Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

BEST PRACTICES MANUAL – MONITORING FOR CO_2 STORAGE

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 9 – Deliverable D51

Prepared for:

William W. Aljoe

National Energy Technology Laboratory
U.S. Department of Energy
626 Cochrans Mill Road
PO Box 10940
Pittsburgh, PA 15236-0940

DOE Cooperative Agreement No. DE-FC26-05NT42592

Prepared by:

Kyle A. Glazewski
Ted R. Aulich
Neil Wildgust
David V. Nakles
Nicholas A. Azzolina
John A. Hamling
Shaughn A. Burnison
Amanda J. Livers-Douglas
Wesley D. Peck
Ryan J. Klapperich
James A. Sorensen
Scott C. Ayash
Charles D. Gorecki
Edward N. Steadman
John A. Harju
Daniel J. Stepan
Nicholas S. Kalenze
Mark A. Musich
Kerryanne M. Leroux
Lawrence J. Pekot

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

October 2017
Revised March 2018
Approved

2018-EERC-03-15

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ACKNOWLEDGMENTS

This work was performed under DOE NETL Cooperative Agreement No. DE-FC26-05NT42592. The EERC would like to thank Denbury Resources Inc. (Denbury) for providing necessary data to perform this work. Special thanks go to the members of Denbury's Bell Creek team for their valuable input and fruitful discussions.

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EXECUTIVE SUMMARY

This best practices manual (BPM) describes lessons learned and best practices for monitoring carbon dioxide (CO_2) geologic storage (herein “storage”) projects derived from extensive Plains CO_2 Reduction (PCOR) Partnership regional characterization and field demonstration experience acquired via activities conducted throughout the PCOR Partnership region. This BPM is intended to 1) provide guidance to project developers, regulators, and other stakeholders in evaluating and developing CO_2 storage opportunities and 2) serve as a reference for CO_2 storage technical specialists.

Monitoring, verification, and accounting (MVA) is one of four technical elements of the adaptive management approach (AMA) formalized by the PCOR Partnership for storage project development and execution. The other technical elements are site characterization, modeling and simulation, and risk assessment. This BPM focuses on the monitoring strategies and technologies that support the verification of storage; accounting procedures are not addressed. Lessons learned and recommended best practices presented here are applicable to either dedicated storage projects (typically in deep saline formations) and associated storage projects (most commonly resulting from CO_2 enhanced oil recovery). Monitoring programs for dedicated and associated storage projects may share many common objectives, but the design of monitoring programs may be influenced by markedly varying circumstances and risk profiles.

Because of the unique geologic setting and characteristics of all storage sites, projects will require a site-specific approach to monitoring and verification. Monitoring objectives should be defined based on overall project goals (e.g., the quantity of CO_2 to be stored), prioritized risks, and regulatory requirements. Management of the operations, for example, informing the management of injection rate and pressure for optimum efficiency within safe limits, can also be aided by monitoring. A site-specific suite of technologies that may be applied to meet objectives should be specified by monitoring plans, together with such details as the proposed location, frequency, and duration of monitoring activities. Preoperational (baseline), operational, and postclosure phases of the project will typically have distinct monitoring requirements.

Monitoring programs can be arbitrarily divided into 1) deep-focused techniques and 2) shallow/near-surface/surface (or environmental assurance) techniques:

1. Proven data collection methods for establishing deep subsurface baselines include seismic surveys, pulsed-neutron and other well-logging techniques, pressure/temperature measurements, analysis of core samples and reservoir fluids, and analysis of existing

nearby injection and production operations. With establishment of accurate baseline conditions in the deep subsurface, the subsequent migration and behavior of injected CO_2 in the operational phase can be effectively monitored with the same or a similar range of technologies. Deep subsurface monitoring is used to demonstrate that CO_2 is securely contained within the reservoir and storage complex and to calibrate predictive simulations through a process known as history matching. Postclosure monitoring is intended to demonstrate the long-term security and low-risk profile of a storage site, in agreement with history-matched predictive simulations.

2. While deep subsurface environments are relatively stable, shallow and surface environments are subject to climate-driven variability, which means the establishment of accurate baselines usually requires a range of seasonal measurements. Appropriately selected and characterized storage sites should typically have low and manageable risks associated with any potential leakage of CO_2, defined as unintended migration out of the storage complex. Nevertheless, monitoring of relatively shallow and surface environments may be required to provide further assurance to stakeholders/regulators and provide a warning system in the unlikely event of a significant leak. The absence of any evidence of leakage can build confidence during monitoring of the operational phase, with the potential to decrease costs through reduced survey locations and frequency. Baseline and operational measurements can also be used to identify key parameters and streamline environmental monitoring programs.

Many of the demonstration projects to date, at both large industrial and pilot scales and encompassing both dedicated and associated storage, have received government funding to support extensive research-monitoring programs. The motivation of these programs has been to demonstrate both the technical viability and security of storage and the technical feasibility of monitoring CO_2 in the subsurface within a risk management framework. Commercial project operators will inevitably seek to rationalize monitoring programs with a more focused and cost-effective approach. This BPM includes some narrative on the relative costs and benefits of various monitoring technologies based on PCOR Partnership knowledge and experience. However, site-specific assessment and engineering judgment will always be required to select an optimal suite of technologies for any given storage project.

Plains CO_2 Reduction (PCOR) Partnership

Energy & Environmental Research Center (EERC)

BEST PRACTICES MANUAL – MONITORING FOR CO_2 STORAGE

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 program. The PCOR Partnership has included stakeholders from over 120 public and private sector entities 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. The PCOR Partnership region (Ayash and others, 2016).

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

- 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 published BPM encompasses best practices for integrating these technical elements into an iterative, fit-for-purpose adaptive management approach (AMA) for commercial storage project deployment. This document 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.

As defined by the PCOR Partnership AMA, most storage projects comprise the following five life cycle phases:

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

This BPM describes monitoring activities and their application throughout the entire duration of a storage project, with the understanding that monitoring activities are typically not a major project focus until well into the feasibility assessment phase, and in some cases, activities may not commence until the design phase. The reduced emphasis, in this document, of monitoring activities for the closure/postclosure phases is simply because of a lack of experience, as storage projects in the PCOR Partnership region are still operational. The technical terms used in this document are in general agreement with the definitions of Canadian Standards Association (2012) (CSA) Group Standard Z741-12, a joint Canada–U.S. initiative, with the exception of "site characterization" (see Section 3.0).

2.0 GEOLOGIC STORAGE

Storage projects can be broadly divided into two types. ***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 industrial 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 factors. 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 the 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.

The PCOR Partnership region encompasses significant storage resources, with large-scale operational CCS projects including both dedicated and associated storage (Peck and others, 2016). Extensive MVA 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 AMA

The PCOR Partnership has formalized and implemented an AMA for assessment, development, and deployment of commercial storage projects (Ayash and others, 2016). 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 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).

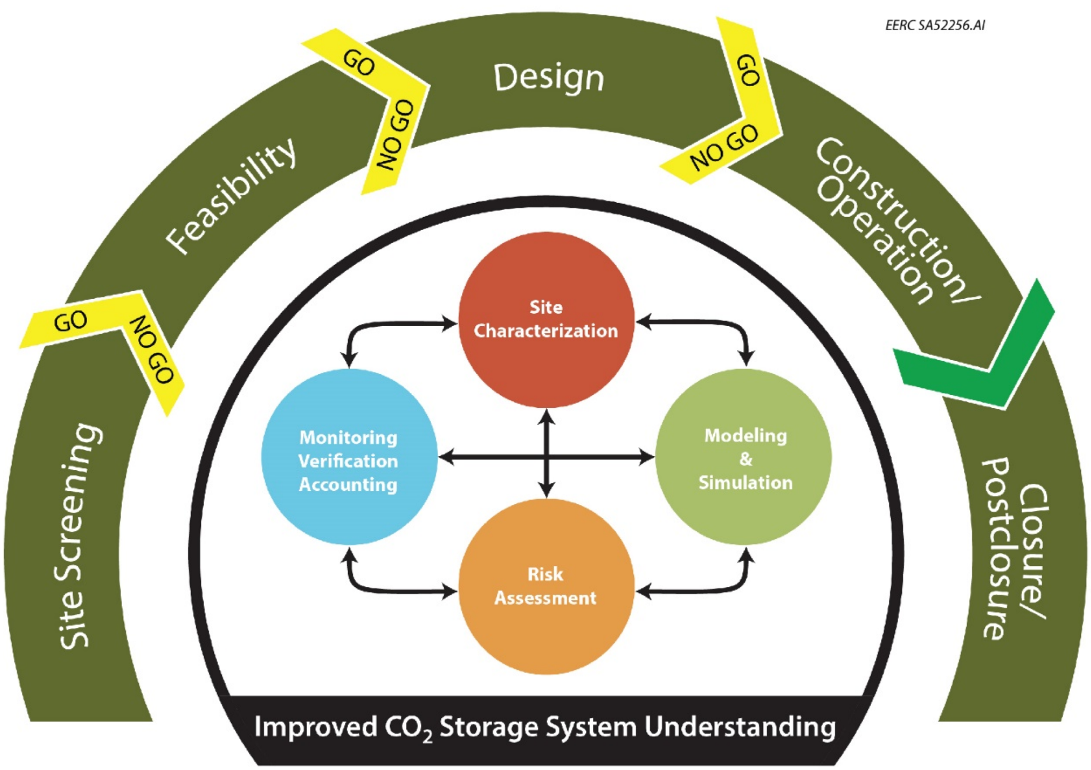


Figure 2. PCOR Partnership AMA for CO_2 storage project development (Ayash and others, 2016).

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 and 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.

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 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).

4.0 MVA OVERVIEW

As previously discussed, MVA is the common term used to describe one of four technical elements that are necessary for any successful CO_2 storage project (Ayash et al., 2016). This document defines "monitoring" as the measurement and surveillance activities necessary to provide an assurance of the integrity of CO_2 storage and defines "verification" as the comparison of the predicted and measured safe performance of a storage project. These definitions are consistent with the definitions of CSA Group Standard Z741-12, a joint Canada–U.S. initiative (Canadian Standards Association, 2012). The "accounting" component of an MVA entails methods for quantifying the amount of stored CO_2, typically for the purposes of deriving GHG emission reduction credits (e.g., American Carbon Registry, 2015). This BPM does not address the accounting component of an MVA and focuses instead on monitoring activities that are designed to provide the data required for the storage verification required by regulatory processes. Since most existing and emerging regulatory frameworks for storage encompass a risk-based approach, verification will likely require monitoring strategies and plans designed with an emphasis on the management of project and technical risks.

The unique geologic setting and characteristics of different storage sites requires a site-specific approach to monitoring and verification. Rather than define a prescriptive monitoring program, this document focuses on the systematic planning process for building and implementing a monitoring program for a storage project and provides relevant case studies based on scenarios considered as realistic examples for storage projects within the PCOR Partnership region.

The planning process entails several key elements, including 1) establishing monitoring objectives, 2) establishing baseline (preoperational) thresholds for these monitoring objectives, and 3) conducting operational and postclosure monitoring during CO_2 injection. Section 6 describes these aspects in detail. The planning process results in a monitoring program which includes a set of monitoring technologies that may be applied to meet the monitoring objectives, together with details about the implementation of the monitoring program, such as the location, frequency, and duration of the monitoring activities. Section 7 describes the deployment of various monitoring technologies with examples based on the PCOR Partnership experience.

Monitoring programs for dedicated and associated storage projects may share many common objectives, but markedly varying risk drivers may influence the design of the monitoring program. For example, associated storage projects would typically have a greater numbers of existing wells intersecting the reservoir. Consequently, these existing wells represent a potential pathway for out-of-zone migration of CO_2 from the reservoir into the overlying strata, which makes well monitoring a critical focus of the monitoring program for an associated storage site. Conversely, dedicated storage sites may have few wells penetrating the reservoir but may have greater uncertainty about the containment properties of sealing formation(s) because of a lack of historical characterization data. Thus monitoring technologies that focus on the primary sealing formations may be the critical focus of the monitoring program for a dedicated storage site. Sections 6 and 7 explore the design and implementation of monitoring programs, with an emphasis on plan development, baseline collection, and operational monitoring. Postclosure monitoring is discussed, although information presented on this stage of a project is limited simply because PCOR Partnership region storage projects are still operational.

Many of the demonstration projects to date, at both large industrial and pilot scales and encompassing both dedicated and associated storage, have received government funding to support extensive research-monitoring programs. The motivation of these programs was to demonstrate both the security and efficiency of storage and the technical feasibility of monitoring CO_2 in the subsurface within a risk management framework. These monitoring programs were intentionally broad and consisted of several innovative, as well as redundant, monitoring technologies. As storage projects become more widely accepted and increase in number, storage site operators will inevitably seek to implement monitoring programs that are technically robust and satisfy the monitoring objectives but are more cost-effective. While this document provides the basis for selecting an optimal monitoring program from a broad set of monitoring technologies, the best practices do not advocate for a particular set of monitoring technologies. The selection of particular monitoring technologies will be site-specific.

To help better organize the different types of monitoring technologies, this document divides the monitoring program into two broad categories: 1) deep subsurface monitoring and 2) environmental monitoring. As the name implies, deep subsurface monitoring focuses on the deep subsurface, primarily the storage reservoir and overlying sealing units. In contrast, environmental monitoring focuses on the shallow/near-surface/surface regime and generally includes groundwater aquifers, surface waters, the soil vadose zone, and the atmosphere immediately above the surface. The paragraphs below provide additional information about deep subsurface and environmental monitoring.

4.1 Deep Subsurface Monitoring

Deep subsurface monitoring provides measurements to track the migration of injected CO_2 within the storage reservoir(s) and provides data that can directly demonstrate the degree of conformance with predictive simulations. Essentially, deep subsurface monitoring builds confidence that CO_2 is securely contained within a defined storage complex (reservoir[s]) and overlying seal[s]) and allows identification and further investigation of any significant divergence from the anticipated behavior of the injected CO_2. Specific technical risks that deep subsurface monitoring addresses include:

1. Reservoir/storage formation capacity. Capacity refers to the ability of the reservoir to accept the planned amount of CO_2 to be injected and stored over the project lifetime. Capacity assessments are based on key reservoir properties and condtions, most notably, area, thickness, porosity, pressure, and temperature

2. Injectivity. Injectivity refers to the ability to inject CO_2 into the reservoir at the required rate over the course of the project lifetime. Injectivity assessments are based primarily on key reservoir properties, most notably thickness and permeability. Injectivity may change over time, for example, in response to CO_2 injection-driven geochemical or geomechanical changes.

3. Vertical containment. Injected CO_2 and other reservoir fluids should remain within the storage complex. Injected CO_2 is typically buoyant compared to native brine and other reservoir fluids and will, therefore, tend to rise upward over time. Therefore, monitoring data that can support ongoing risk evaluation of the integrity of overlying seals and penetrating wellbores provide information about vertical containment of CO_2 in the reservoir.

4. Lateral migration. Storage reservoirs may or may not have physical boundaries that prevent lateral flow of CO_2 beyond a certain distance (e.g., changes in lithology). Lateral migration of CO_2 beyond the planned extent of the storage project could change the likelihood of certain risks, for example, by bringing injected CO_2 into contact with potential leakage pathways like existing wells or other subsurface features. In some cases, issues of pore space ownership or other private rights may also be affected.

5. Induced seismicity. Changes to subsurface pressure and stress regimes resulting from subsurface fluid injection or extraction have the potential to generate seismic activity, through either reactivation or creation of faults and/or fractures. In the case of CO_2 injection operations, data from both associated and dedicated storage-monitoring programs has indicated that, in cases where seismicity has been induced, the magnitude of these events is very small ("microseismicity") such that resulting risks are low. However monitoring of microseismicity, both natural and induced, using passive monitoring techniques may provide assurance to stakeholders and regulators about the potential for induced seismicity of a given magnitude from CO_2 injection.

6. Wellbore integrity. Existing wells provide a potential CO_2 migration pathway from the reservoir to the overlying strata and represent a risk scenario for many sites, especially in cases such as some onshore CO_2 EOR projects where significant numbers of existing wells intersect the storage reservoir.

Baseline conditions in the reservoir, storage complex, and adjacent formations may be established using a range of technologies. Storage reservoirs are typically at sufficient depth such that seasonal influences are absent and conditions are relatively stable; therefore, a limited number of baseline measurements may be sufficient to establish baseline conditions. However, sites undergoing subsurface activity, such as subsurface fluid injection or extraction (including EOR), can create more dynamic conditions which require additional baseline measurements to quantify the inherent variability attributable to causes other than the planned CO_2 injection.

4.2 Environmental Monitoring

Appropriately selected and characterized storage sites should have low and manageable risks associated with potential leakage, defined herein as the unintended migration of CO_2 or other reservoir fluids out of the storage complex. Nevertheless, monitoring of relatively shallow, surface, and atmospheric environments may be required to provide further assurance to stakeholders and to provide valuable information in the unlikely event of leakage.

Typical onshore environmental monitoring programs focus on the chemical characterization of the following media:

- Groundwater, especially shallow aquifers with significant resources for potable supply or other uses.

- Surface water, including wetlands, lakes, ponds, rivers, and streams.

- Soil gas from the soil vadose zone, which typically contains natural, highly variable concentrations of biogenic CO_2 and other gases.

- Atmosphere above and adjacent to the storage site.

In contrast with deep subsurface monitoring, the chemical compositions of groundwater, surface water, soil gas, and the near-surface atmosphere are subjected to strong seasonal effects and are influenced by a wide range of natural processes and human activities. Baseline conditions should be established where possible over multiple seasons to quantify the natural background variability of these systems and to establish action levels (threshold concentrations) of key parameters that could be indicative of leakage and, therefore, warrant further investigation. In this context, wider regional environmental monitoring beyond the planned extents of the storage project can provide valuable supplemental data to help quantify the natural background variability of these systems.

5.0 PROJECT DEFINITION

Prior to initiating any site evaluation or development work 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?
  - How will the storage complex be defined?

- 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?

6.0 BUILDING A MONITORING PLAN – KEY ELEMENTS

As described in Section 4, the primary goal of monitoring is to collect measurements necessary to provide an assurance of the integrity of CO_2 storage and to provide the data required for the storage verification required by regulatory processes. Developing a monitoring program that achieves this goal requires three key elements:

1) **Establish monitoring objectives.** Monitoring objectives refer to specific risks that will be measured during the monitoring program using one or more monitoring technologies. Depending on the project-specific risks, the monitoring objectives may include deep subsurface monitoring, environmental monitoring, or both.

2) **Establish baselines.** After the monitoring objectives have been established, appropriate data acquisition activities should be conducted prior to CO_2 injection to establish baseline (preoperational) conditions in relevant subsurface and shallow/surface environments. The primary goal of the baseline data acquisition is to capture the natural variability attributable to causes other than CO_2 injection, which provides context for subsequent measurements collected during the operational monitoring.

3) **Conduct operational and postclosure monitoring.** After baselines have been established and CO_2 injection begins, the storage project transitions into the operational phase. Monitoring data are acquired during this operational phase to track project performance and to compare these operational monitoring data against the established baselines. Ideally, the deep subsurface monitoring data will provide evidence of CO_2 storage as predicted by modeling, and the environmental monitoring data will provide no evidence of CO_2 leakage, thereby providing multiple lines of evidence that the storage complex is performing as predicted and is safely storing CO_2. This monitoring continues as the project ceases CO_2 injection and transitions into a postclosure phase.

The remainder of this section describes a process for establishing monitoring objectives, establishing baselines, and conducting operational monitoring, while Section 7 describes the selection of monitoring techniques and selected techniques used in PCOR Partnership projects.

6.1 Risk-Based Monitoring Objectives

The monitoring objectives for nearly all storage projects must address, at a minimum, a set of generic risks that affect most storage projects, e.g., storage capacity, injectivity, and vertical/lateral containment. However, the manner in which these risks occur depends upon site-specific conditions. In addition, other risks beyond this generic list are likely present, and these specific risks will reflect some combination of site-specific conditions, stakeholder assurance concerns, and regulatory requirements. Consequently, the project-specific risk assessment (RA) is generally the best starting point for establishing monitoring objectives. The primary outcome of the RA includes a risk register, which is a list of potential project-specific risks. The RA is typically developed in consultation with internal and external stakeholders and subject matter experts. Therefore, the RA provides a relatively comprehensive summary of potential adverse events that could affect the storage project and represents the opinions of multiple experts. In addition to the risk register, the RA provides rankings for these potential risks in terms of both the likelihood of a particular risk occurring and the consequence(s) of the risk to the storage project should the risk occur (Azzolina and other, 2017). Thus the RA outlines the specific risks that the monitoring objectives should include and provides a relative ranking of these risks such that the monitoring program can focus appropriate resources on higher-ranking risks.

Recommended Best Practice – Utilize the Project Risk Assessment to Establish Monitoring Objectives
The project RA represents a comprehensive summary of potential adverse events that could affect the storage project and is, therefore, generally the best starting point for establishing monitoring objectives.

In addition to establishing monitoring objectives to monitor project-specific risks, it may be useful to collect additional measurements that provide data to guide and/or optimize project operations, especially regarding CO_2 injection rate. Additional monitoring objectives may be established to monitor these aspects of the operation, which are not necessarily risk-based.

Therefore, in some cases, monitoring objectives can serve a dual-purpose, providing data for monitoring both potential project risks and CO_2 injection operations.

Figure 3 illustrates an iteration of the PCOR Partnership AMA to storage project development (see Section 3) and shows how the project-specific RA provides the basis for establishing monitoring objectives. As shown in the figure, the RA encompasses knowledge gained through geologic models and numerical simulations, which themselves are developed based on site characterization data (acquired during initial site screening and feasibility assessment project phases). In addition to these modeling and simulation inputs, the RA takes into consideration applicable regulatory requirements, regional stakeholder attitudes regarding the project, and other potential risk factors. Thus the RA represents the integration of multiple storage project elements and, therefore, provides an informed basis upon which the project team may establish risk-based monitoring objectives.

More details regarding the key RA source materials of models/simulations, regulations, and regional stakeholder attitudes are provided below.

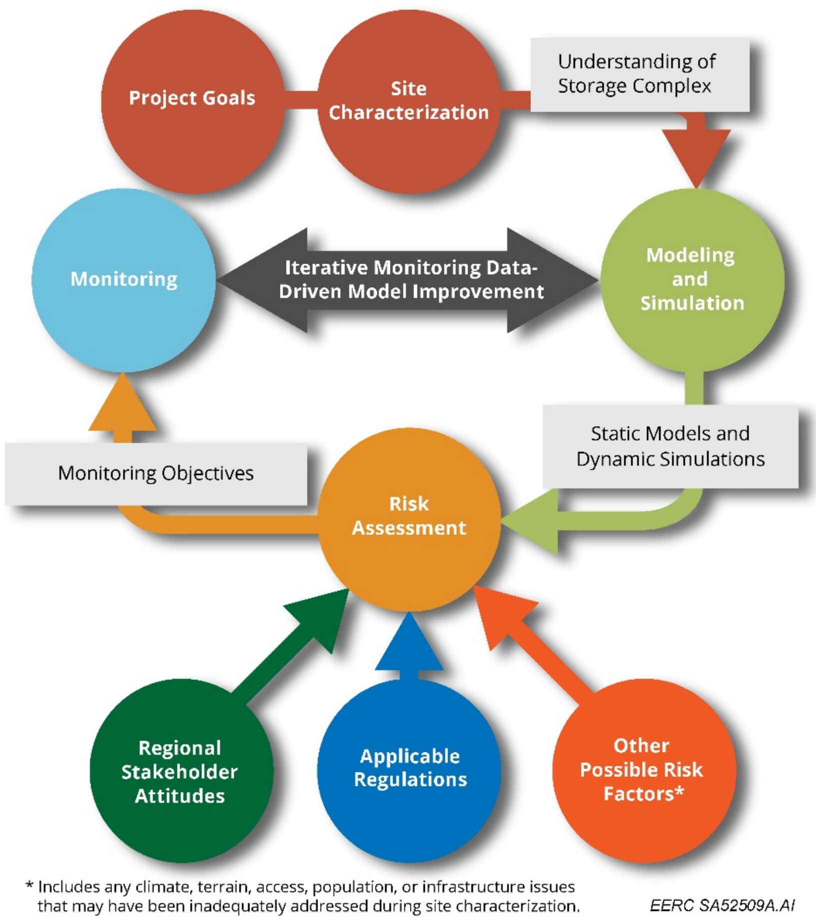


Figure 3. AMA progression highlighting path to monitoring objective establishment and subsequent dynamic monitoring–modeling interaction.

Geologic Models and Numerical Simulations – Geologic models are used to integrate the site characterization data into a three-dimensional (3-D) conceptualization of the storage complex, including petrophysical properties of the subsurface and key geologic features (e.g., stratigraphy, structure, or faults). Numerical simulations are subsequently used to predict the behavior, interactions, and movement of CO_2 and formation fluids within the geologic model in response to CO_2 injection. The close interaction between geologic models and numerical simulations results in these terms commonly used together to denote a single element: “modeling and simulation.”

The modeling and simulation predictions estimate the extent of the CO_2 injection-driven pressure plume, which provides one means of defining the project area of review (AOR). While this AOR definition approach is valid for many storage complexes, in some cases where excellent reservoir properties combine with very significant storage capacity, injected CO_2 can extend beyond the pressure plume, in which case the extent of the free-phase CO_2 plume will define the AOR. The modeling and simulation predictions may also be used to estimate changes to the subsurface stress field in the reservoir. All of these predictions provide information that can be used to determine the type, location, and frequency of monitoring activities needed to satisfy the monitoring objectives.

As illustrated in Figure 3, there is a direct relationship between modeling/simulation and monitoring, which results in ongoing, iterative modeling/simulation improvements throughout a storage project. While modeling and simulation play a major role in the initial monitoring program design, subsequent baseline and operational monitoring data provide inputs used to evaluate, calibrate, and refine models to improve predictive accuracy. Successive iterations of monitoring data collection and subsequent model improvements throughout the operational phase help to reduce uncertainty in the modeling predictions which, in turn, provides greater confidence in the ability to predict the behavior of CO_2 and other fluids in the subsurface in response to CO_2 injection. In the case of associated storage projects, monitoring-driven improvements to modeling and simulation can translate to significant commercial value by providing more accurate information regarding CO_2 utilization, incremental oil recovery, and CO_2 flood scenario planning (including phasing of CO_2 and water-flooding events). The PCOR Partnership Modeling and Simulation BPM provides best practices regarding modeling and simulation activities for storage projects (Pekot and others, 2017).

Applicable Regulations – A thorough understanding of the regulatory environment is required to ensure that the monitoring plan complies with all applicable federal, state, and local regulations. In general, regulations specify environmental standards or objectives, and the project team is responsible for developing a monitoring plan that yields the data necessary to demonstrate compliance with these regulatory standards. In some cases, monitoring plan review and approval by regulatory authorities may be required.

Regional Stakeholder Attitudes – This document defines “regional stakeholders” as encompassing project-affected and nearby landowners and the regional general public. Good relationships with regional stakeholders are helpful and often essential to storage project success. This is especially true when access to privately held land is needed to conduct monitoring activities like seismic surveys or environmental monitoring. A monitoring program that adequately addresses landowner and regional environmental concerns can be helpful to securing regional stakeholder project support, which is achieved through building and sustaining positive relationships. Primary landowner concerns are usually related to maintaining the quality of surface water, groundwater, and land resources and ensuring against interference with land use practices. Environmental monitoring involving the collection and analysis of water and soil samples—and making the results publicly available—provides assurance to landowners that the storage project and related activities are not compromising their resources.

In addition to obtaining support from regional stakeholders, environmental monitoring data can be useful to address concerns or complaints about a storage project. As an example, an EOR project in the Weyburn oil field of southern Saskatchewan, Canada, was confronted by a landowner who alleged that the EOR project was resulting in negative impacts to surface waters, including abnormally large algal blooms and chemical changes that resulted in livestock deaths. However, baseline and operational environmental monitoring data collected from nearby surface water and soil gas, along with additional monitoring activities, were used to disprove these allegations and show that the EOR project did not cause the alleged impacts (International Journal of Greenhouse Gas Control, 2013).

Recommended Best Practice – Engage Regional Stakeholder and the Public
Establishing positive relationships with regional stakeholders is key to developing and implementing a successful monitoring program.

6.2 Establishing Monitoring Objectives

As briefly discussed in Section 4, the following generic risk categories are likely to be common to most storage projects and typically represent the minimum set of risks included in a monitoring program:

- Reservoir/formation storage capacity
- Injectivity
- Vertical containment
- Lateral migration
- Induced seismicity
- Wellbore integrity (Depending on the number and condition of project site wells, wellbore integrity risk may be incorporated within the vertical containment risk category.)

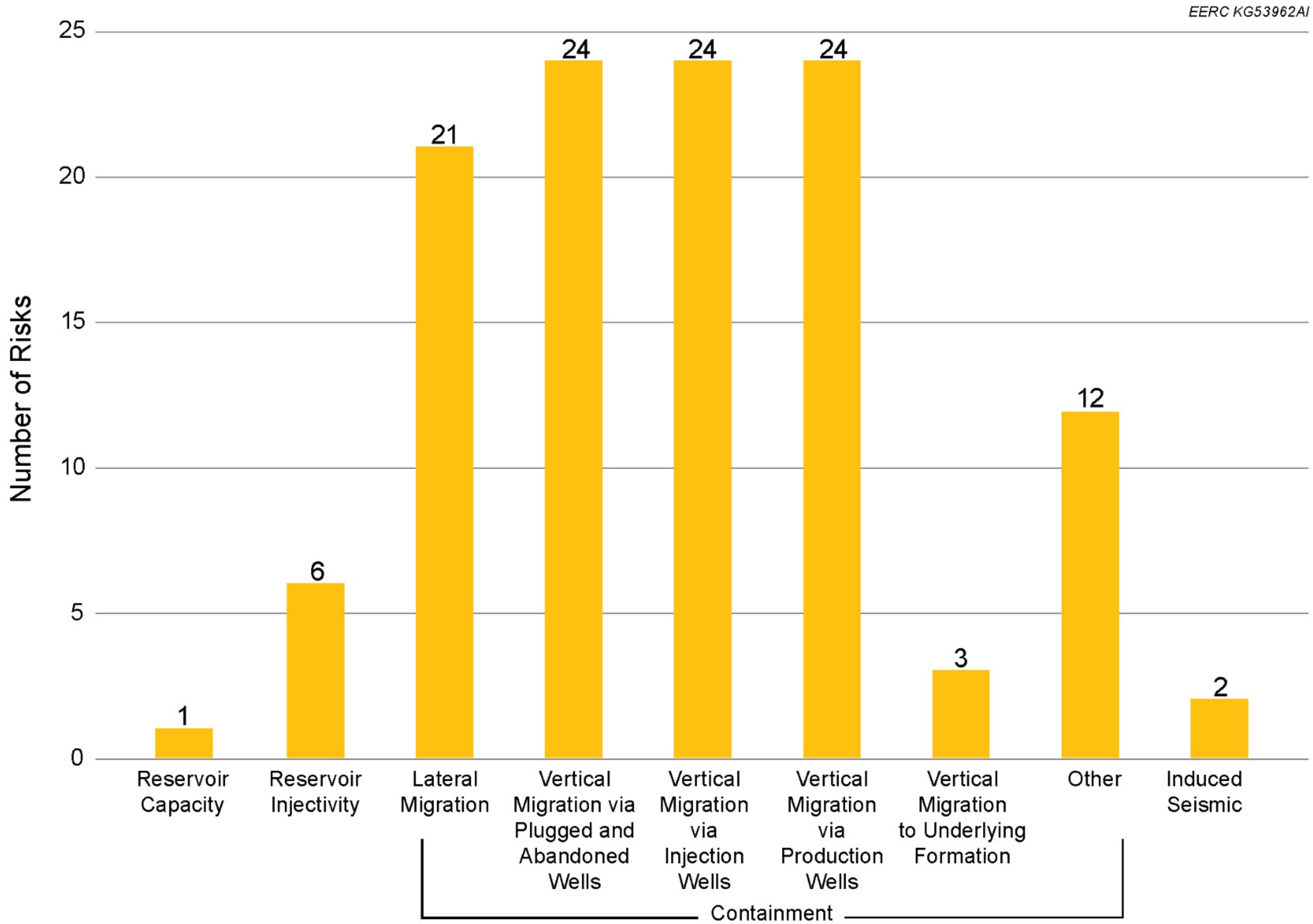
However, the bullet list above describes broad risk categories but does not describe risks with sufficient specificity to establish monitoring objectives. Depending on the storage project and site-specific conditions, each of these risk categories can represent multiple risks. The risk register prepared as a component of the RA for an ongoing PCOR Partnership associated storage project provides an example of how one risk category may yield multiple specific risks and result in multiple monitoring objectives. For instance, while vertical migration of fluids through existing wellbores falls under the broader risk category of "vertical containment," the project team felt that distinguishing vertical migration via P&A wells, injection wells, and production wells provided the appropriate level of specificity for establishing monitoring objectives. In addition to the type of well, the project team further discretized the individual risks based on the locations of these wells relative to the planned CO_2 injection locations. Consequently, this one risk category, vertical containment, represented multiple individual risks: 24 specific risk permutations for P&A, injection, and production wells (Figure 4).

In addition to parsing risk categories into multiple specific risks, one risk may lead to multiple monitoring objectives. Because many project risks relate to the potential migration of CO_2 and other fluids from the storage complex into overlying subsurface and near-surface environments, establishing monitoring objectives generally requires developing a physical understanding of 1) potential fluid migration pathways, 2) options for monitoring these fluid migration pathways, and 3) limitations and sensitivities/detection limits associated with monitoring approaches and technologies. This process may result in one risk requiring multiple monitoring objectives. For example, wellbores within the AOR (either operating wells or plugged and abandoned wells) provide potential fluid migration pathways through the interior of the well casing, outside of the casing, or both. Depending on the site-specific conditions, more than one monitoring technology may be needed to adequately address wellbore leakage risk at different points along the wellbore. This is an example of where one specific risk—leakage of fluids via a wellbore— translates to multiple monitoring objectives.

As the previous examples suggest, a seemingly simple set of potential risk categories may result in a large number of monitoring objectives. Rather than develop monitoring objectives for each risk permutation, which could result in an onerous monitoring program, PCOR Partnership experience suggests that it is more effective to identify common sets of risk pathways, thereby identifying a more parsimonious set of monitoring objectives. This process of establishing monitoring objectives requires quantifying the relative ranking of individual project risks and understanding how individual risks are connected. In some cases, monitoring objectives can be developed for a relatively complex risk category based on consideration of:

- The highest-ranking individual risk(s), as defined by the project RA.
- Possibilities for eliminating some risks from consideration for monitoring because of sufficiently low (acceptable) risk likelihood of occurrence (probability) and risk impact.
- Relationships and/or commonalities in the failure modes associated with two or more risks that may enable establishing one monitoring objective that is applicable to more than one risk.

Establishing monitoring objectives from the project RA risk register can sometimes be straightforward. For example, the risk category of storage capacity often comprises the single risk that the storage complex may prove to have less CO_2 storage capacity than predicted by site characterization and modeling and simulation activities. In this case, likely monitoring objectives would be to 1) document the amount of CO_2 being injected and 2) acquire data to inform calibration of predictive simulations ("history matching"). However, monitoring objectives established from some risks can be more complicated, as the previous examples for wellbore leakage illustrated. Ultimately, the number and type of monitoring objectives are site-specific.



* Includes migration via natural (but undetected) faults and faults resulting from geomechanical failure or geochemical degradation.

Figure 4. Category-based risk distribution for an associated storage project.

As an example, using the risks shown in Table 3 as a basis, the following monitoring objectives were established:

- Injectivity – Monitor the CO_2 injection rate and bottomhole pressure, and evaluate whether a change in the relationship between these two measurements, such as increasing bottomhole pressure, could be indicative of injectivity loss.

- Vertical containment – Monitor the dissolved CO_2 concentration for selected wells that penetrate selected USDWs (underground sources of drinking water). Consult the project RA for selection of higher-ranking wells.

- Lateral migration – Acquire data specific to determining whether and to what extent CO_2 is laterally migrating to selected (based on RA) out-of-boundary plugged and abandoned wells.

Table 3. Individual Risks Selected from the Risk Register of a PCOR Partnership Storage Project to Represent Three Technical Risk Categories for the Project

Risk Category	Risk Description
Injectivity	Cannot inject 1 million tonnes/year CO_2 (target injection rate) because of project-driven geochemical changes to reservoir.
Vertical Containment	Vertical leakage of CO_2 to USDWs via updip plugged and abandoned wells.
Lateral Migration	Lateral migration of CO_2 beyond boundary into updip plugged and abandoned wells.

Recommended Best Practice – Establish Specific and Focused Monitoring Objectives

Establish specific and focused monitoring objectives by quantifying the relative ranking of individual project risks, identifying common sets of risk pathways, and understanding how individual risks are connected.

6.3 Establishing Risk Indicators

As described above, the monitoring objectives are largely risk-based and informed by the project-specific RA. The monitoring objectives are generally a verbal description of specific risks and the associated physical element to be monitored. The next step in the planning process is to identify quantifiable metrics that can be measured using relevant technologies. These quantifiable metrics represent surrogates for the established monitoring objective(s). For example, a monitoring objective may be potential leakage of displaced formation brine into overlying groundwater aquifers; however, the quantifiable metric may be the concentration of total dissolved solids (TDS) in a groundwater sample. This document refers to these quantifiable metrics as “risk indicators.” Other examples of risk indicators include bottomhole pressure in the CO_2 injection well(s) as an indicator of injectivity; water chemistry parameters such as pH, alkalinity, or dissolved CO_2 as measures of CO_2 impacts to groundwater; or measurements of CO_2 saturation using pulsed-neutron logs (PNL) for individual wellbores. Monitoring these risk indicators involves comparing measured values against preestablished threshold values (action levels). Measurements exceeding these action levels indicate a change from baseline conditions and warrant further investigation.

Table 4 provides an example set of risk indicators for a representative list of potential monitoring objectives for an associated storage project. This example lists the monitoring objectives in the rightmost columns: reservoir capacity, reservoir injectivity, containment, and induced seismicity. The specific risk indicators are in the left column grouped by different technologies nested within the environmental and deep subsurface monitoring program. For example, soil gas sampling and analysis is part of the environmental monitoring and includes measurements of CO_2 and hydrocarbon gases in samples collected from the soil vadose zone. These measurements provide monitoring data specific to vertical migration of either CO_2 or hydrocarbon gases; thus the columns “CO_2” and “HCs” are marked with an “X” to denote that these risk indicators cover those specific monitoring objectives. Similarly, subsurface CO_2 detection via geophysical techniques is part of the deep subsurface monitoring and provides information specific to reservoir capacity, injectivity, and the vertical or lateral migration of CO_2. Table 4 provides a useful matrix for ensuring that one or more risk indicators provides monitoring coverage for each of the established monitoring objectives.

6.4 Monitoring Program Implementation

The monitoring objectives and risk indicators define the monitoring program, which also includes details about the location, frequency, and duration of the monitoring activities. Implementation of the monitoring program occurs throughout the life-cycle phases of the storage project: design, construction/operation, and closure/postclosure phases (see Section 3). This document defines three distinct phases of monitoring program implementation: 1) baseline, 2) operational, and 3) postclosure. Baseline monitoring typically occurs during the design phase to evaluate preinjection subsurface and near-surface conditions and quantify the natural background variability of these systems. Operational monitoring occurs during the active injection phase of a project and compares monitoring data against the baseline measurements. Postclosure monitoring occurs after injection is completed and continues until site conditions meet requirements previously agreed upon by the operator and regulatory authority. Existing and emerging regulatory frameworks place a strong emphasis on postclosure monitoring. The essential objective of postclosure monitoring is to demonstrate long-term storage integrity and accompanying low-risk profiles, such that operating permits can be surrendered to the regulatory authority after a period of time. Because relatively few storage projects around the world have transitioned from the operational phase to the postclosure phase, this document focuses primarily on baseline and operational monitoring. Section 6.7 provides additional discussions about postclosure monitoring.

Table 4. Example Risk Indicators for Evaluating a Set of Generic Monitoring Objectives

Data Collection Environments/Methods Data Types/Risk Indicators	**Technical Risk Categories/Monitoring Objectives**								
			Containment						
			Vertical Migration			**Lateral Migration**			
	Reservoir Capacity	**Reservoir Injectivity**	**CO_2**	**HCs***	**Brine**	**CO_2**	**HCs***	**Brine**	**Induced Seismicity**
Environmental Monitoring									
Soil Gas Sampling and Analysis									
CO_2 and Hydrocarbon Gases			X	X					
Surface and Groundwater Sampling and Analysis									
pH, Alkalinity, Conductivity, Dissolved CO_2			X	X	X				
Deep Subsurface Monitoring									
CO_2 Injection Rate	X	X							
Pressure/Temperature									
Injection Wellhead Pressure and Temperature		X				X	X	X	
Monitoring Well Downhole Pressure and Temperature			X	X	X	X	X	X	
Monitoring Well Distributed Fiber Optic Temperature			X	X	X	X	X	X	
Injection Well Bottomhole Pressure		X				X	X	X	
Subsurface CO_2 Detection via Geophysical Techniques									
Seismic Survey for CO_2 Detection Throughout Large Subsurface Volume	X	X	X			X			
Vertical Seismic Profiles for Near-Wellbore CO_2 Detection		X	X			X			
Passive Seismic									
Seismic Activity									X
Near-Wellbore Data Acquisition via Monitoring Well Logging Techniques									
CO_2, Hydrocarbons, pH, Alkalinity, Conductivity	X		X	X	X	X	X	X	
In Situ Downhole Fluid Analysis via Monitoring Wells									
CO_2, Speciated Hydrocarbons, pH, Alkalinity, Conductivity	X		X	X	X	X	X	X	
Reservoir Fluid Sampling (via Monitoring Wells) and Analysis									
CO_2, Speciated Hydrocarbons, pH, Alkalinity, Conductivity	X		X	X	X	X	X	X	

* Hydrocarbons including oil species and hydrocarbon gases including methane, ethane, and propane.

Lessons Learned – Important Considerations When Establishing Risk Indicators

When establishing risk indicators, important considerations include:

- Overall project objectives.
- Completeness – At least one risk indicator covers each monitoring objective.
- Redundancy – Particularly important for higher-ranking risks, having more than one risk indicator for a particular risk provides redundancy. This redundancy results in greater confidence that the monitoring program will satisfy the monitoring objectives.
- Sensitivity – Sensitivity refers to the limit of detection for a particular risk indicator to detect a change from baseline conditions and thereby trigger additional investigation. Technologies with a higher sensitivity can detect a smaller magnitude of change.
- Time to detection – While some measurements are collected in near real-time (e.g., bottomhole pressure and temperature), other measurements require weeks to months of data processing (e.g., 3-D seismic). These differences in data acquisition and processing time result in different time-to-detection.
- Measurement scale – Many technologies acquire measurements at a localized scale (e.g., PNL logs measure the wellbore scale), while other technologies acquire measurements at larger scales (e.g., 3-D seismic can collect measurements at the field-scale).
- Relationships between risk indicators – In cases where one risk indicator is directly related to another (e.g., CO_2 concentration and pH of brine in near-wellbore environment), these relationships can often be used to help define action levels and improve monitoring reliability and efficiency.

Recommended Best Practice – Review Monitoring Objectives with Project Stakeholders

Following establishment of monitoring objectives and associated risk indicators, project owners/operators should review these against applicable federal, state, and local regulations.

6.5 Establishing Baselines

Establishing baselines refers to quantifying the natural background variability of the risk indicators in deep subsurface and shallow/near-surface/surface systems such that subsequent operational monitoring measurements can be compared against these values to assess whether the system is or is not consistent with baseline conditions (Gilbert, 1987). New measurements beyond the natural variability of the established baselines may indicate a potential storage system failure and, therefore, warrant further investigation. The nature of the baseline measurements differs between the deep subsurface and environmental monitoring regimes, as described below.

6.5.1 Establishing Baselines for Deep Subsurface Monitoring

Many deep subsurface monitoring techniques (e.g., seismic surveys) do not directly measure CO_2 presence. For this reason, baseline measurements provide important context to aid interpretation of subsequent surveys with respect to the presence and migration of CO_2.

The site characterization activities during the site screening and feasibility assessment phases of a storage project provide an initial understanding of subsurface baseline conditions. The primary objective of site characterization is to acquire data needed to assess the viability of a storage site, especially including data describing:

- The targeted storage formation(s), including data describing formation geology, geologic structure, pressure/temperature regimes, and geochemistry.
- Overlying sealing formation(s), ideally obtaining similar information as for the storage formation(s).
- Existing wells (active or plugged and abandoned) penetrating the sealing and storage formations.
- Other subsurface geologic features with the potential to impact project performance.

Additional information required for establishing baselines for monitoring purposes should also include the following key subsurface properties/parameters:

- Temperature and pressure ranges in reservoir and sealing layer(s).
- CO_2 concentration in reservoir and sealing layers, where applicable.
- Porosity and permeability of reservoir and sealing layer(s).
- Concentrations of other gases (including hydrocarbon gases, oxygen, nitrogen, and hydrogen sulfide) present in reservoir and sealing layers.
- Chemical properties (including pH, alkalinity, conductivity, total dissolved solids, and major ion constituents) of fluids/brine in reservoir and sealing layers.
- Mineralogy and geochemistry (primarily focused on mineral and elemental composition) of reservoir and sealing layers.

Site characterization data sets acquired for most storage projects typically include a combination of previously existing data sets (historical – prior to the storage project initiation) and data generated via additional site characterization activities (specifically acquired for the storage project) such as well logging, analysis of drill core or fluid samples, or geophysical surveys. As a first step toward establishing baselines for the deep subsurface, the project team should assess the quality and completeness of available site characterization data and evaluate the need for additional data acquisition. Because deep subsurface data have the advantageous characteristic of representing features and properties that are typically slow to change, even relatively old data—provided they are of high quality—can often be of significant value. Key considerations regarding the possible need for updating and/or supplementing the available site characterization data to improve the accuracy in establishing baseline conditions are:

- Quality of the existing site characterization data (*e.g., have appropriate data collection protocols been adequately documented?*), especially data describing the storage and sealing formations.

- Reliability of the sampling and/or analytical/characterization techniques used for data acquisition.

- Possibilities for reprocessing existing data (typically applicable to historical seismic data).

- Knowledge or evidence of potential subsurface changes (e.g., well drilling, oil/gas production, produced water disposal) that may have occurred since the acquisition of the historical site characterization data.

The adequacy of characterization data for establishing baselines in the deep subsurface should also be evaluated in the context of subsurface risks. Typically, higher-ranking risks should be given greater consideration to ensure that critical subsurface baselines are established as accurately as possible. In some cases, the viability of site characterization data for use as baseline measurements may be enhanced with reprocessing; for example, seismic data can often be reprocessed with new software capabilities or through calibration of old data against additional measurements such as downhole pressure, well logging, and sample collection and analysis. In other cases, more expensive and time-consuming options such as new seismic surveys or drilling campaigns may be necessary to confirm site characterization findings and definitively establish baselines for the deep subsurface.

6.5.2 Establishing Baselines for Environmental Monitoring

Environmental monitoring generally encompasses groundwater, surface water, soil gas, and the near-surface atmosphere, with greater emphasis generally placed on groundwater and soil gas monitoring. As noted in Section 4, in contrast with deep subsurface monitoring, the near-surface and surface environment are subjected to seasonal effects and are influenced by a wide range of natural processes and human activities. Consequently, the risk indicators in groundwater and soil gas typically have greater variability, which adds uncertainty to the baselines. Establishing baseline conditions for environmental monitoring typically includes sampling and analysis of:

- Vadose zone soil gas for:
  - Concentrations of CO_2, methane, ethane, oxygen, nitrogen, and volatile organic hydrocarbons (VOCs).
  - Other parameters necessary to address site-specific risks and/or regulatory requirements.

- Groundwater (and selected surface waters) for:
  - Parameters indicative of the presence of CO_2, such as pH, alkalinity, and dissolved CO_2, or the presence of brine impacts, such as conductivity or TDS.
  - Other parameters necessary to address site-specific risks and/or regulatory requirements.

Recommended Best Practice – Ensure Baseline–Monitoring Data Comparability
In general, baselines should be established using data acquired via the same technique(s)—deployed with the same acquisition parameters—planned for use in operational monitoring. Good comparability is especially important when considering the use of existing data (rather than acquiring new data) for establishing baselines. Poor comparability between the techniques and parameters used to establish baselines and the subsequent operational monitoring could result in difficulties interpreting the operational monitoring results.

Recommended Best Practice – Review Existing Subsurface Data
Existing data, collected prior to storage project initiation, can vary significantly in quality and reliability. While these historical data may be invaluable for initial site screening and feasibility studies, using these data to establish baseline conditions for a monitoring program should be subject to quality assurance review. The cost savings from using existing data should be balanced against limitations that could affect interpretation of the subsequent operational monitoring data.

Natural and anthropogenic influences, including naturally occurring biological and chemical processes that occur within soil and groundwater systems, will affect the concentrations of these parameters. For example, biological respiration and microbial processes in soils will significantly affect soil gas CO_2 levels, while denitrification and redox reactions in groundwater will significantly affect pH, alkalinity, and dissolved CO_2 levels. Seasonal cycles and even diurnal cycles will influence these processes, as warm spring and summer months generate different effects than colder and drier fall and winter months. Therefore, in the absence of any influences from CO_2 injection, these naturally occurring processes will result in a range of concentrations in soil and groundwater, all of which constitute the natural variability in the baseline. Some examples of potential influences on the risk indicators for environmental monitoring include:

- Groundwater chemistry and flow regimes.
- Aquifer geology and geochemistry.
- Soil type and geochemistry.
- Land/soil use.
- Thickness and displacement/volume of soil or groundwater zone of interest.
- Climatic variables like precipitation and temperature.
- Nearby industrial activities.

These examples of chemical/biological processes and their respective influences on the soil gas and groundwater regimes illustrate the challenges associated with establishing baselines for environmental risk indicators. The natural variability in these background measurements requires that establishing baselines for environmental monitoring go beyond collecting data at regular intervals over a multiseason/year period and deriving statistical thresholds. Instead, baseline monitoring data should be used in conjunction with relevant data from literature and experimental studies to develop a practical and quantitative understanding of the natural chemical/biological processes and the environmental/climatic/anthropogenic factors influencing them that determine and control baselines. This quantitative understanding of native systems provides the basis for interpreting future operational monitoring data that may fall outside of anticipated baseline ranges. For example, it is likely that at some point during a storage project's operational or closure/postclosure phases, which can extend for 20 years or greater, climatic changes (excessively hot or cool periods), extreme meteorological events, or other impacts to the storage project's near-surface environment will occur. These influences will likely result in monitoring data risk indicators exceeding the baseline values established from a relatively short data set collected over a baseline monitoring phase of generally less than 3 years. Stated differently, the baseline monitoring data collected today may not be representative of the operational and closure/postclosure monitoring phases of the future if the system is nonstationary, or changing over time. Therefore, having a quantitative understanding provides a framework for evaluating future monitoring data in the context of the established baseline system.

Developing a data set for establishing environmental baselines should include samples collected and analyzed multiple times during each year to capture seasonal variability. For example, quarterly sampling will capture the four seasons of winter, spring, summer, and fall. Higher-frequency sampling (e.g., monthly) provides better time-series resolution, which has a greater likelihood of capturing seasonal variability. For example, Case Study 6.1 illustrates soil gas CO_2 concentration seasonal variability recorded over a nearly 4-year sampling/analysis campaign conducted to establish baseline conditions for a PCOR Partnership storage project. While longer (multiyear) baseline monitoring generally provides a more complete and representative native system data set, the length of the baseline monitoring period is often limited by budget and schedule constraints. As a result, baseline monitoring periods are generally less than 3 years. Project-specific risks should dictate the number and type of sampling locations; however, the sampling plan should be adequate to address the identified risk scenarios with potential to affect the near-surface environment within the AOR. Supplemental background data collected from additional monitoring locations—both within and outside of the AOR—provide additional information about the natural variability of the native system near the storage project.

Lessons Learned – Groundwater Systems Generally Provide Greater Sensitivity and Time to Detection Than Surface Water and Soil Gas Measurements
Chemical concentrations in groundwater systems typically have less variability than surface waters and soil gases, which provides greater sensitivity for detecting change from baseline conditions. In addition, groundwater systems are deeper (closer to the storage reservoir), thereby enabling more timely detection of potential deviations from baseline conditions that could be indicative of leakage.

Recommended Best Practice – Establish Groundwater Baseline and Subsequent Monitoring
Groundwater baselines should be established for primary indicators of CO_2 presence (including pH, alkalinity, dissolved CO_2, and TDS) and parameters needed to address regulatory requirements. Operational monitoring can then focus on these primary CO_2 indicators, with the understanding that the sampling plan can be amended over time in the event of monitoring data that suggest a deviation from baseline conditions for these primary indicators.

Lesson Learned – Value of Surface Water Baselines
Surface water monitoring is typically of limited technical value since localized climatic conditions and other extraneous factors can significantly influence surface water chemistry. Care should be taken in interpretation of any surface water sample results. Preinjection surface water quality baseline measurements may assist in responding to any subsequent surface water issues.

6.6 Operational Monitoring

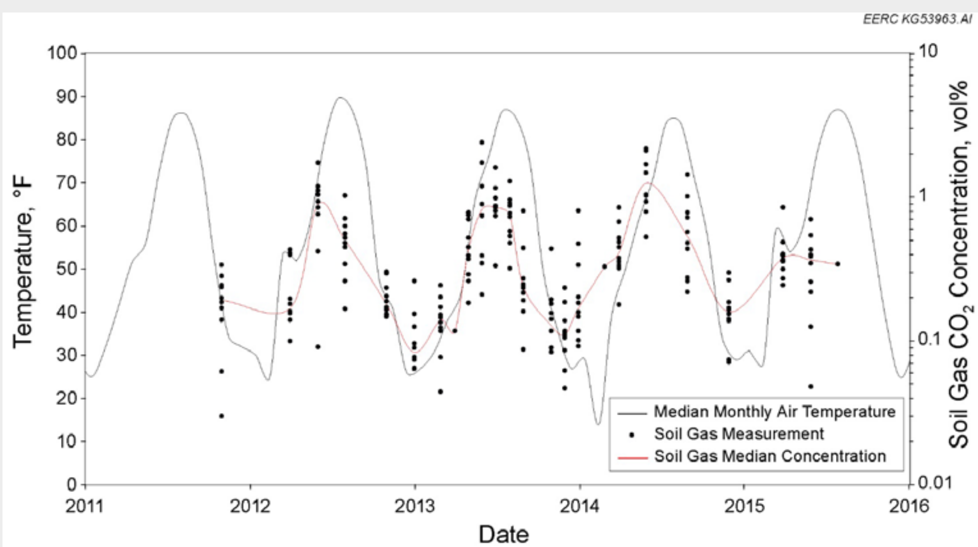
With the beginning of CO_2 injection, the monitoring program transitions from baseline to operational monitoring. Operational monitoring serves a different function. Whereas the goal of baseline monitoring was to quantify the natural background variability of the risk indicators in deep subsurface and shallow/near-surface/surface systems, the goal of operational monitoring is to continue measuring these risk indicators and to determine whether they are consistent with baseline conditions. The operational monitoring may initially maintain the same sampling plan and schedule as the baseline monitoring. However, as the operational monitoring phase progresses and yields more information about the storage complex performance and the behavior of injected CO_2, the sampling plan and schedule will likely evolve. Operational monitoring activities typically decrease in frequency, scope, or both when no significant changes from baseline conditions occur, thereby indicating a low-risk profile.

Case Study 6.1 – Soil Gas CO_2 Concentration Seasonal Variability

The figure below shows time series measurements of soil gas CO_2 concentrations (black circles) measured at interspaced locations at a CO_2 storage site from November 2011 through August 2015. The red line shows the median soil gas CO_2 concentration measured during a particular sampling event. There are clear seasonal cycles in the soil gas CO_2 concentrations, with the highest average concentrations measured during the warmer months (June through August) and the lowest average concentrations measured during the colder months (November through February). The gray line shows the median monthly air temperature measurements obtained from the National Climatic Data Center at a measuring station located approximately 20 miles west of the study area. As shown in the figure, the seasonal cycles in the soil gas CO_2 concentrations mirror the seasonal cycles in air temperature.

Baseline data describing seasonal cycles in soil gas CO_2 concentration are needed for deployment of soil gas analysis as part of a long-term monitoring program. In addition to providing an indication of typical concentration ranges, baseline data representative of seasonal variability are also needed to develop an understanding of the natural biological and chemical processes underlying seasonal (and climatic) variability. As an example, air temperature over longer timescales may be nonstationary (changing). Consequently, soil gas measurements collected during the baseline phase may not be representative of future soil gas monitoring data acquired under changing climatic conditions (e.g., anomalously warmer or colder periods). Therefore, the ability to relate soil gas CO_2 concentration to climatic variables like air temperature, which are surrogates for the rates of various soil chemical/biological processes, provides climatic context for future soil gas CO_2 measurements that may fall outside of baseline ranges.

Another useful monitoring strategy would be to establish baseline "control points" located outside of the AOR and, therefore, beyond the influence of the CO_2 injection operations. These locations could provide additional evidence of natural climatic variability. These control points would be particularly important as the operational monitoring period extends decades into the future—well beyond the timescales used to establish environmental baselines. Individual operators will need to conduct their own site-specific analysis to determine if additional regional monitoring points are beneficial to a project.



As described in Section 6.3, risk indicators are quantifiable metrics that represent surrogates for the established monitoring objectives. For environmental monitoring, these risk indicators are typically chemical parameters measured in water or soil gas samples. Alternatively, for deep subsurface monitoring, these risk indicators are generally measurements using technologies that acquire data at individual wellbores (e.g., bottomhole pressure/temperature or PNLs) or across broad areas of the storage site (e.g., 3-D seismic). Table 5 summarizes a set of risk indicators that form the basis of a monitoring plan developed for a PCOR Partnership associated storage project.

The specific chemical parameters included in the original environmental monitoring program for the project included:

- Soil gas:
  - CO_2, nitrogen (N_2), oxygen (O_2), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), carbon monoxide (CO), ethane (C_2H_6), ethylene (C_2H_4), carbonyl sulfide (COS) H_2S, and total VOCs.
  - Isotopes of carbon-13 and carbon-14 measured in CO_2 ($\delta^{13}C$ and $\delta^{14}C$, respectively).

- Groundwater (and targeted surface water locations):
  - Field measurements of pH, temperature, alkalinity, conductivity, dissolved CO_2, dissolved oxygen (DO), TDS, and chloride.
  - Inorganic and organic chemicals and radionuclides listed in the National Primary Drinking Water Regulations (enforceable standards).
  - Odor and aesthetics, in addition to TDS, pH, aluminum, copper, iron, zinc, chloride, fluoride, and sulfate as listed in National Secondary Drinking Water Regulations (nonmandatory, guidelines).
  - Isotopes of hydrogen-2 (δD-H_2O), oxygen-16 and oxygen-18 ($\delta^{16}O_{H2O}$ and $\delta^{18}O_{H2O}$, respectively), tritium, and carbon-13 and carbon-14 in dissolved inorganic carbon ($\delta^{13}C$ and ^{14}C DIC, respectively).

The deep subsurface monitoring for this case study project focused primarily on detecting the presence and movement of CO_2 and fluids in the deep subsurface and secondarily on monitoring for induced seismicity. Because this case study project is a commercial EOR operation that is actively injecting and producing fluids from the reservoir, the deep subsurface monitoring technologies needed to have minimal impact on daily EOR operations. As a result, the deep subsurface-monitoring program integrated measurements that were already included as part of the EOR commercial operations (e.g., oil production/CO_2 injection rates, wellhead pressure, and bottomhole temperature and pressure) with supplemental monitoring data collected to satisfy the established monitoring objectives (e.g., distributed fiber optic temperature, geophysics, and PNLs). These supplemental monitoring technologies either utilized a dedicated well, were able to monitor the reservoir without the need for a well (e.g., various seismic methods), or had minimal impact on well operations. This hybrid approach allowed the flexibility to collect measurements at times that were convenient for both the EOR operator and the monitoring team and minimized the impact of the monitoring program on the EOR operations. Section 7 provides detailed descriptions of the types of subsurface monitoring technologies listed in Table 5, along with considerations and recommendations regarding technology deployment.

Table 5. Monitoring Plan Foundation for a Case Study Associated Storage Project

Data Collection Technologies/Techniques	Data Collected: Monitoring: Near-Surface	Data Collected: Monitoring: Subsurface	Data Collected: Process[1]	Technical Risk Categories/Monitoring Objectives: Reservoir Capacity	Reservoir Injectivity	Containment: Vertical Migration: CO_2	Containment: Vertical Migration: HCs[2]	Containment: Vertical Migration: Brine	Containment: Lateral Migration: CO_2	Containment: Lateral Migration: HCs[2]	Containment: Lateral Migration: Brine	Induced Seismicity
Soil Gas												
Soil Gas Probes	X					X	X					
Soil Gas Profile Stations	X					X	X					
Water												
Surface Water Sampling/Analysis	X					X	X	X				
Groundwater Well Sampling/Analysis	X					X	X	X				
Deep Groundwater Well Sampling/Analysis	X					X	X	X				
Oil Production/CO_2 Injection Rates (EOR)			X	X	X							
Pressure/Temperature												
Wellhead Pressure and Temperature	X		X		X				X	X	X	
Downhole Pressure and Temperature		X				X	X	X	X	X	X	
Distributed Fiber Optic Temperature[3]		X				X	X	X	X	X	X	
Bottomhole Pressure		X	X		X				X	X	X	
Geophysics												
3-D Seismic Surveys[3]		X		X	X	X			X			
3-D VSP[3]		X			X	X			X			
Passive Seismic[3]		X										X
PNLs[3]		X		X		X	X	X	X	X	X	

[1] Process data are collected as part of day-to-day CO_2 EOR operations and provide value-added information for the monitoring program.

[2] Hydrocarbons including oil species and hydrocarbon gases including methane, ethane, and propane.

[3] These data are collected primarily for monitoring purposes but also provide value-added information for day-to-day CO_2 EOR operations.

Because this case study project combined a commercial EOR project with a federally funded demonstration/research project, the project budget was sufficiently large to support a significant level of redundancy in addressing subsurface monitoring objectives. An important project objective was to evaluate the performance of a variety of geophysical techniques (in both stand-alone and combined applications), which intentionally consisted of several redundant monitoring technologies. This level of redundancy is unlikely to be characteristic of most commercial projects. In addition, environmental monitoring activities were also more extensive than would likely be needed for a commercial project, with an abundance of samples collected (locations broadly distributed across the site and collected at almost monthly frequency) and a broad set of chemical parameters analyzed for each sample.

For commercial projects without a research component, a subset of the above technologies and chemical parameters would likely be appropriate for satisfying the monitoring objectives while simultaneously reducing redundancy and cost. The selection of particular monitoring technologies will be site-specific.

Lesson Learned – Defensible Environmental Monitoring Data

Use of established sampling and analytical protocols helps ensure generation of more defensible data sets. Supplemental data/information (including details regarding nearby well installations and/or natural or anthropogenic events with potential environmental impacts) may often be required to determine valid reasons for observed deviations from baselines that are unrelated to the injection of CO_2.

Recommended Best Practice – Use Existing Wellsites for Soil Gas Monitoring

Soil gas monitoring should focus on areas around existing wells since they provide the most likely pathways for potential CO_2 migration from the reservoir to the surface. Sampling program prioritization (site selection and list of analytes) should be guided by a detailed assessment of available information for these wells, including age, cement bond logs, etc. (Watson and Bachu, 2009).

Recommended Best Practice – Optimize the List of Soil Gas Risk Indicators/Analytes

While the initial suite of soil gas analyses should be comprehensive in scope (i.e., a broad list of risk indicators/analytes), based on results of the initial rounds of environmental monitoring data, opportunities to reduce the analyte list should be investigated.

6.7 Closure/Postclosure Monitoring

As CO_2 injection ceases, a storage project will transition into the closure/postclosure phase. Monitoring activities during this phase are focused on ensuring that the injected CO_2 remains contained within the storage complex within the AOR and does not pose a hazard to the environment. The monitoring techniques employed at the beginning of this phase will likely be the same as during the end of the operational phase, but as the CO_2 plume stabilizes over time (e.g., years-to-decades), monitoring frequencies and extent may be reduced as geologic models and simulations are confirmed by observations in the field; thus confidence that the CO_2 is contained increases. The ultimate goal of monitoring, in concert with the models and simulations, is to demonstrate that the project site is suitable for certification, final abandonment, and transfer of ownership.

7.0 MONITORING TECHNIQUES

The preceding sections outlined the systematic process for establishing monitoring objectives and identifying quantifiable risk indicators. This section focuses on specific techniques or technologies used to measure the risk indicators as part of a monitoring program for a CO_2 storage project. The PCOR Partnership Program has investigated the utility of several monitoring techniques in conjunction with pilot- and large-scale CO_2 injection projects. Based on this experience, this section discusses 1) general considerations for selecting monitoring techniques, 2) lessons learned from applying specific monitoring techniques to PCOR Partnership storage projects, and 3) the value of integrating multiple monitoring techniques to achieve the monitoring objectives.

7.1 General Considerations for Selecting Monitoring Techniques

Many different techniques are available for monitoring CO_2 and other fluids in the deep subsurface and shallow/near-surface environments (e.g., Canadian Standards Association, 2012; U.S. Department of Energy, 2017; IEAGHG, 2018). One challenge for a project team is to determine which techniques both satisfy the monitoring objectives and provide the proper balance of various selection criteria. Ultimately, the final selection of monitoring techniques will be site-specific; however, general considerations for selecting monitoring techniques include:

- Data quality objectives (DQOs). The technologies utilized to generate monitoring data should satisfy the previously described criteria for establishing risk indicators: completeness, redundancy, sensitivity, time to detection, and measurement scale. In addition, these data should be of sufficient quality and quantity for use as inputs to validate and/or revise geologic models and numerical simulations.

- Site-specific geologic constraints. The storage reservoir and overlying formations will have site-specific characteristics that can influence the effectiveness of a given monitoring technique. For example, a thick geologic layer that is composed primarily of salt can inhibit the effectiveness of seismic measurements. These geologic constraints should factor into the ability of a particular technology to achieve the established DQOs.

- Budget. The combination of collecting multiple rounds of monitoring measurements (e.g., quarterly sampling) over the baseline, operational, and closure/postclosure phases (perhaps 20 years or longer) may make certain monitoring techniques cost-prohibitive. Therefore, a monitoring technique should provide a cost-effective means of satisfying the monitoring objectives and achieving the DQOs. In addition, the project team should evaluate ways to combine and integrate a monitoring technology with other monitoring techniques to provide greater overall value to the monitoring program.

- Regulatory requirements. Certain regulatory requirements may dictate specific monitoring activities. The project team should incorporate monitoring techniques into the monitoring program that satisfy applicable federal, state/provincial, and local regulations.

- Additional risk and impact. Some monitoring techniques may introduce additional risk or cause localized impacts from implementing the technique. For example, installation of a monitoring well that penetrates the overlying seal formation to monitor the storage reservoir introduces a potential fluid migration pathway for out-of-zone migration of CO_2 or other fluids. A 3-D surface seismic survey requires access to the land within and in proximity to the AOR, which may affect landowners or local wildlife.

- Stakeholder/landowner concerns. The local community and land use within and around the storage project area can affect the selection of monitoring techniques. For example, dense population centers or landowner attitudes about CO_2 storage may limit access to private properties, which could affect the successful implementation of the monitoring activities.

7.2 Lessons Learned from PCOR Partnership Storage Projects

Large-scale demonstration projects within the PCOR Partnership Program have provided the opportunity to evaluate several different monitoring techniques. These techniques were suitable for the site-specific aspects of each storage project and satisfied the established monitoring objectives. The following paragraphs describe some of these monitoring techniques and provide useful performance details for evaluating these techniques in the context of the preceding list of general considerations. The inclusion of these techniques is not meant to provide a prescriptive list of technologies, nor should they be misconstrued as the preferred techniques applicable to all storage projects. Instead, the techniques described below provide lessons learned from applying specific monitoring techniques on PCOR Partnership storage projects.

7.2.1 Deep Subsurface/Storage Complex

As previously discussed, deep subsurface monitoring builds confidence that CO_2 is securely contained within a defined storage complex and allows identification and further investigation of significant divergence from the anticipated behavior of the injected CO_2. Deep subsurface monitoring techniques such as downhole or wellhead pressure and temperature measurements, fluid sampling, and well logging, acquire measurements at the wellbore scale, while other techniques such as geophysical methods provide broader information about the storage complex through some type of signal propagation. The following examples describe these monitoring techniques.

7.2.1.1 Wellbore Measurements

7.2.1.1.1 Pressure and Temperature

Pressure and temperature measurements provide valuable data to either dedicated or associated storage projects. Pressure/temperature gauges may be deployed in contact with overlying geologic horizons for monitoring out-of-zone monitoring or in the wellbore annulus for monitoring wellbore integrity. These pressure/temperature gauges collect measurements at nearly continuous frequency (e.g., 1- or 5-minute intervals), which provides rapid time to detection. In addition, these pressure/temperature gauges provide good measurement sensitivity and can measure changes of a few pounds per square inch or degrees Fahrenheit. These are discrete measurements, collected at one or more gauges in a wellbore and, therefore, provide a wellbore- and location-specific measurement scale. As the case study below describes, fiber optic distributed temperature/pressure systems can provide a profile along the length of a wellbore, thereby expanding the measurement scale. An additional benefit of pressure and temperature measurements, particularly for commercial associated storage projects, is that collecting these measurements does not disrupt well operations; therefore, the monitoring activity does not affect commercial operation.

Permanent Downhole Monitoring (PDM) Systems

One method for monitoring downhole temperature and pressure is to install a PDM system. The PDM system uses casing-conveyed temperature and pressure acquisition systems to provide continuous, real-time information to support decision-making, active reservoir management, well diagnostics, and evaluations of storage performance.

The PDM collects pressure and temperature measurements at user-specified time intervals (e.g., every 5 minutes) and specific depths. For example, casing-conveyed pressure-temperature gauges can be positioned at discrete locations along the outside of the casing string such as at the storage reservoir and overlying seal(s). A casing-conveyed fiber optic distributed temperature system can run the entire length of the well’s casing and provide a temperature profile from the bottom of the well to the surface.

PDM data can add value to a monitoring program by providing 1) continuous pressure and temperature measurements to monitor dynamic reservoir conditions without interfering with well operations, 2) a means to correlate reservoir pressures to injection and/or production pressures at a wellhead, and 3) pressure/temperature communication information within the monitored interval (e.g., reservoir and/or seal).

7.2.1.1.2 Fluid Sampling

Fluid sampling provides information about the arrival of the CO_2 plume at a particular well. For example, prior to the arrival of CO_2 at a well, or "CO_2 breakthrough," fluid samples collected from that well may contain little or no measurable CO_2. Therefore, when a fluid sample collected from that well shows a maked increase in CO_2, this result may indicate the arrival of the CO_2 plume at this particular location. In addition, fluid sampling can yield information about potential geochemical changes in the reservoir. For example, mineral dissolution and/or precipitation aids in understanding the potential implications on reservoir porosity, permeability, and CO_2 storage capacity. This information about the timing of CO_2 breakthrough and geochemical changes can serve as inputs into geologic modeling and simulation efforts.

Similar to pressure and temperature measurements, fluid sampling is a discrete measurement, commonly collected at the wellhead and, therefore, provides a wellbore-specific measurement scale. Laboratory analysis of the fluid sample generally provides good measurement sensitivity with low method detection limits. Potential sources of error that affect fluid sampling results include pressure and temperature changes between the reservoir and the surface or contact between the fluid sample and the atmosphere before laboratory analysis occurs. Adhering to proper sampling and handling methods can, however, minimize the likelihood of these potential sources of error and ensure good data quality. A limitation of fluid sampling is that the time to detection is a function of the sampling frequency. For example, collecting fluid samples at quarterly or semiannual frequency could result in missing the initial CO_2 breakthrough. Similar to pressure measurements, fluid sampling exposes the wellbore to reservoir fluids, thus increasing the exposure of the well casing and cement to these fluids, potentially accelerating the risk of degradation, depending on reservoir fluid characteristics.

7.2.1.2 Well Logging

Well logging is an established technology that lowers tools into the wellbore on wireline cables to collect electrical and physical measurements of the wellbore casing, wellbore cement, or the near-wellbore region of the geologic formation. Well logging, therefore, provides wellbore-specific measurement scale; however, unlike discrete measurements collected from a particular gauge or at the wellhead, well logging provides a continuous measurement along the length of the wellbore. Dozens of well logging technologies are available. The primary driver for developing these tools has been characterization of reservoir properties for oil and gas development. However, two specific well logging technologies provide useful information for both oil and gas development and CO_2 monitoring: pulsed-neutron logs (PNLs) and wellbore integrity logging, as described below.

7.2.1.2.1 PNL

PNLs emit neutrons into the near-wellbore region of the formation and measure the rate of decay of gamma ray counts (gamma rays are produced as neutrons generated by the tool are "captured" by rock and formation fluids). When operating in sigma mode, PNLs provide a quantitative assessment of liquid/gas saturations, and when operated in the saturation (inelastic capture) mode, PNLs provide a quantitative measurement of water, oil, and CO_2 saturations

(Schlumberger, 2007). Therefore, PNLs can measure the vertical distribution of CO_2 and other fluids within the target injection horizon. This information provides valuable input for simulation models attempting to predict the movement of CO_2 and other fluids in response to CO_2 injection. In addition, PNL measurements acquired above the target injection horizon provide monitoring data for detecting out-of-zone CO_2 migration along a wellbore.

PNLs are particularly useful at associated storage projects because they can be deployed across multiple wellbores to track the presence of CO_2 and changing oil and water saturations, which together inform the operator about the movement of fluids during the CO_2 flood development. However, detecting changes over time requires that each well have a baseline PNL measurement against which subsequent PNLs collected during operational monitoring may be compared. As a result, PNL campaigns require careful planning to optimize the value of the tool and minimize impact to project operations.

For example, Figure 5 shows a time series of PNLs collected from a PCOR Partnership associated storage site and illustrates changes in fluid saturations (water, oil, and CO_2 saturations) in the reservoir interval between baseline and repeat campaigns for three injection wells and one production well. The increase in CO_2 saturation (red color shading) through time provides direct measurements that can constrain the timing and vertical distribution of CO_2 within the reservoir.

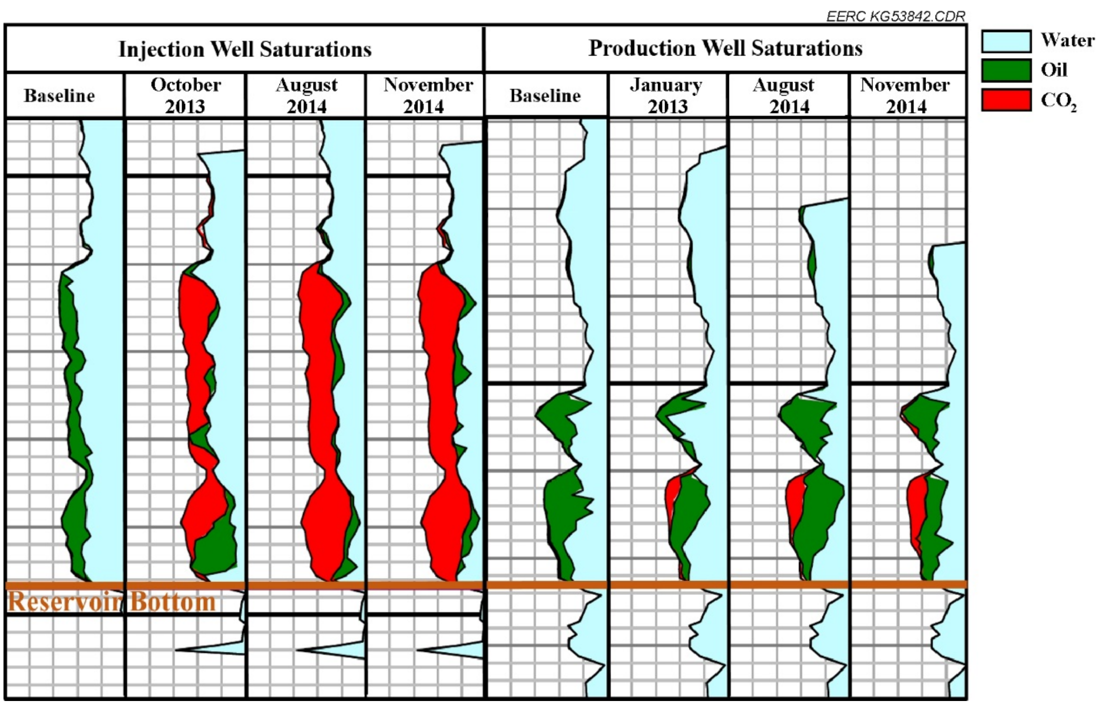


Figure 5. Time series of PNLs showing changes in fluid saturations in the reservoir interval between baseline and repeat campaigns for three injection wells and one production well.

PNLs are sensitive to reservoir conditions, and well completions have an impact on the tool; therefore, wellbore-specific factors may influence the precision of the PNL measurement. The depth of investigation for PNLs is approximately 10–18 inches from the wellbore; thus the measurement is specific to near-wellbore conditions (Schlumberger, 2007; Alberty, 1992; Ellis and Singer, 2008). PNLs will have a lower sensitivity for detecting change from baseline conditions in freshwater, which means that the prior waterflood phase or water alternating gas phase(s) for associated storage projects can affect the performance of PNL logs within the reservoir (Alberty, 1992). Lastly, acquiring PNLs may affect well operations, depending on the infrastructure of the well.

Lesson Learned – PNL Campaign Planning
PNL campaigns require careful planning to optimize the value of the tool and minimize impact to project operations. Detecting fluid changes over time requires that each well have a baseline PNL measurement against which subsequent PNLs collected may be compared.

7.2.1.2.2 Wellbore Integrity Logging

An important component of ensuring CO_2 containment in the target injection horizon is that wellbores located within the AOR have adequately maintained integrity, i.e., the well, casing, and cement conditions are intact and do not permit out-of-zone migration of CO_2 and other fluids from the reservoir into overlying geologic units. Periodic well log evaluation of well casing and cement is necessary to ensure that CO_2 exposure has not compromised the integrity of the well. These wellbores present potential leakage pathways for CO_2 through the casing–cement interface, within the cement, through the casing, through fractures, and along the cement–formation interface (Figure 6).

Varieties of cement bond log (CBL) tools that evaluate the condition of the cement are commercially available. In addition to CBLs, wellbore integrity evaluations should include mechanical integrity tests that confirm that a wellbore can maintain pressure. Similar to CBLs, there are varieties of logging tools that can evaluate the condition of the well casing. Multifinger caliper tools, for example, measure the internal diameter of the well casing. However, these casing evaluation tools may also have limited resolution; thus mechanical integrity tests should be used in conjunction with casing evaluation tools to confirm that the wellbore can maintain pressure.

7.2.1.3 Geophysical Techniques

Wellbore measurements provide information about near-wellbore geologic features and properties to support assessments of capacity, injectivity, and seal effectiveness. However, interpolating between wells may be challenging, since these discrete samples represent a small fraction of the total subsurface within the AOR and may not be representative of the heterogeneity throughout the three-dimensional (3-D) storage formation volume. Geophysical techniques such as surface-based 2-D and 3-D seismic surveys provide a means of integrating wellbore measurements (which are effectively 1-D measurements collected at a single location) and developing a broader interpretation about spatial variations throughout the storage formation.

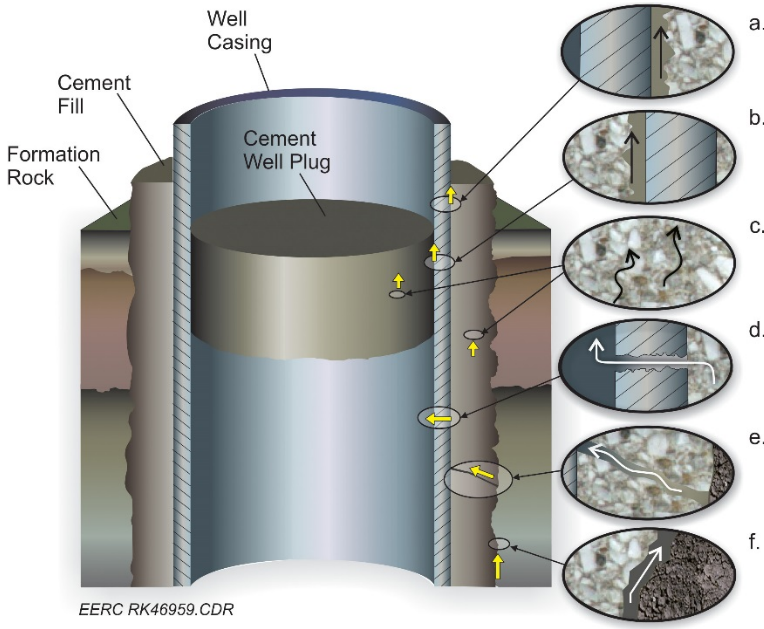


Figure 6. Conceptual illustration of the potential leakage pathways for CO_2 through a well along the casing–cement interface (a and b), within the cement (c), through the casing (d), through fractures (e), and along the cement–formation interface (f) (from Celia and others, 2004).

7.2.1.3.1 Time-Lapse Seismic Surveys

Both 2-D and 3-D seismic surveys utilize a seismic source located at the surface and a set of receivers that are also located at the surface to infer properties of the subsurface using seismic reflection. Two-dimensional seismic surveys deploy the receivers in a single line, send seismic waves into the ground, and record the seismic reflections that come back (Figure 7). Three-dimensional seismic surveys use the same technique, but instead of arranging receivers in a single line, they deploy a grid layout (seismic array) to measure seismic reflections in a plane at the surface (Figure 8). Therefore, 2-D seismic surveys provide information about the subsurface along a single depth profile (hence “2-D”). In contrast, 3-D seismic surveys provide information about the subsurface within the volume underneath the seismic array (hence “3-D”).

Both 2-D and 3-D seismic surveys frequently constitute a major element of monitoring programs because they provide data for large tracts or volumes of the subsurface. When multiple seismic surveys are collected over time, the change from one survey to the next represents a fourth dimension: time. These repeat seismic surveys are often referred to as “time-lapse” or “4-D” seismic surveys. The 4-D seismic technique can illuminate the changing reservoir environment through time, particularly with regard to the movement of CO_2. For example, the presence of CO_2 will change the fluid properties within the reservoir, which shows up as a change in the seismic amplitude between the baseline (preinjection) and operational phases. As a result, areas of the reservoir that contain CO_2 will have a greater amplitude difference in the operational 4-D seismic survey, and the magnitude of the amplitude difference is proportional to the amount of CO_2 (Figure 9).

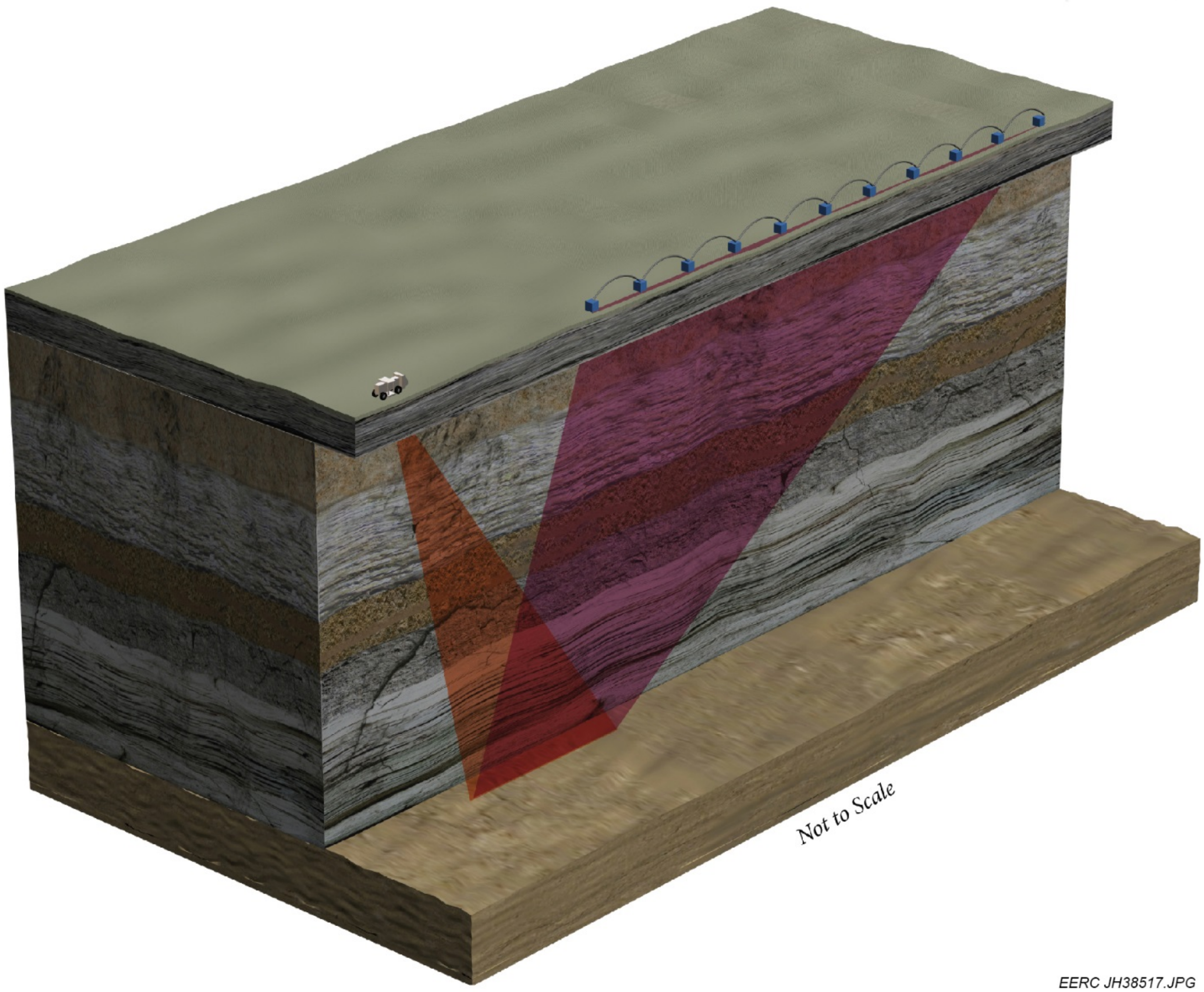


Figure 7. Schematic of 2-D seismic line collection (Hamling and others, 2011).

If the subsurface exhibits minimal structural changes throughout the AOR (e.g., gently dipping bedding planes), then 2-D seismic lines can be used to produce vertical slice images of the geologic structure and formation continuity. One benefit to collecting 2-D surface seismic surveys is that they are less expensive and cause less impact to the landscape during data acquisition than 3-D seismic surveys. However, 2-D seismic surveys only provide visibility of the subsurface along the line trace (the line of receivers at the surface).

If the subsurface exhibits a more complex structure, then 3-D seismic surveys allow detailed geologic analysis in any direction or orientation within the subsurface volume encompassed by the survey. However, 3-D seismic surveys may require hundreds to thousands of surface sensors and the deployment of large field crews. Consequently, these surveys are more expensive to acquire and can have significant impact across the landscape, such as acquisition with large vibrator trucks where they need to traverse the seismic area. In some regions, these 3-D seismic surveys can only take place during fair-weather months, as land access may be limited by ground conditions.

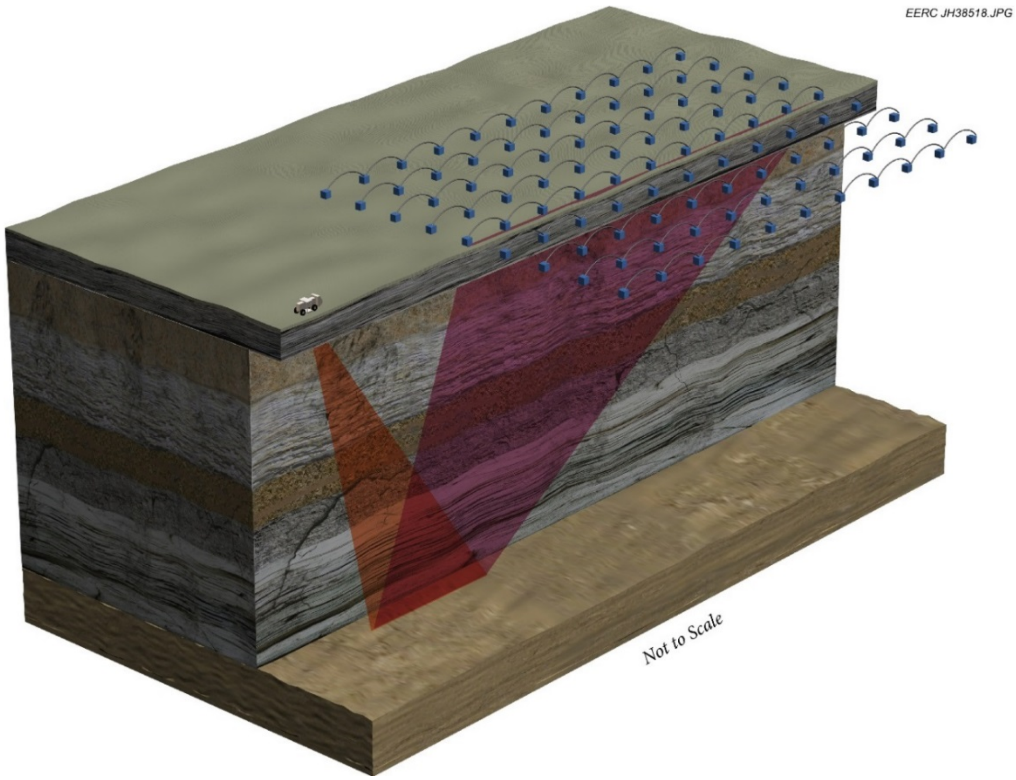


Figure 8. Schematic of 3-D seismic survey collection (Hamling and others, 2011).

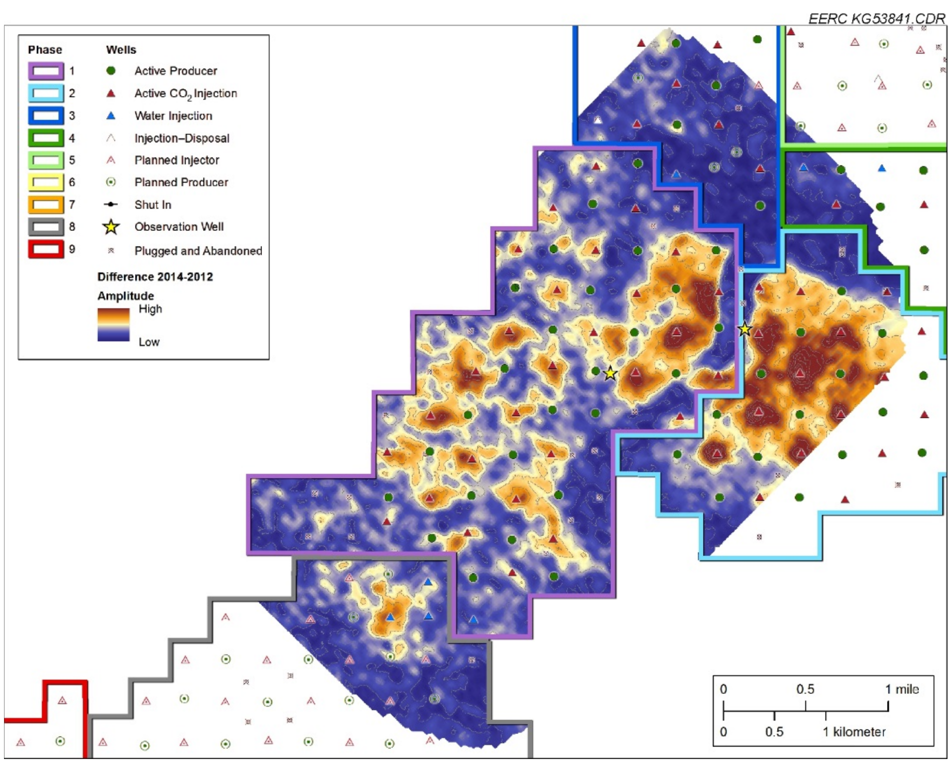


Figure 9. Example 4-D seismic analysis. Areas with greater yellow-to-brown shading indicate regions of greater CO_2 (modified from Salako and others, 2017).

An alternative method used for surface seismic surveys is to install a permanent array of surface sensors (i.e., receivers) to cover an area of interest. Typically, these permanent arrays are used in dedicated storage projects as the project area is smaller than many associated storage projects. The permanent array allows for repeat seismic survey acquisition without having to re-deploy the seismic receivers, which saves time and cost. There is a larger up-front cost for the initial installation of the permanent array, but over time, this method may be more economical than using typical 4-D surveys.

Lesson Learned – Seismic Survey Baselines
In establishing storage complex baselines, seismic surveys may be worth the relatively high investment by providing data across large volumes of the subsurface and providing appropriate detail to support sophisticated geologic models and predictive simulations. Such data sets can also support the interpretation of specific geologic features, which could affect the performance of a storage project.

7.2.1.3.2 3-D/4-D Vertical Seismic Profile (VSP)

Both 2-D and 3-D seismic surveys collect measurements as a function of two-way travel time, or the time it takes for the signal to go from the source at the surface, reflect off some geologic feature, and return to the receivers at the surface. Another related approach, vertical seismic profile (VSP) surveys, places the receivers down a wellbore, which then measure the seismic signal as a function of vertical position within the formation. These VSP surveys use temporary or permanently installed downhole sensors to create images of the subsurface from the near-surface to a depth at or below the reservoir, similar to surface seismic surveys (Figure 10). Data from VSP surveys are sometimes higher resolution than 3-D seismic surveys, because source energy travels through the near-surface geologic units only once to reach the sensors. However, VSP surveys only image an area in the near-wellbore environment; thus the measurement scale is much smaller than the 2-D or 3-D seismic surveys. Processing of VSP survey data is specialized and may be cost-prohibitive for smaller projects. Emerging technologies such as digital acoustic sensing, which uses fiber optic cables that are permanently cemented downhole to acquire seismic data, may reduce the cost of VSP surveys. Given their reduced measurement scale, VSP surveys may be better suited for dedicated storage projects as the project area may be smaller than associated storage projects and it may be possible for a VSP repeat to capture the entire CO_2 plume in the subsurface.

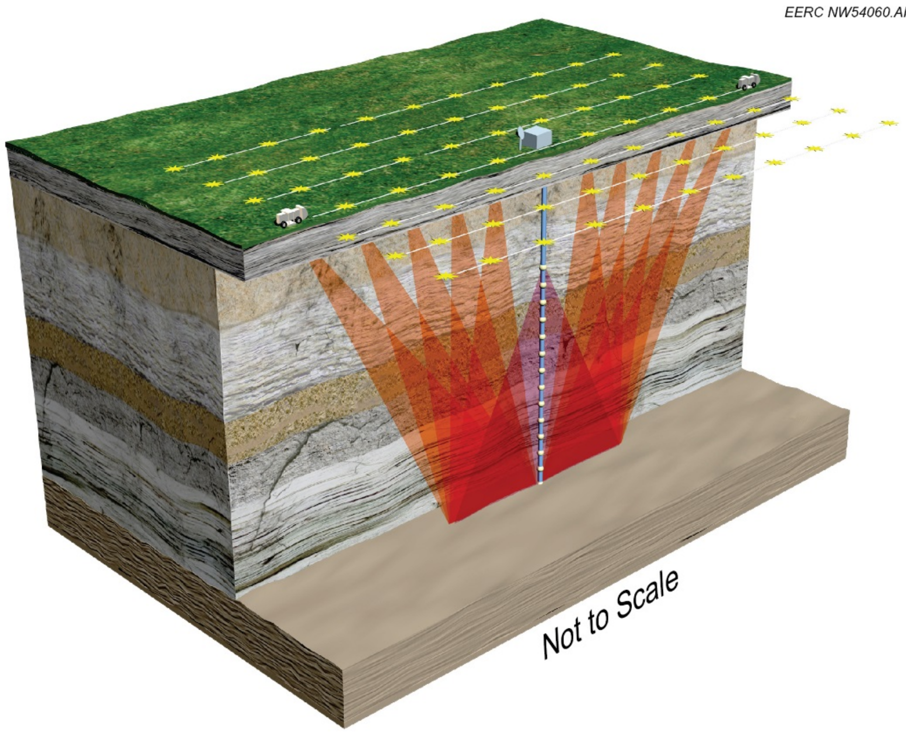


Figure 10. Schematic of VSP survey (Hamling and others, 2011).

7.2.1.3.3 Passive Seismic

Passive seismic involves installing sensors either in a wellbore or at the surface and continuously monitoring for vibrations in the subsurface. Passive seismic techniques are used to monitor microseismic events associated with small releases of energy such as rock fracturing attributable to changes in formation pressure. Passive seismic monitoring can benefit either dedicated or associated storage projects and is particularly advantageous in regions that have high seismic activity or when mandated by regulations. Once the sensors are in place, passive monitoring involves little risk or impact to project operations. However, passive seismic data collection generates large amounts of data, which currently take time to manually process. In addition, there is significant effort required to distinguish seismic events from background noise (i.e., low-level seismic activity attributable to other causes beyond the CO_2 injection).

7.2.2 Environmental Monitoring Techniques

Typical onshore environmental monitoring programs focus on the chemical characterization of groundwater, surface water, the soil vadose zone, and the near-surface atmosphere. In contrast to deep subsurface monitoring, the chemical compositions of the near-surface and surface environments are subjected to strong seasonal effects and are influenced by a wide range of natural processes and human activities. Therefore, baseline conditions should be established where possible over multiple seasons to quantify the natural background variability of these systems and to establish action levels (threshold concentrations) of key parameters that could be indicative of leakage and, therefore, warrant further investigation.

7.2.2.1 *Soil Gas Samples*

Soil gas monitoring of the vadose zone can be accomplished using hand-driven probes or fixed soil gas profile stations to collect soil gas samples and measure a set of chemical parameters. The parameters in the soil gas samples may be measured using field instruments or sent to the laboratory for analysis. Handheld meters provide sufficient measurement sensitivity to screen multiple locations and identify a subset of locations for further analysis. Field-based measurements generally provide a smaller set of chemical parameters; however, these field-based instruments provide rapid turnaround times for analysis, thereby reducing the time-to-detection. In contrast, laboratory analysis generally provides a broader set of chemical parameters but requires storing and shipping the soil gas samples to a laboratory. Soil gas sampling is applicable to either dedicated or associated storage projects, and the level of effort is dependent on the size of the project area and the number of sample sites required to satisfy the monitoring objectives.

The concentrations of many soil gas parameters, in particular CO_2, N_2, and O_2, are affected by climate variability (e.g., temperature and precipitation) and their effects on biological activity (see Case Study 6.1). Further, soil gas parameters are sensitive to the method of collection and soil disturbance. For example, fixed soil gas profile stations generate more reliable data because of the ability to collect samples from greater depths (>10 ft) that are less affected by climate variability. Soil gas sampling may require significant personnel time depending on the number of sample locations within the study area, although collecting data via a reliable handheld instrument can expedite the field sampling program.

Lesson Learned – Fixed Soil Gas Profile Stations
Fixed soil gas profile stations generally provide the most reliable soil gas measurements when an extended (years) monitoring program is planned, especially for increased sampling depths.

7.2.2.2 *Surface and Groundwater Monitoring*

Surface and groundwater monitoring collects samples from select surface water features (e.g., wetlands, lakes, or streams) and groundwater and analyzes these samples for a range of water chemistry parameters. These water chemistry parameters include, at minimum, key indicators for CO_2 storage projects, including pH, alkalinity, DIC, major cations and anions, and TDS. For example, pH, alkalinity, and DIC provide information about whether excess CO_2 has contacted the water, which would result in decreasing pH and alkalinity below baseline values, but increasing DIC above baseline values. Measurements of TDS provide information about whether formation brine has contacted the water, which would result in increasing TDS above baseline values. Isotopic analysis of the water samples for oxygen (oxygen-16 and -18), carbon (carbon-12, -13, and -14), and hydrogen (hydrogen-1 and -2) may provide additional information about the potential sources of these elements in the water sample.

Interpreting Soil Gas Measurements: A Process-Based Approach

While biological activity is usually the primary driver of soil gas composition, geochemical reactions with soil particles and dissolution of soil gases during precipitation and infiltration also affect soil gas chemistry. Romanak and others (2012) developed a process-based approach for assessing whether soil gas CO_2 measured in the vadose zone is the result of natural background soil respiration, soil disturbance, or CO_2 migration from an outside source or a combination of these. The approach accounts for soil gas composition resulting from aerobic microbiological activities including both biological respiration:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad \text{[Eq. 1]}$$

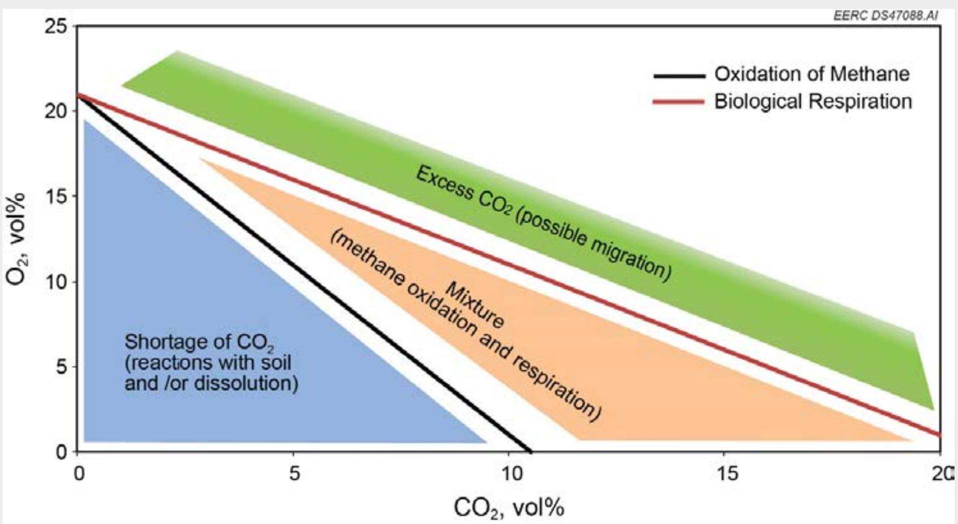
and methane oxidation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{[Eq. 2]}$$

which are two dominant soil biological processes that deplete oxygen and produce CO_2. The figure below is a plot of soil gas oxygen versus carbon dioxide concentrations, including lines representing the stoichiometric relationships associated with either biological respiration (Eq. 1, red) or methane oxidation (Eq. 2, black). Graph interpretation is as follows:

- Samples that plot below the "Oxidation of Methane" line (blue region) represent soil gas CO_2 removal from the system through reactions with soil particles and/or dissolution and infiltration with rain water.
- Samples that plot between the "Oxidation of Methane" and "Biological Respiration" lines (orange region) represent normal biological processes in soils under a range of CO_2 and O_2 concentrations.
- Samples that plot above the "Biological Respiration" line (green zone) indicate a condition where excess CO_2 exists, which triggers a more detailed investigation.

Use of this analysis technique at a PCOR Partnership case study project enabled rapid assessment of soil gas data, even in cases where an individual data point exceeded established baseline concentrations. These instances either plotted in the biologic respiration zone, showing increased biologic activity over previous seasons, or were determined to be the result of recent and nearby land retilling that entrained more atmospheric gases in the soil.



Biological process-based method for CO_2 source attribution (modified from Romanak and others, 2012).

Similar to soil gas samples, water samples may be analyzed using field-based instruments or by sending the samples to the laboratory. Field-based methods for parameters such as pH, conductivity, and alkalinity provide sufficient measurement sensitivity to detect a deviation from baseline conditions. In addition, field-based methods expedite the analysis results and, therefore, decrease time to detection. However, other analyses are generally not available through field-based methods and, therefore, require laboratory analysis (e.g., isotopes).

Surface and groundwater monitoring may be used at both dedicated and associated storage projects, and the level of effort will depend on the presence of surface water features and the relative importance of groundwater aquifers in the project area (e.g., a primary drinking water source).

Analogous to soil gas, the concentrations various chemical parameters are affected by climate variability and their effects on biological activity. Therefore, water-monitoring programs require collection of baseline data, from consistent sampling points and ideally over multiple seasonal cycles, to quantify the natural variability present in these systems and to provide good comparability between baseline and operational monitoring.

Lesson Learned – Field-Based Measurements
Most operational-phase surface and groundwater monitoring can be conducted in the field using relatively inexpensive handheld instrumentation and field test kits. Field methods for monitoring risk indicators such as pH, conductivity, and alkalinity are typically sensitive enough to detect a statistically significant deviation from baseline conditions that would then trigger a more detailed investigation into probable cause. Soil gas composition can also be monitored using handheld instrumentation.

Recommended Best Practice – Focus Groundwater-Monitoring Indicators
Groundwater monitoring should focus on measuring key indicators of CO_2 presence (such as pH, alkalinity, and DIC) using field-based methods, followed by more extensive analysis if these screening-level measurements detect significant deviations from baseline.

7.3 Integration of Monitoring Techniques

While each monitoring technique provides information about the specific risk indicator it measures, the value of some monitoring techniques can be enhanced by integrating them with complementary techniques. A prime example of the advantages of such data coupling is seismic surveys. As described above, 2-D and 3-D seismic surveys utilize seismic reflection to infer properties of the subsurface. While advanced seismic processing minimizes errors, there is still uncertainty in the seismic interpretation. However, downhole well logging measurements can provide additional information to refine the seismic data within the logged interval, thereby improving the overall accuracy and value of the seismic survey. When combined with wellbore measurements of reservoir pressure and saturation measurements derived from gauges and well logs, seismic surveys may be of great assistance in mapping the distribution of CO_2 and pressure changes in the subsurface.

Another example of the benefits of combining monitoring techniques is using lower-cost monitoring techniques to guide the timing, frequency, and extent of higher-cost technologies. For example, collecting PNLs from a broad suite of wells can constrain the timing for when CO_2 breakthrough occurred at specific locations, which informs when to run a repeat 3-D seismic survey within a specific portion of the project area.

All measurements contain some level of uncertainty. This uncertainty translates into the potential for false positives—believing a problem exists when one does not—or false negatives —not identifying a problem when one does exist. Finding the right balance in the overall false positive/false negative rate of the monitoring program depends on the site-specific monitoring objectives and subsurface conditions. Integrating multiple monitoring techniques can provide redundancy, where two or more measurements provide information about a particular monitoring objective. This redundancy provides greater confidence in the ability to distinguish a true problem from background variability.

Recommended Best Practice – Use Complementary Monitoring Techniques
Certain subsurface data collection techniques are most valuable when used in combination with one or more additional techniques. When considering a technique for use in a monitoring program, attempt to determine whether the technique requires data from an additional technique to provide maximum value.

Lesson Learned – PNLs + Seismic Survey = Extended Monitoring Capability
PNLs provide greater value when paired with other monitoring techniques—especially seismic surveys—because PNL-acquired fluid measurement data for the near-wellbore environment can be extrapolated between a network of wellbores using seismic survey data.

Call Out Box: Improving Model Predictions with PNLs and Seismic Surveys

Modeling and simulation provide predictions of the movement of CO_2 in the reservoir in response to CO_2 injection. These predictions are only as reliable as the accuracy of the underlying assumptions used to build the models, which can be updated as new information becomes available. Two important pieces of information for updating these models are the timing of when CO_2 has actually reached a specific well (sometimes referred to as "breakthrough") and the extent of CO_2 migration between wells. Coupling PNLs with 3-D seismic surveys provides this information.

Monitoring of the reservoir with pressure sensors and fluid sampling from observation wells can constrain the timing of breakthrough. After breakthrough occurs, subsequent PNLs may be acquired across the reservoir in the observation well to measure fluid saturations versus depth, which determines the degree of breakthrough.

To determine the extent of CO_2 migration between wells, acquisition of time-lapse 3-D seismic surveys is an effective method to image CO_2 saturation in the reservoir. Seismic surveys generally take two forms: surface surveys, where the source and geophones are arranged in a grid at the surface, or VSPs, where the geophones are hung vertically in a wellbore. One disadvantage for VSPs is that the lateral coverage away from the well is limited to, at most, one-half the depth of the reservoir. In contrast, surface seismic surveys can be scaled to cover any size area around the wells.

Time-lapse seismic works by measuring the velocity and density changes that have occurred in the reservoir, which are caused by the injection of CO_2. Time-lapse seismic requires comparison to a preinjection (baseline) seismic survey. After carefully processing and cross-equalizing the baseline and monitoring surveys, the amplitude difference between them is computed, which under good conditions can produce a clear image of the areal extent of the CO_2 in the reservoir. The image can then be used to update the geologic models in order to produce more accurate saturation distribution maps going forward.

8.0 CASE STUDIES

The PCOR Partnership 2017 Annual Meeting included a half-day workshop focused on developing a commercial approach to monitoring storage projects (hereafter "MVA Workshop"). The MVA Workshop participants included technical experts and carbon capture, utilization, and storage (CCUS) professionals who discussed realistic examples of CCUS projects within the PCOR Partnership region. Four breakout groups comprising four to six individuals were presented with two hypothetical case study scenarios: one dedicated storage project and one associated storage project incidental to CO_2 EOR operations. These groups were asked to propose monitoring strategies and suites of technologies for one of the two case studies using an initial list of potential deep subsurface and environmental monitoring techniques. In addition to selecting technologies based on their ability to measure the anticipated risk indicators, participants were asked to consider the relative costs of their technology selections. The costs for each technology were provided by the EERC using simplified, nominal dollar-value costs (broadly representing normalized costs over the full life cycle duration of a CCUS project) (Table 6). The remainder of this section summarizes the case studies and MVA Workshop outcomes, including key discussion points from the meeting.

Table 6. List of MVA Workshop Monitoring Techniques and Simplified, Normalized Lifetime Costs

Technique/Technology/ Monitoring Target	Case Study 1 – Dedicated Storage (nominal $ value)	Case Study 2 – Associated Storage (nominal $ value)
Deep Subsurface Monitoring		
4-D Seismic	5	5
Permanent Array for 4-D Seismic	3	4
4-D VSPs	2	3
Monitoring Wells*	3	3
Passive Seismic	2	2
InSAR	1	1
Electrical Techniques	2	3
Injection Rate**	1	0
Wellhead T, P**	1	0
Downhole T, P	1	2
Fiber Optics	1	2
PNLs	1	3
Well Logging (other)	1	3
Reservoir Fluids	2	1
Wellbore Integrity	1	4
Tracers	1	2
Environmental Monitoring		
Soil Gas	2	2
Surface Water	1	1
Groundwater	2	2
Atmospheric	1	1
Lidar	1	1
Other		
Wildcard***		

* Up to three monitoring wells could be selected at nominal cost of $3 each.
** Undertaken during routine surveillance of EOR operations.
*** Breakout groups were allowed to select a novel technology not in the list provided, and suggest a nominal dollar value.

8.1 Case Study 1 – Dedicated Storage in a Deep Saline Formation

The proposed project would receive 25 million tonnes (Mt) of CO_2, captured from a coal-fired power station over a 25-year period, and store the CO_2 in a DSF. Four workshop breakout groups were asked to outline a monitoring program that would satisfy regulatory requirements and ensure that the following objectives could be met:

- Establish baseline reservoir and environmental conditions
- Ensure safe operations to stakeholders

- Demonstrate that CO_2 is securely contained within the reservoir
- Enable history-matching with predictive models
- After closure, demonstrate that long-term risks are sufficiently low to warrant the site operator filing for a permit surrender

In addition to these objectives, the breakout groups were also asked to consider the following additional factors for their proposed monitoring plans:

- The monitoring plan should address concerns over induced seismicity.
- The monitoring plan should address concerns of local landowners that the project should not affect surface and groundwater quality.

The proposed storage complex is a 150-foot-thick Basal Cambrian Sandstone (BCS) reservoir located 6000 feet below ground level, with 300 feet of overlying shales as sealing layers. The BCS reservoir follows a normal pressure gradient and gently dips to the north at less than 1 degree. The anticipated CO_2 plume after 25 years of injection would have a 1.5-mile radius, and predictive simulation predicts a required AOR of approximately 50 square miles based on pressure considerations. There are no identified faults within the AOR.

The injection site lies within an expansive area of flat agricultural land, with a small lake and two small rivers located within the AOR (Figure 11). A groundwater aquifer located at depths of approximately 200 to 600 feet provides potable water through abstraction wells for both domestic and agricultural use. There is a single plugged and abandoned well located 2 miles to the north of the planned injection site, and a conventional oil field located 3 miles to the south (see Case Study 2). There is a township with 200 residents located approximately 2 miles to the west of the planned injection site, and the local community is broadly supportive of the local oil industry.

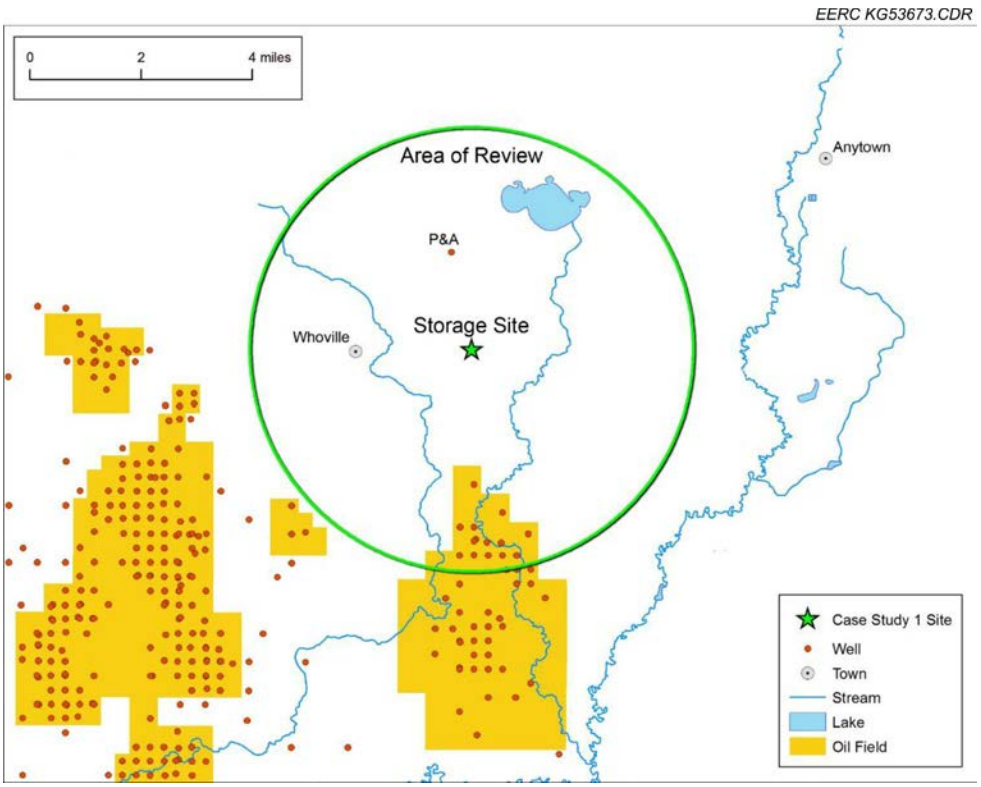


Figure 11. Conceptual map of Case Study 1 showing the planned injection location and estimated AOR based on pressure considerations.

8.2 Case Study 2 – Associated Storage Incidental to EOR

A company with significant GHG emissions wants to store 10 million tonnes of its CO_2 over a 10-year period to qualify its industrial products for low-carbon markets. The oil field located to the south of the Case Study 1 site (Figure 11) has already utilized approximately 10 million tonnnes of CO_2 for EOR from a different source. Under this scenario, no additional permitting of the EOR operation would be required for the oil field to utilize a new source of CO_2.

The oil field undergoing EOR was discovered in the 1970s and has over 100 injection and production wells. Some legacy plugged and abandoned wells from the 1970s are also present. The reservoir is a carbonate reservoir located 4000 feet below the surface. The operating permit for the oil field requires reservoir surveillance consisting of injection rates, wellhead temperature and pressure, and periodic surveys of wellbore integrity. As a result, there are no significant additional costs associated with using these measurements in the monitoring program, which is why their nominal cost is zero in Table 6.

The breakout groups were asked to propose a monitoring program to demonstrate associated storage to support applications for low-carbon product standards. The cost of additional monitoring would be paid either directly by the industrial company selling the CO_2 or indirectly through the negotiated CO_2 price to the oilfield operator.

The environment overlying the EOR operation is effectively the same as for the dedicated storage site to the north, although one local landowner has had a difficult relationship with the oilfield operator. The breakout groups were asked to specifically account for two additional criteria in their proposed monitoring programs:

- How would the additional monitoring measurements for associated storage add value to the EOR operations?
- Describe the potential usefulness and challenges of establishing meaningful "baseline" measurements of the reservoir and local environment, prior to injection of CO_2 from the new source.

8.3 MVA Workshop Results and Key Discussion Points

Tables 7 and 8 show the monitoring technologies selected by the breakout groups for Case Studies 1 and 2, respectively. These results illustrate the variability in proposed monitoring programs among the breakout groups. For example, rarely did all four of the breakout groups select the same technology (total score of four), and some technologies were selected by only one group (total score of one). While the variability in proposed monitoring technologies should probably be of no surprise given the short duration of the workshop and somewhat arbitrary nature of the activity, each breakout group was presented with the same set of information and objectives. Tables 7 and 8, therefore, highlight the challenge of a "one-size-fits-all" approach to monitoring storage projects. Every team followed and reported a logical process in selecting combinations of techniques to align with monitoring objectives, demonstrating that a number of alternative approaches could be viable. As noted above, each breakout group included both technical experts and participants with broader management or business backgrounds.

Table 7. Workshop Monitoring Technique Selections for Case Study 1

Technique/Technology/ Monitoring Target	Nominal $ Value	Breakout Group Selections				
		Group B	Group D	Group F	Group J	Total Score
Deep Subsurface Monitoring						
4-D Seismic	5					0
Permanent Array for 4-D Seismic	3	Yes		Yes	Yes	3
4-D VSPs	2					0
Monitoring wells	3	Yes (1)		Yes (1)		2
Passive Seismic	2	Yes				1
InSAR	1					0
Electrical techniques	2					0
Injection Rate	1		Yes	Yes	Yes	3
Wellhead T, P	1		Yes	Yes	Yes	3
Downhole T, P	1	Yes		Yes		2
Fiber Optics	1		Yes		Yes	2
PNLs	1			Yes		2
Well Logging (other)	1			Yes		2
Reservoir Fluids	2		Yes			1
Wellbore Integrity	1		Yes	Yes	Yes	3
Tracers	1					0
Environmental Monitoring						
Soil Gas	2		Yes		Yes	2
Surface Water	1	Yes			Yes	2
Groundwater	2	Yes	Yes	Yes	Yes	4
Atmospheric	1		Yes		Yes	2
Lidar	1					0
Other						
Wildcard – Reenter P&A Well	1	Yes	Yes			2
Wildcard – SASSA	0.1			Yes		1
Total Cost, $		13	12	14.1	13	

Despite the different combinations of technologies chosen, the breakout groups for Case Study 1 (dedicated storage) arrived at broadly similar costs within the context of the activity (all between $12 and $14.1). This partly reflected the perception that, without revenue from sales for EOR, dedicated storage represents a cost that project operators will seek to minimize.

In contrast, breakout groups for Case Study 2 (associated storage with EOR) arrived at widely varying total costs, ranging from $6 to $22. This may have partly reflected the more vague case study objective of “demonstrating associated storage to qualify industrial products for low-carbon standards,” but more significantly resulted from widely different perceptions of the degree to which existing reservoir and site characterization (plus routine EOR surveillance) reduces the need for (and value of) additional monitoring.

Table 8. Workshop Monitoring Technique Selections for Case Study 2

		Breakout Group Selections				
Technique/Technology/ Monitoring Target	**Nominal $ Value**	**Group A**	**Group C**	**Group E**	**Group G**	**Total Score**
Deep Subsurface Monitoring						
4-D Seismic	5		Yes			1
Permanent Array for 4-D Seismic	4	Yes				1
4-D VSPs	3					0
Monitoring wells	3	Yes (1)			Yes (2)	2
Passive Seismic	2					0
InSAR	1			Yes		1
Electrical Techniques	3					0
Injection Rate	0	Yes	Yes	Yes	Yes	4
Wellhead T, P	0	Yes	Yes	Yes	Yes	4
Downhole T, P	2	Yes	Yes		Yes	3
Fiber Optics	2					0
PNLs	3	Yes	Yes			2
Well Logging (other)	3	Yes				1
Reservoir Fluids	1	Yes	Yes		Yes	3
Wellbore Integrity	4				Yes	1
Tracers	2					0
Environmental Monitoring						
Soil Gas	2	Yes	Yes			2
Surface Water	1	Yes			Yes	2
Groundwater	2	Yes	Yes	Yes	Yes	4
Atmospheric	1	Yes		Yes	Yes	3
Lidar	1					0
Other						
Wildcard – Reenter P&A Well	1					0
Wildcard – SASSA	2			Yes		1
Wildcard – Public Perception of Site	1				Yes	1
Total Cost, $		22	15	6	18	

8.3.1 Environmental Monitoring

Despite the low risks generally associated with potential leakage from carefully selected and characterized storage sites, all breakout groups (both case study scenarios) recognized the importance of environmental monitoring for stakeholder assurance:

- All breakout groups selected groundwater monitoring.

- A majority of the breakout groups chose soil gas and/or atmospheric monitoring, although not necessarily as alternative approaches (i.e., several breakout groups chose both techniques as complementary, rather than alternatives).

- Half of the breakout groups chose surface water monitoring, but some groups noted the ephemeral and highly variable nature of surface water chemistry as a reason to avoid this monitoring target.

8.3.2 Deep Subsurface Monitoring

In comparison to environmental monitoring, the different breakout groups adopted quite divergent approaches to monitoring of the reservoir/storage complex and adjacent deep strata.

The majority of breakout groups recognized the importance and relatively low costs of monitoring injection rate and wellhead or bottomhole pressure/temperature.

A majority of breakout groups also recognized the technical merit of 4-D seismic surveys, but only one group opted for conventional seismic surveys; the other groups preferred permanent seismic arrays for potential advantages in terms of flexibility and long-term cost savings.

Lastly, only one of the breakout groups selected passive seismic as a monitoring technique, despite the stated extra sensitivity in Case Study 1 of concerns over induced seismicity. No groups selected VSPs as a monitoring technology.

9.0 STATE OF BEST PRACTICE MONITORING

The PCOR Partnership has formalized AMA for development of CO_2 storage projects. As one of four technical elements underpinning AMA, the essential role of monitoring is to track/monitor storage project performance, with the primary objectives of demonstrating that the project is:

- Securely storing CO_2 in the reservoir.

- Maintaining a low-risk profile, with no evidence detected of significant impacts on the environment or other resources.

The four AMA technical elements are applied through each life cycle phase of a project (site screening, feasibility, design, construction/operation, and closure/postclosure) in an iterative fashion to reflect the complexity of storage projects and the need for a flexible approach to address often widely differing individual project needs. This document documented key lessons learned and recommended best practices from monitoring activities undertaken in PCOR Partnership projects, both for dedicated storage (in DSFs) and associated storage (incidental from CO_2 EOR). Many of these findings are also applicable to storage projects in other geographic regions, regulatory jurisdictions, and geologic or environmental settings (e.g., offshore projects).

CO_2 storage project-monitoring programs may be arbitrarily divided into deep subsurface/ reservoir-focused and shallow or surface environmental monitoring activities. As the first step in a monitoring program, establishing baseline conditions (prior to CO_2 injection) in the storage complex (subsurface) and selected environmental receptors is usually initiated during the project design phase. While deep subsurface environments are often relatively stable, near-surface water and soil environments are subject to climate-driven variability, which means establishing accurate baselines usually requires seasonal sampling and analysis of selected receptors over 2 or more years. With establishment of accurate baselines, the movement and behavior of injected CO_2 can be monitored by comparison of monitoring data with baseline data sets.

During the construction/operation (after commencement of CO_2 injection) and postclosure phases, routine monitoring, history matching of predictive models, and updating of risk assessments become the main technical elements. Monitoring activities may continue after cessation of CO_2 injection to demonstrate the long-term security of storage and associated low-risk profiles.

10.0 SUMMARY OF LESSONS LEARNED AND RECOMMENDED BEST PRACTICES

10.1 Summary of Monitoring Lessons Learned

Lessons Learned – Important Considerations When Establishing Risk Indicators
When establishing risk indicators, important considerations include: • Completeness – At least one risk indicator covers each monitoring objective. • Redundancy – Particularly important for higher-ranking risks, having more than one risk indicator for a particular risk provides redundancy. This redundancy results in greater confidence that the monitoring program will satisfy the monitoring objectives. • Sensitivity – Sensitivity refers to the limit of detection for a particular risk indicator to detect a change from baseline conditions and thereby trigger additional investigation. Technologies with a higher sensitivity can detect a smaller magnitude of change. • Time to detection – While some measurements are collected in near real time (e.g., bottomhole pressure and temperature), other measurements require weeks to months of data processing (e.g., 3-D seismic). These differences in data acquisition and processing time result in different times to detection. • Measurement scale – Many technologies acquire measurements at a localized scale (e.g., PNL logs measure the wellbore-scale), while other technologies acquire measurements at larger scales (e.g., 3-D seismic can collect measurements at the field-scale). • Relationships between risk indicators – In cases where one risk indicator is directly related to another (e.g., CO_2 concentration and pH of brine in near-wellbore environment), these relationships can often be used to help define action levels and improve monitoring reliability and efficiency.

Lessons Learned – Groundwater Systems Generally Provide Greater Sensitivity and Time to Detection Than Surface Water and Soil Gas Measurements

Chemical concentrations in groundwater systems typically have less variability than surface waters and soil gases, which provide greater sensitivity for detecting change from baseline conditions. In addition, groundwater systems are deeper (closer to the storage reservoir), thereby enabling more timely detection of potential deviations from baseline conditions that could be indicative of leakage.

Lessons Learned – Value of Surface Water Baselines

Surface water monitoring is typically of limited technical value since localized climatic conditions and other extraneous factors can significantly influence surface water chemistry. Care should be taken in interpretation of any surface water sample results. Preinjection surface water quality baseline measurements may assist in responding to any subsequent surface water issues.

Lessons Learned – Defensible Environmental Monitoring Data

Use of established sampling and analytical protocols helps ensure generation of more defensible data sets. Supplemental data/information (including details regarding nearby well installations and/or natural or anthropogenic events with potential environmental impacts) may often be required to determine valid reasons for observed deviations from baselines that are unrelated to the injection of CO_2.

Lessons Learned – PNL Campaign Planning

PNL campaigns require careful planning to optimize the value of the tool and minimize impact to project operations. Detecting fluid changes over time requires that each well have a baseline PNL measurement against which subsequent PNLs collected may be compared.

Lessons Learned – Seismic Survey Baselines

In establishing storage complex baselines, seismic surveys may be worth the relatively high investment by providing data across large volumes of the subsurface and providing appropriate detail to support sophisticated geologic models and predictive simulations. Such data sets can also support the interpretation of specific geologic features, which could affect the performance of a storage project.

Lessons Learned – Fixed Soil Gas Profile Stations
Fixed soil gas profile stations generally provide the most reliable soil gas measurements when an extended (years) monitoring program is planned, especially for increased sampling depths.

Lessons Learned – Field-Based Measurements
Most operational-phase surface and groundwater monitoring can be conducted in the field using relatively inexpensive handheld instrumentation and field test kits. Field methods for monitoring risk indicators such as pH, conductivity, and alkalinity are typically sensitive enough to detect a statistically significant deviation from baseline conditions that would then trigger a more detailed investigation into probable cause. Soil gas composition can also be monitored using handheld instrumentation.

Lessons Learned – PNLs + Seismic Survey = Extended Monitoring Capability
PNLs provide greater value when paired with other monitoring techniques—especially seismic surveys—because PNL-acquired fluid measurement data for the near-wellbore environment can be extrapolated between a network of wellbores using seismic survey data.

10.2 Summary of Monitoring Recommended Best Practices

Recommended Best Practices – Utilize the Project Risk Assessment to Establish Monitoring Objectives
The project RA represents a comprehensive summary of potential adverse events that could affect the storage project and is, therefore, generally the best starting point for establishing monitoring objectives.

Recommended Best Practices – Engage Regional Stakeholder and the Public
Establishing positive relationships with regional stakeholders is key to developing and implementing a successful monitoring program.

Recommended Best Practices – Establish Specific and Focused Monitoring Objectives
Establish specific and focused monitoring objectives by quantifying the relative ranking of individual project risks, identifying common sets of risk pathways, and understanding how individual risks are connected.

Recommended Best Practices – Review Monitoring Objectives with Project Stakeholders
Following establishment of monitoring objectives and associated risk indicators, project owners/operators should review these against applicable federal, state, and local regulations.

Recommended Best Practices – Ensure Baseline-Monitoring Data Comparability
In general, baselines should be established using data acquired via the same technique(s)—deployed with the same acquisition parameters—planned for use in operational monitoring. Good comparability is especially important when considering the use of existing data (rather than acquiring new data) for establishing baselines. Poor comparability between the techniques and parameters used to establish baselines and the subsequent operational monitoring could result in difficulties interpreting the operational monitoring results.

Recommended Best Practices – Review Existing Subsurface Data
Existing data, collected prior to storage project initiation, can vary significantly in quality and reliability. While these historical data may be invaluable for initial site screening and feasibility studies, using these data to establish baseline conditions for a monitoring program should be subject to quality assurance review. The cost savings from using existing data should be balanced against limitations that could affect interpretation of the subsequent operational monitoring data.

Recommended Best Practices – Establish Groundwater Baseline and Subsequent Monitoring
Groundwater baselines should be established for primary indicators of CO_2 presence (including pH, alkalinity, dissolved CO_2, and TDS) and parameters needed to address regulatory requirements. Operational monitoring can then focus on these primary CO_2 indicators, with the understanding that the sampling plan can be amended over time in the event of monitoring data that suggest a deviation from baseline conditions for these primary indicators.

Recommended Best Practices – Use Existing Wellsites for Soil Gas Monitoring
Soil gas monitoring should focus on areas around existing wells since they provide the most likely pathways for potential CO_2 migration from the reservoir to the surface. Sampling program prioritization (site selection and list of analytes) should be guided by a detailed assessment of available information for these wells, including age, cement bond logs, etc. (Watson and Bachu, 2009).

Recommended Best Practices – Optimize the List of Soil Gas Risk Indicators/Analytes
While the initial suite of soil gas analyses should be comprehensive in scope (i.e., a broad list of risk indicators/analytes), based on results of the initial rounds of environmental monitoring data, opportunities to reduce the analyte list should be investigated.

Recommended Best Practices – Focus Groundwater-Monitoring Indicators
Groundwater monitoring should focus on measuring key indicators of CO_2 presence (such as pH, alkalinity, and DIC) using field-based methods, followed by more extensive analysis if these screening-level measurements detect significant deviations from baseline.

Recommended Best Practices – Use Complementary Monitoring Techniques
Certain subsurface data collection techniques are most valuable when used in combination with one or more additional techniques. When considering a technique for use in a monitoring program, attempt to determine whether the technique requires data from an additional technique to provide maximum value.

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