of CO_2 storage projects and lack of public risk-related information about those projects, internal and external stakeholders and subject matter experts should be elicited to identify risks for a specific CO_2 storage project. Facilitation by an independent risk management expert is recommended for this process.

A major component of the risk identification process is FMEA, with an evaluation of where the storage complex might fail (i.e., the failure mode – What could go wrong?) and how it might fail (i.e., the failure cause – Why would the failure happen?). Simplified functional models such as the one previously shown in Case Study 1 help to reduce the complexity of the CO_2 storage complex into a set of components about which experts can formulate opinions about the likelihood of different failure modes and causes. The results of this functional analysis can be cross-referenced with existing databases for CO_2 storage projects to develop a comprehensive list of failure modes and causes, which together comprise the subsurface technical risks to the CO_2 storage complex.

Technical staff and subject matter experts should review the list of subsurface technical risks developed through FMEA and, if necessary, refine this list to prepare a final project-specific risk register. The final risk register should only include those risks that have been validated by experts or project leaders to be relevant to the project.

Over the course of conducting risk assessments for both dedicated and associated storage of CO_2 throughout the PCOR Partnership, a common set of primary technical risk categories emerged which included 1) storage capacity, 2) injectivity, 3) vertical and lateral containment of subsurface fluids (e.g., CO_2, formation brines, and/or oil), and 4) induced seismicity. At a minimum, these risk categories should be considered for all storage projects. There may be instances where a particular risk is of key interest to the public or other stakeholders regardless of its technical relevance at a particular site (e.g., induced seismicity). In these instances, the risk assessment group must decide whether or not to include such risks during the identification process. The reasoning behind the inclusion or exclusion of such risks should be thoroughly documented.

Recommended Best Practice – Consider a common set of primary technical risk categories.
At a minimum, the following set of common risk categories should be considered for all storage projects: 1) storage capacity, 2) injectivity, 3) vertical and lateral containment of subsurface fluids (e.g., CO_2, formation brine, and/or oil), and 4) induced seismicity.

Subsequent risk assessment updates during later phases of the storage project should use the existing risk register as a starting point, which the project team can modify as necessary to

accommodate new risks or to remove risks that are no longer relevant to the project. If the project team recognizes that a particular risk is no longer relevant for the project, then it may be removed from the risk register; however, the reasoning as to why it was removed should be documented to provide a detailed accounting of the rationale for the action. Similarly, new risks identified during later phases should be appended to the end of the previous risk register, and this addition should be documented. This documentation provides valuable continuity over multiple risk iterations. Moreover, this documentation can also be used for communication and reporting purposes.

Recommended Best Practice – Thoroughly document all changes to the risk register.
Because of the long-term nature of CO_2 storage projects, which may operate from 20 to 50 years or longer, it is important to keep a detailed accounting of all changes to the risk register that occur over time in order to facilitate the next risk assessment update and provide a detailed record of the rationale for the action.

Case Study 2 provides an example of the risk identification process that was implemented across three separate risk assessments for an associated storage project. This example highlights the use of an expert workgroup facilitated by an independent risk management expert. It also demonstrates how the project phase influences the risk identification process: the project team initially adopted a granular risk register with multiple risk permutations, which was consolidated into fewer technical risks after new operational data became available. Ultimately, the level of detail with which risks are described in the risk register will be project-specific and may depend upon the current project development phase.

The final risk register developed in these workgroup sessions establishes the basis for the remaining steps of the risk assessment.

5.6.2   Risk Analysis

The outcome of the risk analysis step is a set of **probability and impact scores** for each of the individual risks that are in the risk register. This risk analysis step relies on the risk criteria developed while establishing the context of the risk assessment (see Section 5.5).

This risk analysis step includes 1) scoring risk probability and risk impact, 2) finalizing the risk scores that will be used in the risk evaluation phase, and 3) quantifying uncertainty in the risk scores.

A systematic, quantitative risk analysis should be performed by asking subject matter experts to score each of the individual risks in terms of their probability of occurrence and, if they occurred, the potential impact the event would have on specific categories (e.g., cost, schedule). To score the individual risks, the subject matter experts should use the probability and impact scoring criteria previously presented in Section 5.5.

Case Study 2. Risk Identification for an Associated Storage Project

An initial baseline risk register (prior to CO_2 injection) was generated for an associated storage project. A workgroup session of technical staff and subject matter experts facilitated by an independent risk management expert identified a set of potential project-specific technical risks. These risks were grouped into five primary risk categories: 1) storage capacity; 2) injectivity; 3) CO_2 retention; 4) lateral and vertical containment of CO_2, formation fluids, and oil; and 5) induced seismicity.

Many of these were a single physical consequence subdivided into multiple failure causes. As illustrated in Figure CS2-1, a risk related to containment (e.g., vertical fluid migration) was subdivided based on how the vertical fluid migration occurred, the different fluids that migrated, the final destination of the fluid, and the location of the wells from which the migration occurred. Using this approach, one "parent risk" produced many "child risks" after all of the permutations were defined. Consequently, this degree of resolution in the baseline risk register resulted in a relatively large number of risks. However, at the time of the baseline risk assessment, the project team believed that the risk probabilities may differ for the different failure causes and, therefore, justified separating the risks into a greater number of specific categories.
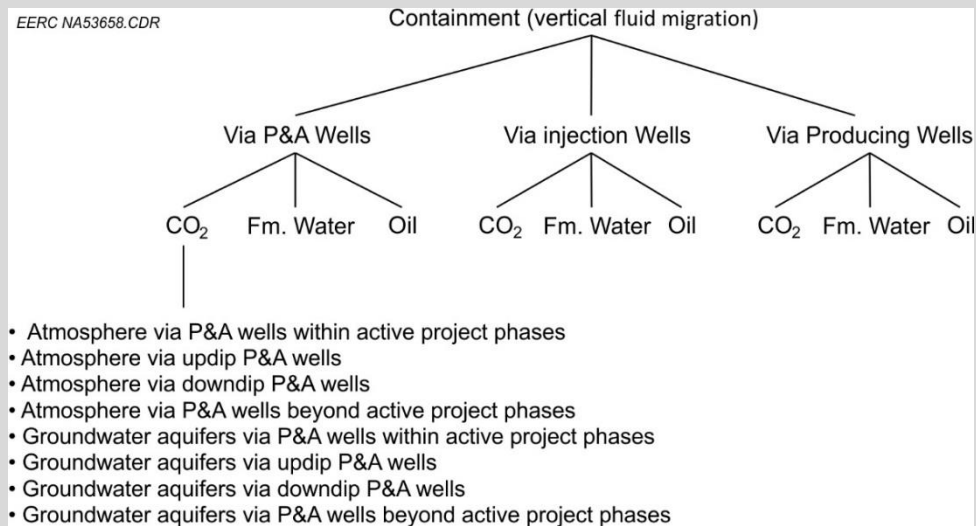

Figure CS2-1. Example hierarchical tree illustrating how one risk, in this case containment (vertical fluid migration), evolves into multiple individual risks when different failure causes, fluids, impact zones, and well locations are included.

In subsequent risk assessment updates, the project team started with the existing risk register and incorporated new information from the operational phase. The team recognized that this parsing of the parent risks was not necessary as it created a risk register containing risks that could not be distinguished from each other during the risk analysis. Accordingly, during the second risk assessment update, the risk register was consolidated at the fluid type without adding the specificity of the final destination of the fluid or the location of the wells of concern. This level of specificity was believed to be sufficient to adequately assess the risks during this particular risk assessment.

5.6.2.1 Risk Probability Scoring

To support the risk analysis, available site-specific data should be obtained from the project developer. Whenever possible, predictive simulations of the subsurface CO_2 injection should be performed and the results of these simulations should be used to estimate the likelihood of individual risks occurring.

Case Study 3 provides an example of how predictive simulations were used to evaluate the likelihood of injected CO_2 affecting nearby gas reservoirs located near a proposed dedicated storage project. These simulation results suggested that injection at the original test well location would likely affect the neighboring natural gas pools, while injection at an alternate location was unlikely to affect these features. Consequently, the subject matter experts were able to assign risk probability scores to the two different injection locations. Case Study 3 illustrates the importance of predictive simulations to analyzing risk probability scores for CO_2 storage projects.

5.6.2.2 Risk Impact Scoring

While the risk assessment respondents can rely on available site data and predictive simulations to estimate a risk probability score, often a common challenge for the respondents is linking technical risks, such as CO_2 leakage, to a project impact (e.g., cost). This aspect of the risk analysis can be supported by a table of physical consequences that describes specific, measurable metrics and assigns them to a physical impact score. Then, in a subsequent step, these physical impact scores are translated to the risk impact scores developed when the context for the risk assessment is established (e.g., Section 5.5).

Case Study 3. Use of Predictive Simulations to Support the Risk Analysis

Figure CS3-1 shows the results of predictive simulations for a subset of the cases that were evaluated in support of a risk assessment update for a dedicated storage project. The assessment evaluated two injection locations: the original test well location and a new alternate drilling location located approximately 5 km west of the original test well.

The left panel in the figure shows the predicted CO_2 plume (gas saturation) at the original location after 50 years of CO_2 injection. These simulation results suggested that injection at the original test well location (indicated by a yellow arrow) would likely impact the neighboring natural gas pools (large colored outline to the right of the arrow) within their commercial lifetime (approximately 30 years). As a result, the subject matter experts scored these particular containment risks a high probability. In contrast, the right panel in the figure shows the predicted CO_2 plume at the alternate injection location. These simulation results showed that injection was not likely to impact the neighboring natural gas pools within their commercial lifetime. As a result, these particular containment risks received lower probability scores as part of the risk assessment update.
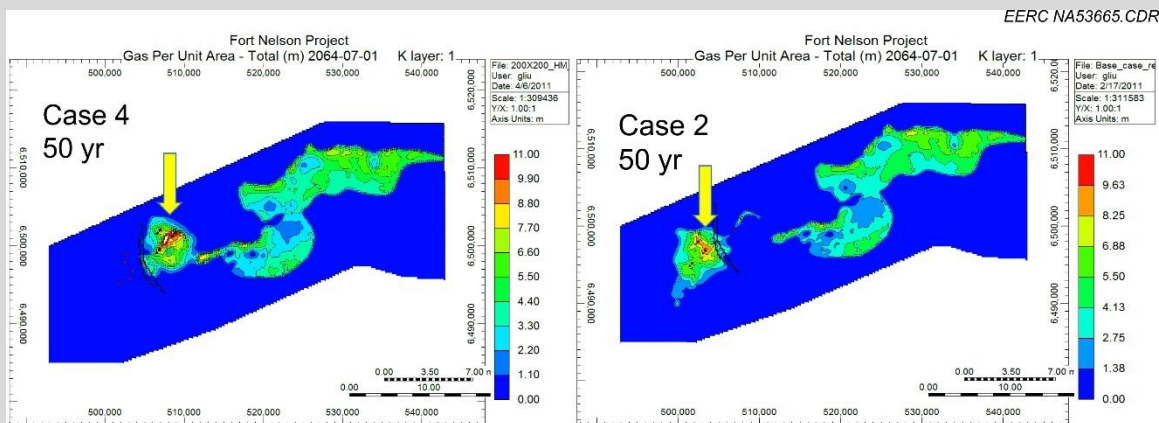

Figure CS3-1. Aerial view of predictive reservoir simulations showing the predicted CO_2 plume (gas saturation) at the original injection location (left panel) and new alternate injection location (right panel) after 50 years of CO_2 injection. The large pool of gas saturation on the right in both panels represents an existing commercial natural gas pool. The yellow arrows show the approximate locations of the planned injection wells.

Additional sensitivity analyses were performed to quantify the change in these predictive simulations as a function of reservoir permeability, well placement, and injection period (25 or 50 years of continuous CO_2 injection). Sensitivity analysis is a vital part of the modeling and simulation process for these types of storage projects, as they permit "what if" scenarios given limited site characterization data. These predictive simulations were a critical input to the risk analysis process, as they allowed the subject matter experts to base their assessment of risk probability on quantitative simulation results, which were conditioned using the available site characterization data and geologic model.

Recommended Best Practice – Consult predictive simulations.
Consult predictive simulations to estimate the likelihood of risks related to injectivity, storage capacity, and lateral and vertical contaminant of CO_2 and other subsurface fluids. These predictive simulations integrate the current state of knowledge about the geology and potential movement of fluids within the storage complex in response to CO_2 injection.

The relationship between the matrix of physical consequence and the risk impact scores should be developed with the input of key stakeholders and reflect the specific concerns of these stakeholders. A given physical consequence does not necessarily affect all impact categories. However, for any physical consequence, an impact "driver" can be determined. The driver is considered to be the most severely impacted category, resulting in the highest range of severity levels stemming from the physical consequence.

Case Study 4 provides an example physical consequence table that was used for a dedicated storage project in a DSF. The matrix of physical consequences provides the subject matter experts with a tangible set of metrics for gauging the relative impact of specific physical risks.

5.6.2.3   Recording Risk Scores

The risk probability and impact scores should be captured for each individual subject matter expert. One tool for recording these scores that was successfully implemented by the PCOR Partnership was a Microsoft Excel© (Excel) template with prepopulated risk register, risk probability, and risk impact scores that the respondents could select using dropdown menus. Key information captured through this template includes the respondent name; date; risk register entry number; risk probability score; and risk impact scores for cost, schedule, scope, and quality. This standardized template approach ensures that all respondents apply the same risk-scoring methods and expedites the subsequent data analysis of the risk scores.

Figure 5 provides an example screenshot of the data entry template that was used. In this example, the respondent scored the first risk in the risk register, which related to CO_2 storage capacity. The probability was assigned a score of 1 (very low). The risk impact scores for cost, schedule, scope, and quality were assigned scores of 3 (moderate), 3 (moderate), 2 (low), and 1 (very low), respectively. The dropdown menu with blue highlights for impacts to project quality is shown as an example. This dropdown menu approach limits the amount of manual data entry, which, in addition to expediting the risk-scoring process, also reduces entry errors.

Case Study 4. Use of Physical Consequence Tables to Score Risk Impacts

Figure CS4-1 provides an example physical consequence matrix for a dedicated storage project in a DSF. This matrix features quantitative values that can be estimated using models and simulations or physically measured during MVA activities. These physical consequences are separated into four families: injectivity loss, decrease in CO_2 storage capacity, containment, and seismicity. The physical consequence that is being measured is shown in the yellow row, labeled Proposed Metric, for example, "injectivity loss for one well." The unit of measure to quantify the proposed metric is in the next row, labeled "Proposed Unit." For example, the unit of measure for injectivity loss is "duration," which is measured in a time of loss of hours, weeks, or months. The next five rows designate increasing ratings of physical consequences. For instance, less than 2 hours of injectivity loss is deemed a very low physical consequence with a corresponding score of "Impact 1," whereas a loss of injectivity for greater than 1 month is considered a worst-case scenario, scoring an "Impact 5." The matrix of physical consequences, therefore, provided the subject matter experts with a measurable set of metrics for gauging the relative impact of specific physical risks.

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Physical Consequence Family	Injectivity Loss		Decrease in CO₂ Storage Capacity	Containment			Seismicity
				Leakage to Atmosphere		Contamination of Usable Water	
Physical Consequence Subfamily				CO₂	CO₂	Brine	
Proposed Metric	Injectivity Loss for One Well	Average Total Monthly Injectivity Loss	Loss with Respect to Initial Storage Volume Estimate	Max. Ground Level Concentration	Overall Loss Volume with Respect to Stored CO₂	Increase of TDS Concentration in Water	Induced Seismicity
Proposed Unit	Duration	% of nominal injectivity	% of initial storage volume estimate	%	% of stored CO₂	ppm	Richter scale
Reference	Time of loss	1 month	Injection period (50 years)	Continuous	Liability period (100 years)	Depth 350 m	Instantaneous
Impact 1 (very low)	<2 hr	<0.1%	<1%	<0.5%	<0.1%	<1000 (freshwater)	<3
Impact 2 (low)	2–10 hr	0.1%–1%	1%–5%	0.5%–5%	0.1%–1%	1000–10,000 (brackish)	3–4
Impact 3 (moderate)	10 hr – 1 week	1%–5%	5%–20%	5%–15%	1%–5%	10,000–15,000 (highly brackish)	4–5
Impact 4 (high)	1 week – 1 month	5%–25%	20%–50%	15%–30%	5%–10%	15,000–40,000 (seawater)	5–6
Impact 5 (very high)	>1 month	>25%	>50%	>30%	>10%	>40,000 (brine)	>6

Figure CS4-1. Example physical consequence matrix for estimating risk impact scores.

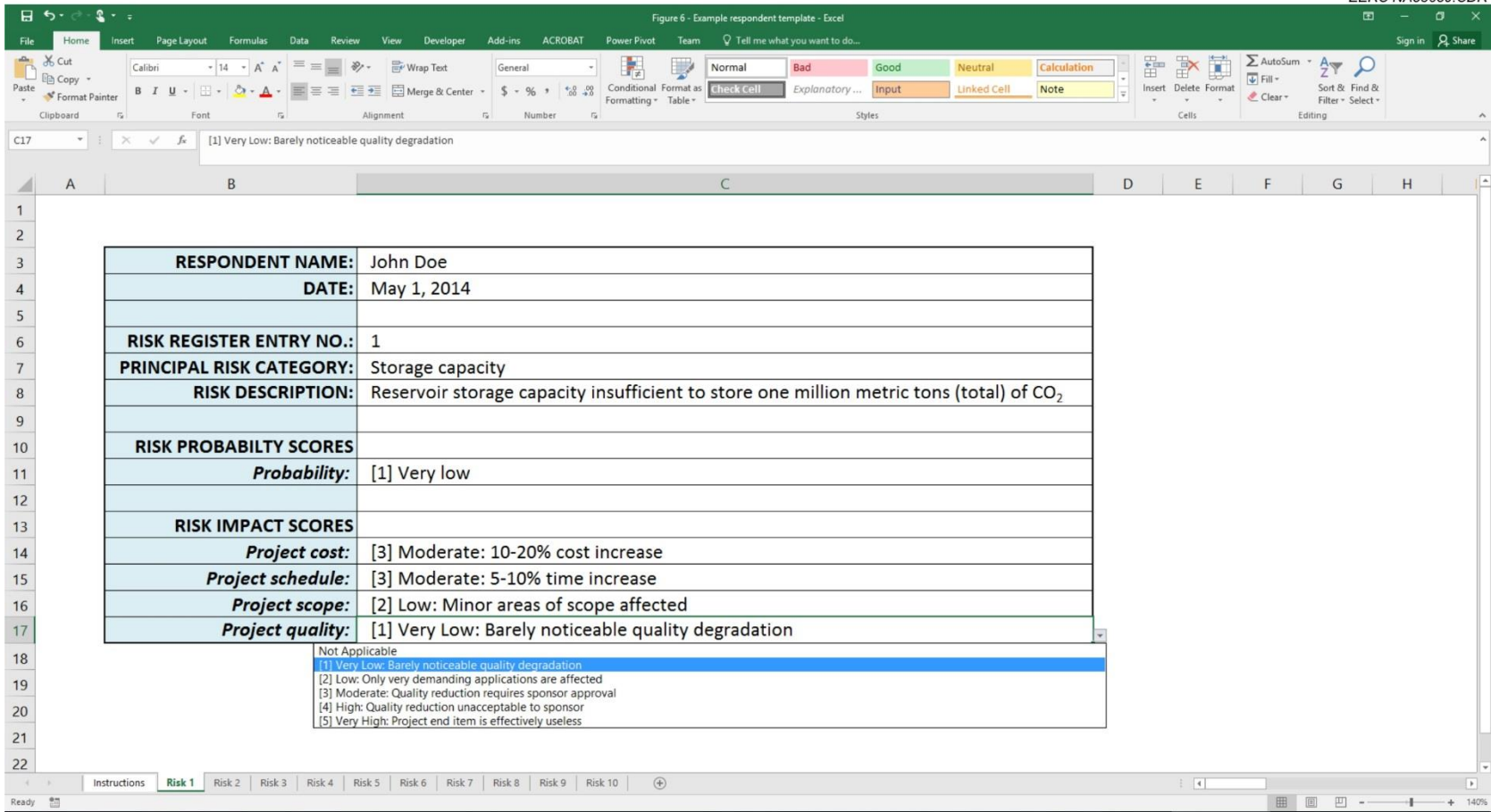| Recommended Best Practice – When appropriate, use physical consequence tables to score risk impacts. |
|---|
| Develop a set of quantifiable physical consequences and a method to link the physical consequences (e.g., CO_2 leakage) to project impacts (e.g., cost increase) where appropriate. |

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Figure 5. Example Excel template used to capture risk probability and risk impact scores.

Recommended Best Practice – Use an electronic template to capture risk scores.
Using an electronic template to capture risk scores ensures that all respondents apply the same risk-scoring methods and expedites the subsequent data analysis of the risk scores. A dropdown menu approach will limit the amount of manual data entry (reducing entry error) and expedite the risk-scoring process.

5.6.2.4   Finalizing Risk Scores

Prior to evaluating the risk scores, a final set of scores must be developed that are representative of the opinions of the subject matter experts. Outlying risk scores provided by one or more respondents should be verified with the individual expert. Respondents may possess unique project knowledge about a particular risk, which caused them to estimate a lower or higher score. Alternatively, the lower or higher score could be attributable to an entry error during the risk-scoring process. After reconciling these outlying risk scores, a final set of scores can be established for quantifying uncertainty and risk evaluation.

Recommended Best Practice – Verify risk score outliers.
Prior to finalizing a set of risk scores, outlying scores (extremely low or high scores relative to the group of scores) should be verified with individual experts. Outlying scores may reflect unique project knowledge about a particular risk, which caused a respondent to estimate a lower or higher score. Alternatively, the lower or higher score could simply be attributable to an entry error during the risk-scoring process.

5.6.2.5   Quantifying Uncertainty in the Risk Scores

The outcome of the risk analysis is a probability and impact score for each individual risk in the risk register, which is then used in the risk evaluation phase. Quite often, the risk probability and impact scores will vary across the different stakeholders, resulting in a level of uncertainty in the risk scores. While expert elicitation aims to achieve scientific consensus, there is often variability in the risk scores attributable to variation inherent in natural systems, incomplete information at the time of the assessment, and differences in expert opinion. Therefore, capturing and quantifying uncertainty in the scores prior to the evaluation stage is an integral component of the risk analysis.

Statistical metrics such as the expected value and standard deviation can be used to quantify the variability in risk scoring. Risk scores with a large standard deviation around their expected value represent greater uncertainty among the subject matter experts. Large variation may stem from true uncertainty about the nature of a particular risk given the current information at the time of the assessment. Alternatively, large uncertainty may reflect misunderstanding among the subject matter experts about the specific risk. If warranted, these risks can be reassessed to ensure a final, representative set of risk scores.

Even within the final set of probability and impact scores, there may be variability around the value. Techniques for quantifying this uncertainty include generating a 10th percentile (P10) and 90th percentile (P90) to define the lower- and upper-bound risk scores. Alternatively, the minimum and maximum values may be used to define the lower- and upper-bound risk scores. The maximum value represents a worst-case score, which is a conservative assumption. The expected value represents the rating given by the subject matter experts that could be thought of as the best estimate based on the available data at the time of the risk assessment. The maximum value is far less likely to be observed in reality; however, it represents a rating that cannot be ruled out as a possibility.

Case Study 5 provides an example of using heat maps, which provided an effective visual tool for understanding variation in the risk-scoring across a large number of respondents.

5.6.3   Risk Evaluation

The purpose of risk evaluation is to assist in making decisions about which risks require treatment based on the outcome of risk analysis and the priority for treatment implementation (International Organization for Standardization, 2009). Two useful approaches include risk maps and probabilistic techniques such as Monte Carlo simulation.

5.6.3.1   Risk Maps

A **risk map** is a method for evaluating the quantitative results of the risk analysis by plotting the risk probability score on the *y*-axis and risk impact score on the *x*-axis for each individual risk. Using this approach, lower-probability, lower-impact risks plot in the lower left-hand corner of these risk maps, while higher-probability, higher-impact risks plot in the upper right-hand corner. The generic risk map in Figure 6 shows an example five-point scale risk map and the associated suggested actions for the different risk ranks:

1. Green: low – no immediate action required, continue to monitor

2. Yellow: transition – uncertainty reduction, risk treatment whenever possible or affordable

3. Orange: moderate – short- to midterm risk treatment required

4. Red: high – immediate, short-term risk treatment required

Case Study 5. Visualizing Uncertainty in the Risk Scores Using Heat Maps

Heat maps were used to visualize and discuss the uncertainty in the risk scores among a relatively large number of respondents who participated in the risk analysis process. An example heat map showing the respondent risk probability and impact scores is provided in Figure CS5-1. The risks are grouped according to a defined set of common risk categories: 1) Group 1 – Capacity, Injectivity, and Retention; 2) Group 2 – Containment (lateral migration); 3) Group 3 – Containment (vertical migration via P&A wells); 4) Group 4 – Containment (vertical migration via injection wells); 5) Group 5 – Containment (vertical migration via producing wells); 6) Group 6 – containment (other)/Seismic; and 7) Group 7 – Executing fieldwork/other.

EERC NA53660.CDR

Risk Grouping	Risk No.	Probability 1	2	3	4	5	6	7	8	Cost 1	2	3	4	5	Schedule 1	2	3	4	5	Scope 1	2	3	4	5	Quality 1	2	3	4	5
Group 1	5	3	7	1						7	2				8	2				5	5				6	4			
Group 1	8	1	10							8	2				8	2				4	6				6	4			
Group 2	11	3	7		1					8	1				9	1				6	4				8	2			
Group 3	32	2	7	2							7	1		1	3	4	1	1		1	5	3		1	3	4	2		1
Group 3	38	1	8	2							7	1	1		3	4	2			1	5	3	1		2	5	2	1	
Group 3	68	7	3	1						1	6	1		1	1	1	5	1	1	2	4	3		1	3	4	2		1
Group 3	74	7	4							1	6	1	1		1	1	5	2		2	4	3	1		3	4	2	1	
Group 4	44	6	4								6	1		1	1	5	1	1		1	4	3		1	2	4	2		1
Group 4	50	6	4								6	1	1		1	5	2			1	4	3	1		2	4	2	1	
Group 4	80	2	7	2						1	6	2			3	5	1			1	6	3			2	6	2		
Group 4	86	2	7	2						1	6	1	1		4	3	2			1	6	2	1		2	6	1	1	
Group 5	56	8	3							1	6	2			1	2	5	1		2	4	4			3	4	3		
Group 5	62	8	3							1	6	1	1		1	2	4	2		2	4	3	1		3	4	2	1	
Group 5	92	7	3								6	2			2	5	1			1	4	4			2	4	3		
Group 5	98	7	3								6	1	1		2	4	2			1	4	3	1		2	4	2	1	
Group 6	104	9	2							2	5	2			1	3	4	1		2	5	3			5	2	3		
Group 6	105	9	2							2	5	2			1	3	4	1		2	4	3			4	2	3		
Group 6	106	10	1							1	5	3			1	3	4	1		1	5	3			3	3	3		
Group 6	107	7	4							1	4	3	1			2	5	2		1	4	4	1		3	2	4	1	
Group 6	110	7	4							1	4	4				2	6	1		1	4	5			3	2	5		
Group 6	113	8	3							1	6	2			1	3	4	1		2	4	3			4	2	3		
Group 6	116	7	4							1	5	3				3	4	2		1	4	4			3	2	4		
Group 6	119	4	6							1	4	4			1	2	5	1		2	3	3	2		4	1	5		
Group 7	123	1	2	3	4	1				5	6				5	6				8	2				8	2			
Group 7	125	3	5	1	1					6	3				5	4				9					9				
Group 7	126	2	8							7	2				2	7				7	2				7	2			
Group 7	127	3	6							5	4				2	7				7	2				7	2			
Group 7	128	1	7	1	1					2	6	1			1	7	1			5	4				6	2	1		
Group 7	129	2	5	3	1					3	6	1				10				5	5				4	6			
Group 7	130	3	5	2	1					3	7				1	9				5	5				3	7			
Group 7	131	5	4		1					3	4	2			2	4	3			3	5	1			4	2	3		

Figure CS5-1. Example heat map for risk probability and impact scores.

The heat map approach provides a visual assessment of the score density or the region within the scoring range that had the greatest number of responses. Dark blue color shading in the figure represents the highest proportion of responses, whereas lighter blue to white (no color) represents the smaller proportion of responses. For example, the probability scores for the first entry in the table (Group 1, Risk 5) included three respondents who scored a "1," seven respondents who scored a "2," and one respondent who scored a "3." The total number of responses for this risk was, therefore, 11. The dark blue coloring shows the most frequent response (the mode). In addition, the minimum and maximum scores are also visible, which illustrates the range of scores provided. The heat map allows the project management team to quickly assess the risk scoring in a single figure. For example, Figure CS5-1 shows that there is relatively little variability in the risk impact scores for Groups 1, 2, and 7 risks, whereas the risk impact scores for Groups 3–6 are more variable.

| Recommended Best Practice – Quantify the uncertainty of the risk scores. |
|---|
| Quantifying the uncertainty in the risk scores is important, as there is often variability in the risk scores attributable to variation inherent in a CO_2 storage complex, incomplete information at the time of the assessment, and differences in expert opinion. Statistical measures such as the expected value and standard deviation provide quantitative, easy-to-calculate values for analyzing uncertainty. Techniques such as heat maps can provide useful tools for visualizing uncertainty in risk score responses. |
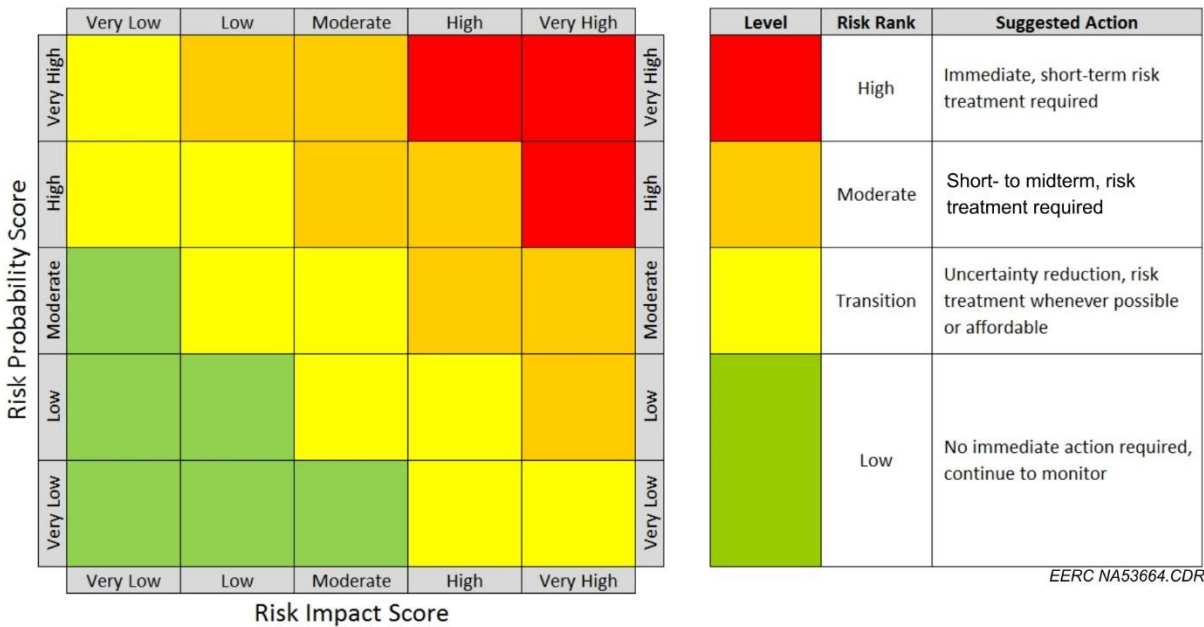
Figure 6. Generic risk map and suggested actions.

The risk map is commonly the final output of the risk assessment process. At this stage, the risk maps are discussed among the various project stakeholders, and the subject matter experts further scrutinize higher-ranking risks. After finalizing the risk maps, the storage project operator then moves to risk treatment for those risks which have been deemed unacceptable while also communicating the risks to both internal and external stakeholders. Case Study 6 provides an example of using risk maps to evaluate project risks associated with two different CO_2 injection locations: an original test well location and an alternate location. These examples illustrate the utility of risk maps to identify higher-ranking risks that require treatment.

Case Study 6. Risk Maps as an Effective Means to Evaluate Project Risks

Figure CS6-1 provides example risk maps for a dedicated storage project in a DSF. The risk maps show the expected value risk probability and impact scores for containment-related risks associated with the two risk tracks that were examined (i.e., Risk Track 1 representing the alternate CO_2 injection well [left panel]) and Risk Track 2 representing the original injection well location [right panel]). See Case Study 3 for more detail regarding these risk tracks. The higher-ranking risks associated with the original test well location (right panel) relate to subsurface pressure changes and lateral CO_2 migration affecting neighboring natural gas pools prior to the end of their commercial life. These examples illustrate the utility of risk maps to identify higher-ranking risks that require treatment, which in this case was moving the potential injection well to an alternate location 5 km west of the originally proposed location.
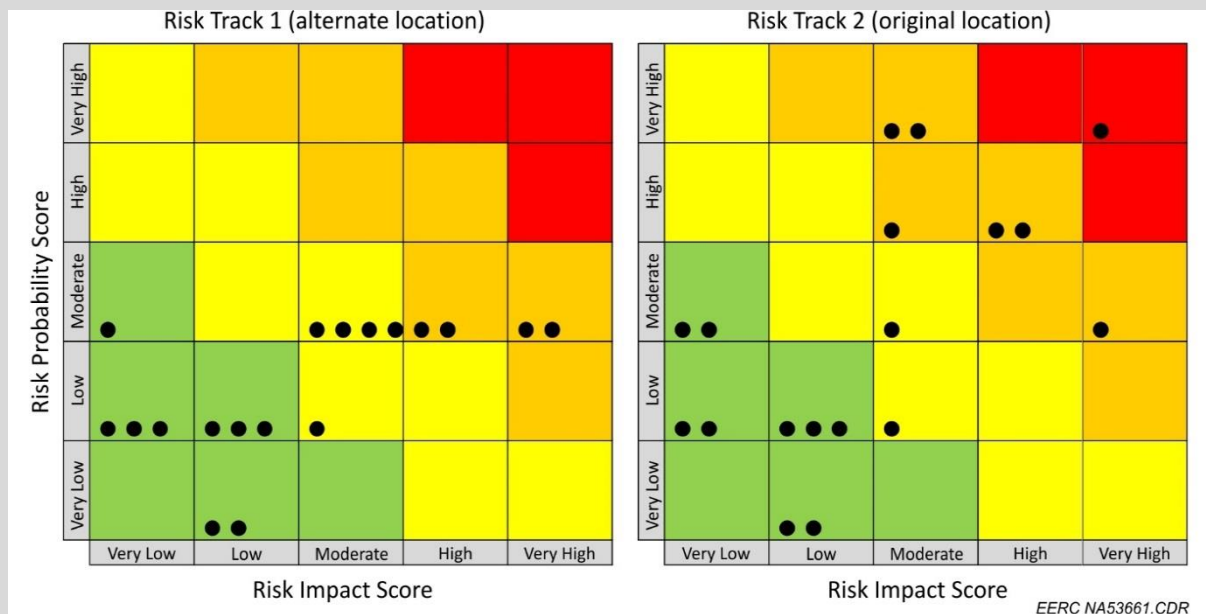

Figure CS6-1. Example risk maps showing the expected value risk scores for containment-related risks associated with Risk Track 1 (alternate injection well [left panel]) and Risk Track 2 (original test well location [right panel]).

Recommended Best Practice – Evaluate risks using risk maps.
Risk maps provide a relative ranking of the storage project risks, with individual risk scores providing a basis for comparing an individual risk to the others. In addition, the risk maps provide a means to assign priorities for further investigation, analysis, and monitoring – key pieces for managing a CO_2 storage project. Equally important, risk maps represent an effective visual tool for discussing the risk assessment with project stakeholders, including those without a technical background.

5.6.3.2 *Probabilistic Risk Evaluation*

As noted in Section 5.3, risk assessment is an active process, and the relevant risks can change for a specific storage project as it matures and moves from one phase to the next (e.g., from site screening, to feasibility, to operation). Consequently, the probability and/or impact scores for an individual risk may change over time through successive iterations of the risk assessment process. Risk maps work best for discrete scores (i.e., one risk probability score and one risk impact score for a single risk). As such, the evaluation of changing risk scores over time generally requires two or more risk maps. For example, to compare risks between a baseline risk assessment and subsequent risk assessment update would require two risk maps: one for each assessment. Similarly, as shown in Case Study 6, comparing risks between two different CO_2 injection locations also requires two risk maps: one for each location. Layered on top of this limitation is the uncertainty in the risk scores: there is not necessarily one unique probability or impact score for each risk, but rather a statistical range based on the variation in the risk scores among the respondents. Regardless of whether the risk map plots the P10/P90 or minimum/maximum, there are drawbacks to using discrete values to illustrate uncertainty. For example, when the expected value and worst-case scenarios are used, the outcomes are likely to cluster near the former, and the latter are very unlikely to be observed. Finally, it is also difficult to compare risk maps showing multiple risks. While point-to-point comparisons can be made for individual risks, comparing groups of risks via risk maps is challenging. To capture a statistical range of potential outcomes and to assess total project risk profiles, a supplemental approach can also be implemented using probabilistic analysis such as Monte Carlo simulation.

Briefly, Monte Carlo simulation involves generating multiple outcomes (realizations) using the underlying statistical distribution of the input variables, i.e., the risk probability and impact scores for each individual risk. The simulated outcomes are then compiled for all risks in the risk register across the realizations to estimate the total project risk.

Case Study 7 provides an example of using Monte Carlo simulation to evaluate risk for a dedicated storage project in a DSF. This technique provided a quantitative answer for the storage site operator by showing that injecting CO_2 at an alternate location resulted in a measurably lower total project risk than injecting CO_2 at the original location.

Case Study 7. Use of Monte Carlo Simulation to Evaluate Risks

The developer of a dedicated storage project in a DSF wanted to evaluate the total project risk profile for CO_2 injection at an alternate proposed injection location ("Risk Track 1") to the total project risk profile for CO_2 injection at the original injection well location ("Risk Track 2"). To capture a statistical range of potential outcomes and to assess total project risk profiles for the two tracks, a different approach was implemented using probabilistic analysis with Monte Carlo simulation. For this approach, risk ranking was defined as the product of risk probability and risk impact:

$$Risk\ Rank = Probability \times Impact$$

The overall project risk was then assessed by summing the risk rank scores across all project risks:

$$Total\ Project\ Risk = \sum_{i-1}^{n}(Probability_i \times Impact_i)$$

Where:
$Probability_i$ = the probability of risk i
$Impact_i$ = the impact of risk i
n = the total number of project risks in the risk register ($n = 31$)

The 1000 simulations of risk probability were multiplied by the 1000 simulations of risk impact for each risk register entry and then summed using the above equation. Figure CS7-1 presents histograms of the simulated outcomes for the total project risk for Risk Track 1 versus Risk Track 2. These histograms illustrate that the total project risk profile for the alternate location is significantly lower than for the original test well location. In other words, moving the injection location approximately 5 km west of the original location significantly reduced overall project risk because it lowered the probability of the containment risks. Thus implementing Monte Carlo simulation to the risk evaluation provided a quantitative answer for the storage site operator to support decision making.
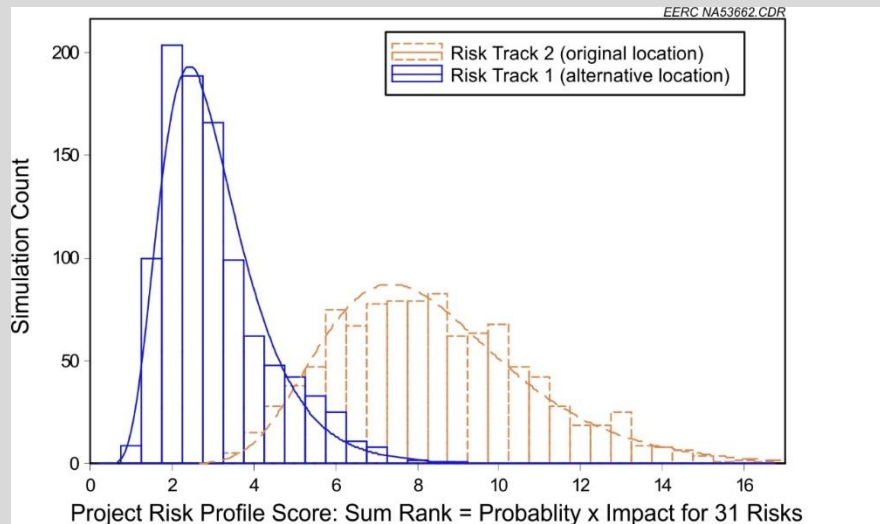

Figure CS7-1. Histograms and fitted statistical distributions for the total project risk for Risk Track 1 (alternate location, blue bars) versus Risk Track 2 (original location, orange dashed bars).

Recommended Best Practice – Probabilistic methods can be used to evaluate risks.
Risk maps are generally limited to discrete values, which requires two or more risk maps to display uncertainty. Multiple risk assessments will be performed over the life of a CO_2 storage project, making analysis and comparison of these discrete values cumbersome. Probabilistic techniques (e.g., Monte Carlo simulation) can be used to supplement risk maps and provide a quantitative approach for evaluating the effects of uncertainty in risk scores.

6.0 STATE OF BEST PRACTICE – CONTEXT AND RISK ASSESSMENT

The case studies in Section 5 summarize extensive experience conducting risk assessments for storage projects within the PCOR Partnership region. Collectively, this experience can be used to develop a best practice for conducting risk assessments for a storage complex.

The ISO 31000 risk management process represents a best practice with respect to defining a *generic* risk management process. This section presents a best practice workflow that informs the core risk assessment steps of ISO 31000 process, in particular the establishing of the context, risk identification, risk analysis, and risk evaluation, with experience gained from storage projects in the PCOR Partnership region.

Figure 7 summarizes the best practices for conducting a risk assessment for implementing CO_2 storage projects, with a focus on subsurface technical risks related to injection into a storage complex. This summary integrates the best practices presented throughout the document, consolidating them into a workflow organized by the three primary risk assessment components of risk identification, risk analysis, and risk evaluation.

The development of a best practice requires the execution of multiple projects where the knowledge gained and lessons learned are accumulated over time and integrated to yield a best practice. This development progression is an adaptive management process whereby best practices constantly evolve over time in response to knowledge gained and lessons learned. Figure 7 encompasses the current body-of-knowledge and best practices for applying a standardized risk assessment within risk management for storage projects. Application of these best practices will provide reliable and consistent standards for identifying project-related risks, analyzing the probabilities and potential impacts of these risks, and evaluating which risks require treatment and the priority for treatment implementation. These best practices will continue to evolve and be refined over time as the commercialization of the storage industry proceeds.

Establish the Context

- Define the storage system and boundaries.
- Define the risk criteria, including probability and impact scoring tables.

Risk Identification

- Conduct elicitation of internal and external stakeholders and subject matter experts.
- Use an independent risk management expert to facilitate the process.
- Aggregate all available site characterization, geologic modeling, and reservoir simulation results to assist in the process.
- Generate a functional model of the storage site, including system components or subsystems, functions of each component, and system interactors.
- Ensure that the following four technical risk categories are considered, as these are common among storage projects: 1) storage capacity; 2) injectivity; 3) lateral and vertical containment of CO_2 or formation fluids, including oil for CO_2 EOR sites; and 4) induced seismicity.
- If this is a risk assessment update and the team is beginning with a prior risk register, then modifications to the risk register should be thoroughly documented for future reference. Moreover, the original risk register entry numbers should be retained for consistency over the project life cycle. New risks should be appended to the end of the original risk register list.

Risk Analysis

- Develop a set of quantifiable physical consequences and a means to link these physical consequences to project impacts.
- Consult predictive simulations to estimate probabilities associated with risks related to injectivity, storage capacity, and lateral and vertical containment of CO_2 and other fluids.
- Use an electronic template to capture risk scores from the respondents.
- Prior to finalizing a set of risk scores, verify outlying scores (extremely low or high scores relative to the group of scores) with individual experts.
- Quantify the uncertainty in the risk scores using either visual tools such as heat maps or statistical measures such as the expected value and standard deviation.

Risk Evaluation

- Plot each individual risk onto a risk map, which plots the risk probability score against the risk impact score.
- To evaluate uncertainty in the risk scores, generate risk maps for both the expected value and maximum risk scores.
- If a more quantitative risk evaluation is needed, employ probabilistic methods such as Monte Carlo simulation.

Figure 7. A best practice workflow for conducting risk assessments for storage projects.

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