MONITORING, VERIFICATION, AND ACCOUNTING (MVA) STRATEGIES: A PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP REGIONAL PERSPECTIVE

Plains CO_2 Reduction Partnership
Task 2 – Deliverable 6

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EXECUTIVE SUMMARY

Implementing carbon capture, utilization, and storage (CCUS) technology offers a practical solution to reduce carbon dioxide (CO_2) emissions from large industrial sources while meeting the rise in demand for low-carbon-intensity energy and products. Monitoring, verification, and accounting (MVA) practices play a critical role in CCUS by providing assurance to all stakeholders, including project operators, regulators, incentive program administrators, governments, and the public, that injected CO_2 volumes are safely and permanently stored in the subsurface.

The U.S. Department of Energy National Energy Technology Laboratory (2017) uses the term MVA to broadly refer to all activities related to measurement, monitoring, verification, accounting, and reporting. Alternatives, such as MRV (*measurement*, reporting, and verification), MRV (*monitoring*, reporting, and verification), MMV (measurement, monitoring, and verification), stress either the legal accounting and reporting practices or the more technical aspects of a strategic plan (i.e., measurement, monitoring, and verification).

MVA strategies are designed to 1) monitor preinjection, injection, and postinjection conditions; 2) verify containment of CO_2 in the storage reservoir; and 3) account for CO_2 volumes stored in the subsurface and any out-of-zone migration. Choosing the appropriate MVA practices (i.e., defining the tools/equipment and their design, cost, testing frequency and duration, and target area) is dependent on many factors, including the scope of the project (e.g., utilization and storage vs. dedicated storage), funding, technology available, industry standards, regulations and incentive program requirements (and their interpretation), site-specific conditions (e.g., geology, CO_2 stream composition, surface facilities and wellbore designs, and land use), and operator preference. In general, a verification strategy is preferred over a monitoring strategy because verification provides more actionable information. When developing MVA strategies, project managers should consider the appropriate policy framework requirements, what information/data gathering is important to project stakeholders, and what can help to ensure project operability.

The purpose of this report is to present the history of MVA strategies and practices implemented in CCUS projects throughout the Plains CO_2 Reduction (PCOR) Partnership region to date. The objectives of this report are to highlight the history and application of novel MVA approaches and point to future advancements in MVA.

The PCOR Partnership has nearly 20 years of experience in CCUS research and development. The first phase (Phase I) activities focused on identifying and characterizing CO_2

sources and sinks throughout the PCOR Partnership region. In Phase II, hundreds to thousands of metric tons of CO_2 were injected into various CO_2 enhanced oil recovery (CO_2 EOR) fields and subsequently monitored with a variety of MVA tools, including wellbore pressure–temperature gauges, near-surface sampling of groundwater and soil gas, time-lapse vertical seismic profiles (VSPs), and crosswell seismic. The general approach was to maximize the utility of existing data sets while minimizing the data collected beyond that which were part of normal field operations. The geophysical methods implemented in Phase II produced limited results for verifying containment in storage reservoirs, which was mainly attributed to the low volumes of CO_2 injected in the pilot (field test) programs.

In Phase III of the PCOR Partnership Program, field demonstrations injected more than 1 million metric tons of CO_2 and tested a wide variety of MVA methods using technology adopted from the oil field. The focus of MVA in Phase III was to deploy geophysics-based tools that were capable of imaging the CO_2 plume in the storage reservoir to verify containment, including time-lapse 2D/3D seismic, electromagnetic, and gravity survey techniques. Phase III projects incorporated more robust geologic models and simulations and risk assessments to inform the MVA strategy. Novel methods for sampling and monitoring reservoir fluids, testing isotopes for source attribution, and analysis of elastic seismic waves were also developed during Phase III activities.

After Phase III, the PCOR Partnership Program entered a new phase focused on commercial deployment and introduced the first wave of commercial CCS projects in North Dakota. Four storage facility permits are either approved or currently under consideration for approval by the state regulator. Overall, the MVA practices adopted by these North Dakota CCS projects were sourced from Phase II and III activities. The application of novel MVA strategies is guided by site-specific conditions and project manager preference. The overall MVA *strategy* should stay the same across all CCS projects, whether in conventional vs. unconventional or single vs. stacked storage reservoirs. Differences arise in MVA *practices* as site-specific conditions, technological advances, and project manager preference warrant.

The International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) Weyburn–Midale Storage and Monitoring Project and the Shell Quest CCS Project are two other CCUS projects that fall within the PCOR Partnership region. Both projects have been important test sites for demonstrating novel MVA practices, such as atmospheric monitoring with Eddy Covariance and line-of-sight laser-based gas analyzers as well as vegetative monitoring via remote sensing.

Based on the history of MVA in the PCOR Partnership region, future directions in MVA seem to be headed toward more continuous, real-time data gathering and processing to provide project operators with the ability to collect data on-demand and allow for faster decision-making based on actionable evidence.

Reference

U.S. Department of Energy National Energy Technology Laboratory, 2017, Best practices – Monitoring, verification, and accounting (MVA) for geologic storage projects: DOE/NETL-2017/1847.

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

MONITORING, VERIFICATION, AND ACCOUNTING (MVA) STRATEGIES: A PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP REGIONAL PERSPECTIVE

1.0 INTRODUCTION

1.1 The Critical Role of MVA in CCUS

Implementing carbon capture, utilization, and storage (CCUS) technology offers a practical solution to reduce carbon dioxide (CO_2) emissions from large industrial sources while meeting the rise in demand for low-carbon-intensity energy and products. A 2022 report from the International Panel on Climate Change (IPCC) highlighted CCUS as "an essential complement to emissions reduction from the hardest-to-abate industries," citing cement production and coal power as examples (International Panel on Climate Change, 2022). The report also concluded that "a political commitment to formal integration [of CCUS] into existing climate policy frameworks is required, including reliable measurement, reporting, and verification (MRV) of carbon flows." MRV practices, more generally referred to as monitoring, verification, and accounting (MVA) practices, play a critical role in CCUS by providing assurance to all stakeholders, including project operators, regulators, incentive program administrators, governments, and the public, that injected CO_2 volumes are safely and permanently stored in the subsurface. All CCUS policy frameworks require project operators to develop and implement MVA strategic plans with the overall goals of protecting human health and the environment and demonstrating the effectiveness of long-term geologic CO_2 storage.

1.2 MVA Terminology, Definitions, and Frameworks

In this report, MVA refers to activities associated with measurement, monitoring, verification, reporting, and accounting practices in CCUS. Corrective and emergency response actions are treated separately from MVA activities and are not discussed in this report.

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) uses the term MVA (U.S. Department of Energy National Energy Technology Laboratory, 2017). MRV (*measurement*, reporting, and verification) is used interchangeably with MVA but is less popular in the United States, as the term is too easily confused with MRV (*monitoring*, reporting, and verification), which specifically references a U.S. Environmental Protection Agency (EPA) strategic plan designed for CCUS project reporting.

Another acronym sometimes used interchangeably with MVA or MRV is MMV (measurement, monitoring, and verification). MMV plans are designed to provide technical descriptions of monitoring and verification activities while MVA and (both) MRV plans also incorporate legal accounting and reporting practices and protocols, respectively (Ringrose, 2020).

Any inconsistencies between MVA framework requirements adds complexity to and may increase the financial burden of implementing MVA, especially when project operators choose to submit applications to multiple regulatory authorities and incentive program administrators (policy frameworks). When existing frameworks use different words to describe a similar or an equivalent rule or regulation regarding MVA, the effects are minimal. For example, the California Air and Resources Board (CARB) Low Carbon Fuel Standard (LCFS) Carbon Capture and Sequestration Protocol, an incentive program with prescriptive requirements, applies the term *sequestration zone* to refer to the geologic interval receiving the injected CO_2 volumes in the same way that the regulatory authority in North Dakota uses the term *storage reservoir*. In cases where terms with the same name are defined differently among frameworks, such as *storage complex* or *deep subsurface* (Figure 1-1), some confusion around the meaning or use of such terms may be generated, but the overall effect on MVA remains relatively low.

A greater impact to MVA occurs when a policy framework includes requirements that cannot be found in another policy framework. For example, CARB's policies do not specify requirements for monitoring the surface transportation equipment (i.e., the CO_2 flow line), while North Dakota has specific requirements for flow line instrumentation and related MVA practices. CARB also requires vegetative surveys and characterization of pressure and fluid dissipation intervals (referred to as *dissipation intervals*), where other frameworks (e.g., Government of Alberta) have no equivalent policies or only partially match (e.g., North Dakota requires characterization of a *pressure dissipation interval* above the storage reservoir). Such policy variation can represent a significant cost difference for conducting site characterization work, establishing data management practices, and implementing MVA strategic plans.

Project operators may wonder why some MVA requirements are important if they appear in one framework and not another. It is useful to recall the overall goals of a MVA strategic plan (Section 1.1) and to consider that in addition to meeting the appropriate policy framework requirements, project operators should also design the MVA strategic plan to understand what information helps to ensure project operability and what data gathering is important to project stakeholders (Ringrose, 2020).

Examples A–C in Figure 1-1 illustrate how several groups use terminology to define environmental zones and target areas that are monitored for onshore carbon capture and storage (CCS) projects. MVA frameworks were included in Figure 1-1 if environmental and target area boundaries were relatively easy to define from reviewing the requirements of the policy framework. The terminology reflects the requirements stipulated in each policy framework and demonstrates how MVA requirements vary, impacting which MVA activities may be planned or implemented for a given project. While every MVA strategic plan should be designed to comply with the appropriate policy framework(s) using site-specific information (Ayash and others, 2017), it is wise to at least have an awareness of the differences between policy frameworks so that the widest range of possibilities may be considered for assessing risks, generating models and simulations, and developing MVA strategic plans. Example D in Figure 1-1 illustrates a composite MVA framework of Examples A–C, with a few additions to further improve clarity. Example D should be thought of as a useful visualization tool for developing MVA strategic plans.

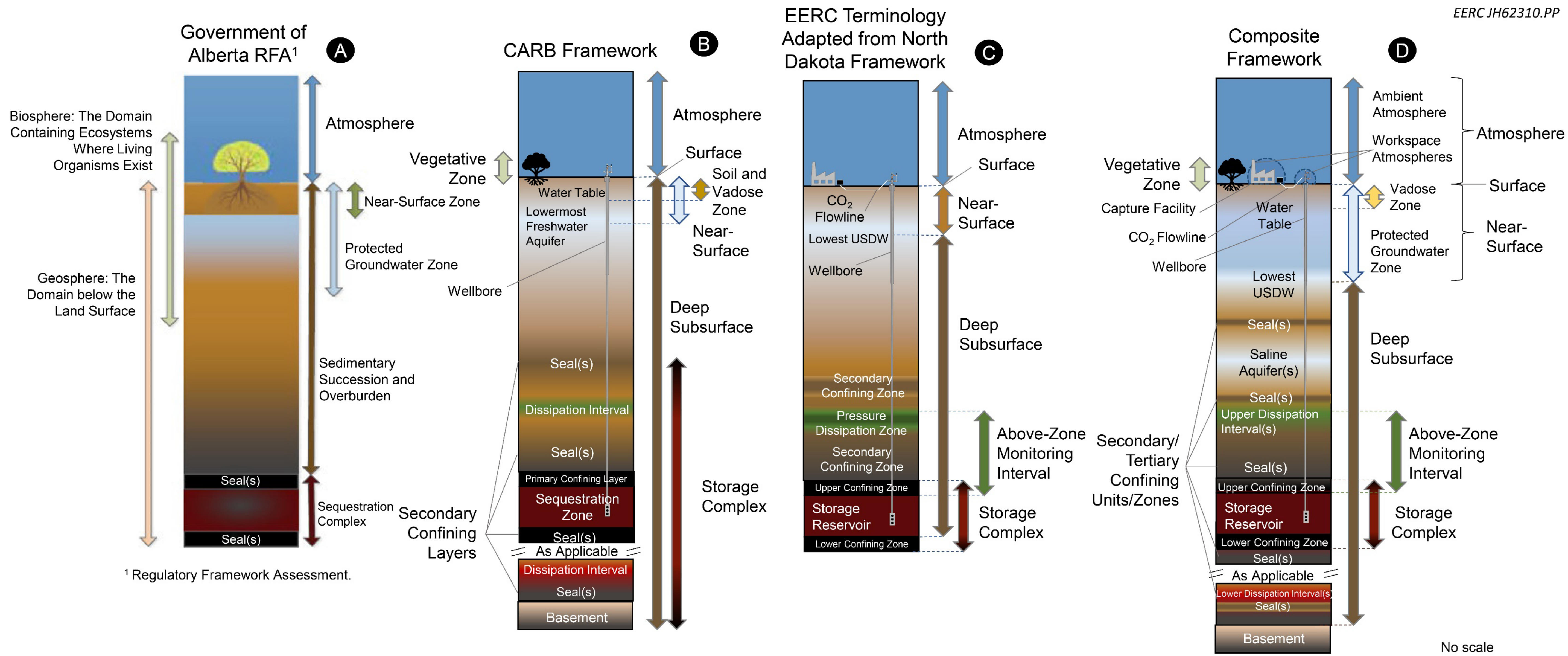

Figure 1-1. Examples of MVA framework terminology for onshore carbon capture and sequestration projects (A–C) and composite MVA framework (D). Dashed lines in Examples B–D illustrate the defined boundaries between the environmental zones and target areas depicted. Example A from Alberta Energy (2013), after which Examples B–D are patterned.

1.3 Scope of MVA

According to a CCS summary report published by the Alberta government, "the purpose of [MVA] is to address health, safety, and environmental risks, evaluate sequestration performance, and provide evidence that [a] site is suitable for closure" (Alberta Energy, 2013). For CCS projects, MVA strategic plans are designed to fulfill this purpose with three main objectives: 1) monitor/measure preinjection, injection, and postinjection conditions; 2) verify containment of CO_2 in the storage reservoir; and 3) account for/report CO_2 volumes stored in the subsurface and any out-of-zone migration. The same three objectives apply generally to carbon utilization and storage projects, with Objectives 1 and 3 being most similar to CCS (dedicated storage) regulations. Objective 2 differs most in that utilization projects either do not need to verify CO_2 storage by nature of the operation (e.g., CO_2-to-fuel projects) or verification of containment of CO_2 in the storage reservoir occurs through monitoring production and injection operations (i.e., enhanced oil and/or gas recovery projects) at the wellbore (e.g., 40 Code of Federal Regulations [CFR] Part 146, Subpart C). The overall goal of the project (i.e., utilization and storage vs. dedicated storage) determines the extent to which Objectives 1–3 must be fulfilled and documented.

Selecting the appropriate MVA practices (i.e., defining the tools/equipment and the testing design, cost, frequency, duration, and target area) to fulfill these three goals and comply with all regulations and incentive program requirements is dependent on many factors, including the scope of the project (e.g., utilization and storage vs. dedicated storage), funding, technology available, industry standards, permit regulations and incentive program requirements (and their interpretation), site-specific conditions (e.g., geology, CO_2 stream composition, surface facilities and wellbore designs, and land use), and operator preference. As a project operator tailors the MVA strategy to a set of dynamic factors and gathers more information, MVA practices are anticipated to evolve throughout the life of the project.

EPA, Wyoming, and North Dakota Class VI underground injection control (UIC) program regulations require project operators to reevaluate approved permit plans (including MVA) at least once every 5 years. CARB also requires project operators to reevaluate permanence certifications every 5 years to qualify for additional credits through the state's LCFS market. The Plains CO_2 Reduction (PCOR) Partnership recommends a formalized adaptive management approach (AMA) for all CCS projects, which includes regularly revisiting plans and adapting to site-specific conditions (Ayash and others, 2017).

In general, verification strategies are preferred over monitoring strategies when implementing MVA. This is because verification provides more actionable information to project operators. For example, monitoring soil gas and groundwater geochemical fluxes, as required in many policy frameworks, may detect statistically significant changes in the fluids under surveillance but cannot attribute source. The advantage of using a verification strategy, such as application of a process-based approach for soil gas (Romanak and others, 2012) or isotope geochemistry in soil gas or groundwater studies (e.g., Risk and others, 2015; Moni and Rasse, 2014; Myers and others, 2013) allows project managers to attribute CO_2 source, providing stronger assurance to stakeholders that operations are proceeding as expected and avoiding incurring unnecessary costs to projects.

While verification strategies may provide more actionable information when compared with monitoring strategies, monitoring data are still very useful. For example, monitoring the tubing–casing annulus pressure in a CO_2 injection well provides useful information related to wellbore integrity and is required to be monitored under multiple policy frameworks (e.g., Class II and VI UIC program and CARB). If an anomaly is detected in the pressure readings, a supplementary method may be required to verify the location and cause of the anomalous reading. Similarly, monitoring pressure and temperature in the storage reservoir at the wellhead or with downhole well equipment provides useful data for operations and model history matching. However, if such measurements detect an anomaly, the data cannot be used to verify why the change occurred. If simpler well logging techniques (e.g., temperature decay or pulsed neutron/RST log), could not identify the issue, a separate strategy, such as crosswell seismic (Gasperikova and others, 2022) or geochemical tracing or sampling from the reservoir, may be required instead. Project operators must weigh the costs and benefits of leaning more heavily on verification strategies, some of which tend to be more expensive and may take more time to process results, compared with monitoring strategies that still provide useful, and if severe enough, actionable information. A detailed cost and benefit analysis of MVA activities was published by the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) (International Energy Agency Greenhouse Gas R&D Programme, 2020).

1.4 Scope of Report

The purpose of this report is to present the history and application of MVA strategies and practices developed for and implemented in CCUS projects throughout the PCOR Partnership region to date. The objectives of this report are to highlight the evolution of novel MVA techniques through the PCOR Partnership's history (Section 2.0) and point to future advancements in MVA (Section 3.0).

2.0 HISTORY OF MVA STRATEGIES WITHIN THE PCOR PARTNERSHIP

2.1 PCOR Partnership

The PCOR Partnership Initiative is one of four Regional Initiative (RI) projects operating under the U.S. Department of Energy (DOE) National Energy Technology Laboratory's (NETL) Regional Initiative program to accelerate CCUS (carbon capture, utilization, and storage). The PCOR Partnership region encompasses ten U.S. states and four Canadian provinces in the upper Great Plains and northwestern regions of North America (Figure 2-1). The PCOR Partnership is led by the Energy & Environmental Research Center (EERC) with support from the University of Wyoming (UW) and the University of Alaska Fairbanks (UAF) and includes over 200 stakeholders from the public and private sectors. The goal of this joint government–industry effort is to identify and address regional capture, transport, use, and storage challenges facing commercial deployment of CCUS throughout the PCOR Partnership region.

Figure 2-1. Map of the current PCOR Partnership boundary compared with PCOR Partnership Phase I boundary. Also shown is the location of the three organizations leading (EERC) and providing leadership support (UAF and UW) to the PCOR Partnership.

The PCOR Partnership Program has nearly 20 years of experience in CCUS research and support of demonstration- and commercial-scale CCUS projects, including enhanced oil recovery (EOR), terrestrial sequestration, and geologic CO_2 storage. The history of CCUS-related project work through the PCOR Partnership illustrates the evolution of MVA practices in the region and influences the future direction of MVA strategies.

2.2 PCOR Partnership: Phases I and II

The PCOR Partnership was established in 2003. At that time, it was one of seven Regional Carbon Sequestration Partnership programs that included all or part of five U.S. states (Minnesota, Montana, North Dakota, South Dakota, and Wyoming) and two Canadian provinces (Saskatchewan and Manitoba). The PCOR Partnership grew substantially during Phase I (2003–2006), as Phase I activities focused on identifying and characterizing CO_2 sources and sinks throughout the PCOR Partnership region (final Phase I boundaries shown in Figure 2-1). Phase I activities identified over 1000 stationary sources of CO_2 with a combined annual output of about 502 million metric tons and estimated more than 219 billion metric tons in total storage capacity for geologic and terrestrial sinks within the region (Steadman and others, 2006). Another takeaway from this phase was that the sparsity of previous CO_2 EOR projects in the region and the lack of monitoring efforts to ensure long-term CO_2 storage in the reservoir emplaced a knowledge gap and, therefore, a need to develop (and field-test) MVA strategies in Phase II (Steadman and others, 2006).

The focus of Phase II (2005–2009) was to demonstrate the effectiveness of MVA and determine the potential of CO_2 utilization and storage for enhanced recovery. Three field locations (pilot program sites) were chosen for Phase II research, including the Zama oil field in Alberta, Canada, the Northwest McGregor Field in Williams County, North Dakota, and an unminable lignite coal seam in Burke County, North Dakota.

2.2.1 Zama Field Test

The primary objective of the Zama field test (2006–2009), the first of three pilot programs in Phase II, was to demonstrate injection of approximately 25,400 metric tons of sour CO_2 (acid gas) into a depleted oil field for disposing of the acid gas, storing CO_2, and enhancing oil recovery volumes. A secondary objective was to implement a cost-effective MVA strategic plan for verifying CO_2 containment in the targeted oil reservoir. The general approach for developing the MVA strategy was to maximize the utility of existing data sets while minimizing the data collected beyond that which were part of normal field operations (Smith and others, 2010). MVA activities included 1) analyzing groundwater and soil gas samples, 2) monitoring pressure in the injection and monitoring wells, 3) analyzing fluid samples from the target reservoir to detect geochemical changes, 4) conducting a tracer survey, and 5) accounting for CO_2 volumes using mass balance calculations (Smith and others, 2006). Key results of the monitoring and verification strategy included 1) detection of a slight increase of pressure in an adjacent oil pool (not the target reservoir) and 2) no detection of geochemical changes or the tracer that was introduced to the project in any of the wells. The results were mixed, meaning the strategy was capable of monitoring operating conditions (detecting anomalies) but could not directly verify containment of CO_2 in the target reservoir (Smith and others, 2010).

2.2.2 North Dakota Lignite Coal Field Test

The overall objective of the North Dakota lignite coal field test, the second pilot program of PCOR Phase II, was to improve understanding of the technical and economic feasibility of CO_2 injection, storage, and enhanced coalbed methane (ECBM) in lignite (Steadman and others, 2009).

Four monitoring wells were placed around a single CO_2 injection well which introduced about 82 metric tons of CO_2 into the target reservoir at a depth of 1100 feet (Dobroskok and others, 2007). Special emphasis was given to implementing MVA strategies capable of imaging the CO_2 plume in the subsurface to verify containment. MVA activities included 1) collecting well log and core data to complement site characterization work; 2) collecting continuous measurements of wellhead pressure, temperature, and flow rate and downhole measurements of pressure, temperature, pH, and conductivity; 3) sampling water and gas from monitoring wellheads, including a perfluorocarbon (PFC) tracer introduced with the injected CO_2 stream; 4) monitoring for microseismicity and fracturing events with a surface array of geophones and tiltmeters; 5) performing a time-lapse crosswell seismic survey; and 6) collecting reservoir saturation tool (RST) measurements (Steadman and others, 2011; Botnen and others, 2009).

Geochemical analyses of water and gases collected from the injection and monitoring wells detected no impacts to water or gas, and no tracer was found in any of the monitoring wells. Because of the low volume of CO_2 injected for this project, the microseismicity equipment recorded no events (Steadman and others, 2009). The MVA activity which proved most effective was downhole pressure, temperature, pH, and conductivity monitoring in the target reservoir during ECBM operation. When the anticipated pressure increase was detected after injection began, all of the associated data sets (i.e., temperature, pH, and conductivity) responded to the introduction of CO_2 in the target reservoir appropriately (Smith, 2010). The correlated data sets produced useful results for operations and upgraded the monitoring strategy from being capable of just detecting changes in the reservoir to providing some evidence for explaining the changes in the data.

RST data effectively verified that CO_2 had entered the coal seam at the injection well and migrated to the closest monitoring well (Smith, 2010). RST data could not be used to reconstruct the plume geometry (Steadman and others, 2009), as RSTs did not detect any CO_2 in more than two monitoring wells. If a larger CO_2 volume was injected into the formation, it is possible the RST time-lapse results would have been capable of delineating the geometry of the injected CO_2 stream in the target reservoir.

The crosswell seismic most clearly imaged the extents of the CO_2 plume in the target reservoir, proving to be the most effective geophysical tool employed for verifying containment in the project. Figure 2-2 illustrates an example of the crosswell seismic results through the two monitoring wells and the injection well that were drilled for the project. The shallower depth of the target interval made data gathering simpler for this pilot project.

No accounting strategies were documented for the North Dakota lignite coal field test.

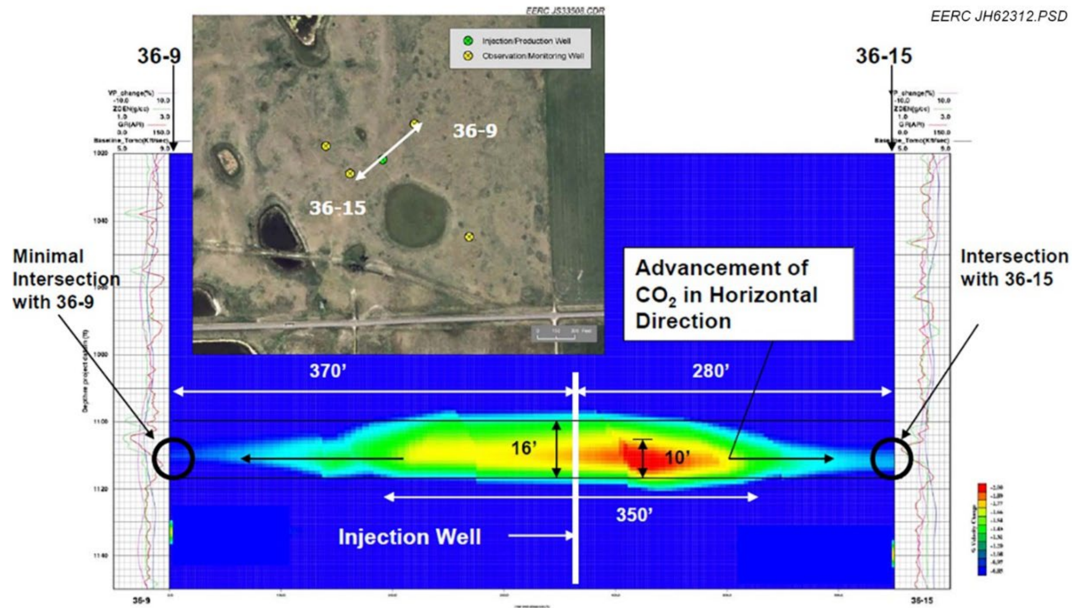

Figure 2-2. Example of crosswell seismic results for the North Dakota lignite coal field test (Smith, 2010).

2.2.3 Northwest McGregor Field Test

A main objective of the Northwest McGregor field test, the third and final pilot program in Phase II, was to further develop MVA, which included a continued focus on applying geophysical methods to image the CO_2 plume and verify containment. Two key technologies introduced to the project, which were adopted from the oil field, included the RST and vertical seismic profile (VSP). The Northwest McGregor field test injected ~400 metric tons of CO_2 in a "huff 'n' puff" operation (i.e., inject, soak, and produce) to enhance oil recoveries from a deep carbonate reservoir (Sorensen and others, 2011). The approach to MVA was different from Zama and the lignite coal pilot programs in that the strategic plan was informed by detailed site characterization activities to produce a more technically defensible and effective MVA program. For example, the hydrogeologic characterization work established baseline conditions (e.g., thicknesses and geometries) in key aquifer systems, informing the MVA planning team where groundwater sampling would be most effective to detect out-of-zone migration over the life of the project (Sorensen and others, 2010).

MVA activities for the Northwest McGregor field test included 1) collecting RSTs and two-dimensional (2D) VSPs; 2) collecting wellhead pressure, temperature, and flow rate data from the CO_2 injection well; 3) analyzing water and gas samples from a deep monitoring well and nearby groundwater well; 4) adding a PFC tracer to the CO_2 injection stream and periodically sampling the monitoring wells; 5) and performing material balance between the injected and produced fluids (Sorensen and others, 2010).

The results of the water, gas, and tracer monitoring showed no statistically significant signs of change throughout the course of the project, suggesting no out-of-zone migration occurred.

Time-lapse RST results clearly showed migration of CO_2 within the geologic reservoir in the near-wellbore environments. The time-lapse 2D VSP data detected a small observable difference in seismic reflectance in the reservoir, but the change was not significant enough to confidently conclude that the difference was due to the introduction of CO_2 in the reservoir. The lack of clear results from the VSP was attributed to the small volume of CO_2 injected for the EOR project which may have resulted in changes that were at or close to the detectable limit of the seismic data (Sorensen and others, 2011). The VSP data were still useful for informing the geologic model for where horizontal sealing rock layers were located within the geologic reservoir (confirmed with RST and core data). Figure 2-3 depicts the results of the first time-lapse VSP deployment.

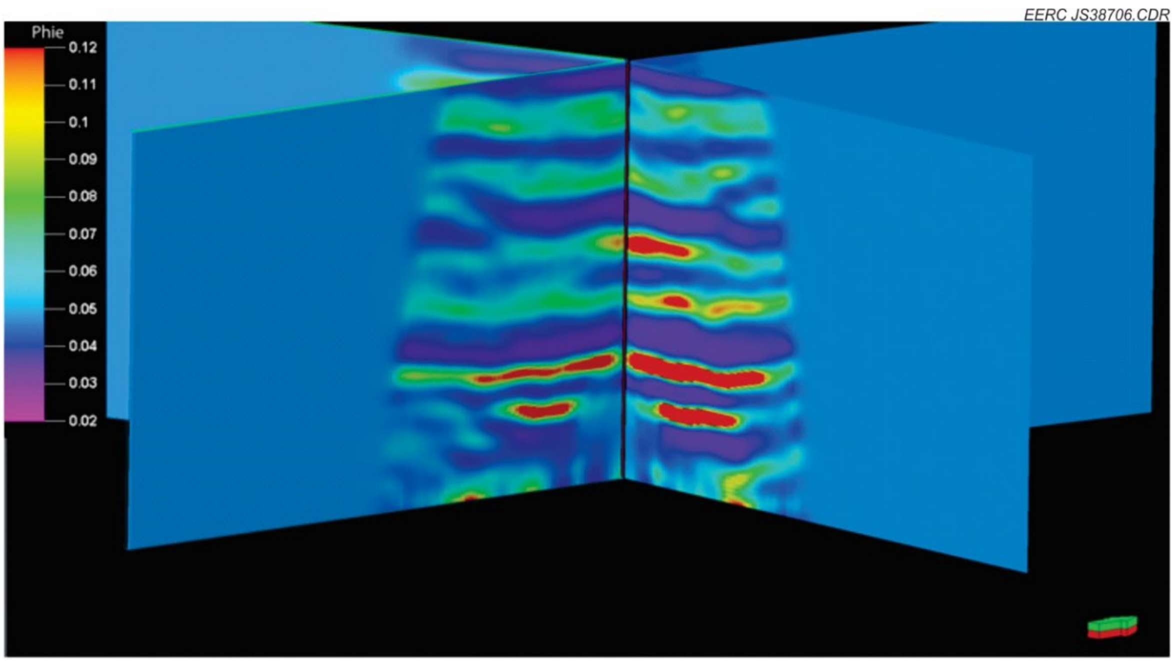

Figure 2-3. Workstation view of the first time-lapse results of the VSP for the Northwest McGregor field test (Sorensen and others, 2011).

2.2.4 Synthesis of Phase II MVA Activities

All MVA strategic plans in Phase II included limited use of continuous and real-time data gathering, such as collecting bottomhole information (e.g., pressure and temperature) from the target reservoir. The North Dakota lignite coal field test also incorporated continuous monitoring, with tiltmeters and geophones installed at the surface for seismicity monitoring.

The use of time-lapse RSTs and crosswell seismic proved to be effective for mapping saturation profiles near wellbores and verifying the location of the CO_2 plume in the target reservoirs, respectively. The effectiveness of using the RST and VSP for verifying the location of the CO_2 plume was negatively impacted by the small volumes of CO_2 introduced to each field test. While the 2D VSP data collected for the Northwest McGregor field test provided uncertain evidence of CO_2 containment in the reservoir, the data still provided useful information about the location and thicknesses of permeable and sealing layers in the target reservoir for refining the project geologic model and simulations.

Temperature and pressure data obtained from the injection and monitoring wellheads and downhole gauges provided useful information for field operations and monitoring the target formation but generally could not verify containment of CO_2 (i.e., attribute the cause of the changes or anomalies detected). However, in the case of the North Dakota lignite coal field test, the downhole data collected (pressure, temperature, pH, and conductivity information) from the target reservoir enhanced the effectiveness of using downhole gauges as an MVA strategy, as the data sets could be correlated and used to explain the movement of CO_2 in the target reservoir.

The well fluid-sampling programs implemented in all three PCOR Partnership Phase II field tests (i.e., water, gas, and produced fluids analyses and tracer surveys) showed no statistically significant signs of out-of-zone migration of CO_2 from the target reservoirs. At Zama, no tracer was recovered from any of the wells, producing an inconclusive test result. For the Northwest McGregor field test, the tracer was recovered, and upon geochemical testing, no statistically significant indications of out-of-zone migration were found. Complementary results of the RST and crosswell seismic data, both of which clearly showed the CO_2 in the target reservoir, also supported the tracer survey interpretation.

None of the field tests in Phase II detected any evidence of out-of-zone migration from the soil gas and groundwater geochemical sampling. While these results suggested no out-of-zone migration occurred in any of the projects, it is difficult to truly determine the effectiveness of these strategies without demonstration of a CO_2-positive result. Previous studies have investigated the effectiveness of shallow soil gas and groundwater sampling at CCUS sites from claims of CO_2 surface leakage (Romanak and others, 2013, 2014) or in controlled-release experiments (e.g., Apps, 2010), but no permitted CCUS project in North America has detected CO_2 related to any CCUS project with this approach. Established CCUS policy frameworks require monitoring of the near-surface environment (e.g., soil gas and groundwater) to protect the environment and human health from any potential threats. Near-surface testing also provides evidence of no leakage for mass balance calculations, which is important from an accounting/reporting perspective.

2.3 PCOR Partnership Phase III

The main objective of Phase III activities (2008–2019) was to demonstrate safe, secure, and effective geologic storage of CO_2 at the commercial scale. This meant upscaling CO_2 injection volumes from tens to thousands of metric tons in Phase II field test work to 1 million metric tons or more. Two projects led by the EERC—the Fort Nelson feasibility study and the Bell Creek demonstration project—were initially planned as full-scale field demonstrations through the PCOR Partnership in Phase III. A third project, Aquistore, was later added to Phase III activities, which included modeling and simulation work.

2.3.1 Fort Nelson Feasibility Study

The purpose of the Fort Nelson feasibility study (2008–2012) was to investigate the feasibility of capturing CO_2 produced by processing natural gas at the Fort Nelson Gas Plant, located in northeastern British Columbia, Canada, and injecting approximately 2.2 million metric tons per year of captured CO_2 into a deep saline carbonate formation for safe and permanent geologic storage (Sorensen, 2014). Activities for the feasibility study included site characterization by determining the geological, geochemical, and geomechanical properties of the storage complex (i.e., storage reservoir and primary and secondary confining zones above the storage reservoir), modeling and simulation for the fate of CO_2 injection over time, risk assessment, and design of a site-specific MVA strategy (Sorensen and others, 2013).

Although planned to begin injection operations in 2014, the Fort Nelson project was delayed and then suspended in 2016 for a combination of factors, including the lack of a Canadian financial incentive program, a reduced market for natural gas, and technical challenges (Plains CO_2 Reduction [PCOR] Partnership, 2022; Bakx, 2017). The MVA strategic plan was never implemented; therefore, the results of the drafted MVA plan cannot be discussed. Figure 2-4 provides an illustrative example of planned MVA activities at Fort Nelson. Pulsed-neutron logging (PNL) and three-dimensional (3D) VSPs and seismic surveys were the key geophysical methods planned for the project, which had not yet been tested for CCUS applications within the PCOR Partnership region.

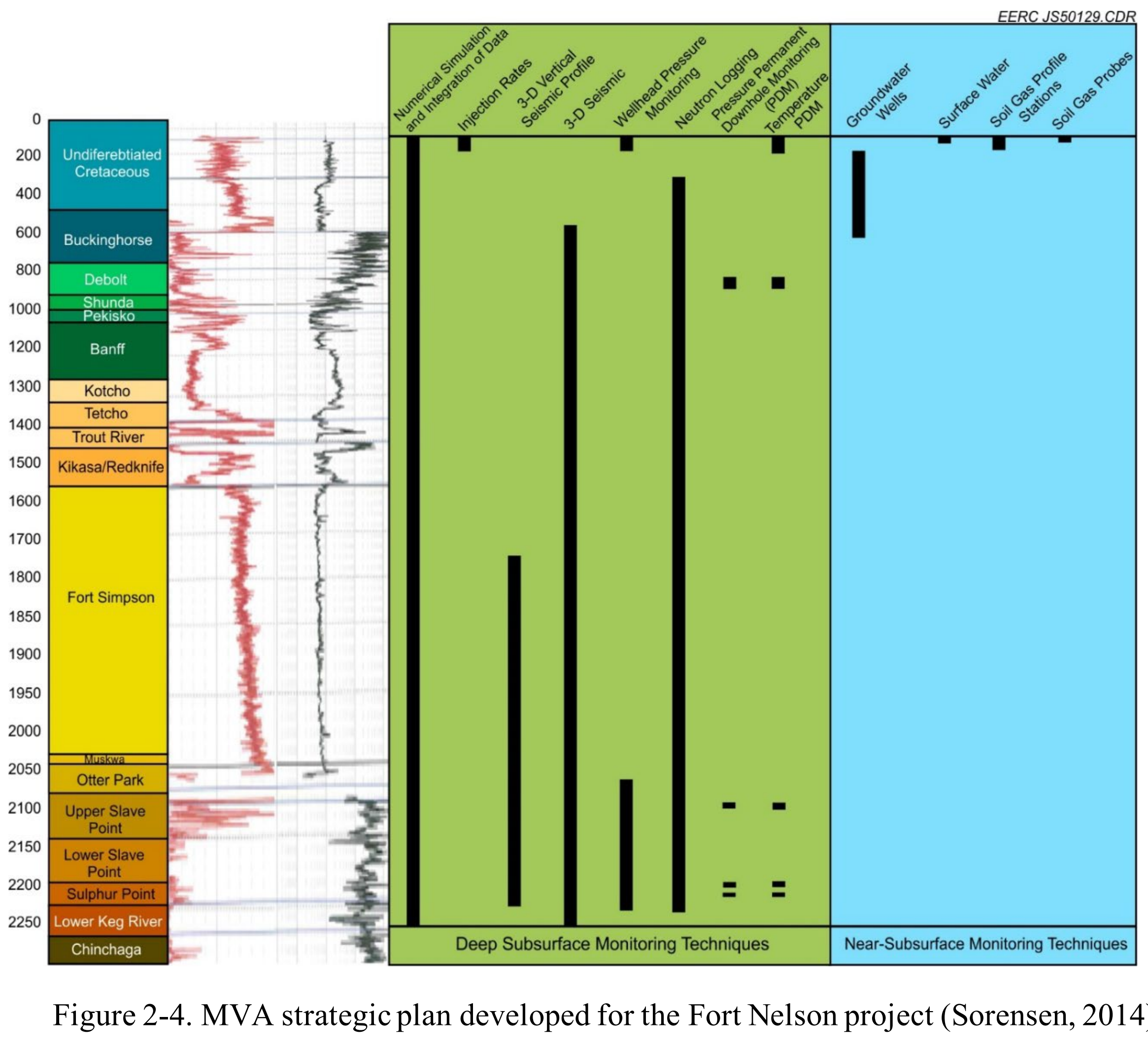

Figure 2-4. MVA strategic plan developed for the Fort Nelson project (Sorensen, 2014).

The Fort Nelson feasibility study was the first CCS project led under the PCOR Partnership to employ the use of risk assessment to document potential project failure mechanisms (technical and nontechnical), which further informed the emergency response (corrective action) and MVA plans. The Fort Nelson project was also the first PCOR Partnership CCS project to develop a MVA strategic plan around a set of regulatory standards (i.e., via the Canadian Standards Association) to ensure compliance within a CCUS policy framework.

The MVA strategic plan developed for the Fort Nelson project included a broader range of activities than any of the plans implemented in Phase II of the PCOR Partnership Program, as shown in Figure 2-4. This reflects the project's larger scale compared with the field tests in Phase II as well as the difference in the overall goal of Phase III to implement CCS technology and test MVA methods at the commercial scale. Phase II objectives were to maximize existing field operations data while minimizing additional data collection. Phase III objectives prioritized 1) providing assurance to the public that the project is safe and protects the environment; 2) developing a rigorous, defendable accounting strategy for CO_2 volumes stored; and 3) complying with policy framework requirements or guidelines (Sorensen, 2014). The Fort Nelson MVA strategy focused on addressing Objectives 1 and 3 but did not provide much detail on plans to address Objective 2.

2.3.2 Transition from Fort Nelson to Bell Creek

In 2010, during the Fort Nelson feasibility study (2008–2012), EPA introduced a new class of well under the Safe Drinking Water Act's UIC Program. This new class of well, UIC Class VI, was designed solely for geological storage of CO_2. EPA also introduced a set of requirements to regulate Class VI well permits, while the U.S. Internal Revenue Service (IRS) contemporaneously expanded the tax incentive program for CCUS under Section 45Q of the U.S. tax code (established earlier in 2008). Together these actions successfully introduced the first CCUS policy framework and incentive program to drive CCUS investments forward in the United States (Hamling and others, 2022) and set the stage for activities at Bell Creek.

2.3.3 Bell Creek CO_2 EOR Demonstration Project

The primary goal of the Bell Creek CO_2 EOR demonstration project (2010–2016 demonstrations) was to determine the effectiveness of large-scale injection (i.e., approximately 1.1 million metric tons per year) of CO_2 into a deep sandstone reservoir for enhancing oil recoveries while simultaneously storing CO_2 in the oil reservoir (Hamling and others, 2013). The purpose of the MVA strategic plan was to provide evidence in support of this primary goal.

The Bell Creek Field is divided into nine CO_2 EOR phases based on geologic flow barriers present in the target (oil) reservoir determined from previous geologic and operations data (Figure 2-5). MVA activities at Bell Creek, summarized in Table 2-1, were implemented in multiple phases. Just like Fort Nelson, the MVA strategy at Bell Creek was guided by site characterization activities, modeling and simulation work, a risk assessment, and consideration of policy framework compliance, following after the AMA project-planning workflow presented in Hamling and others (2013).

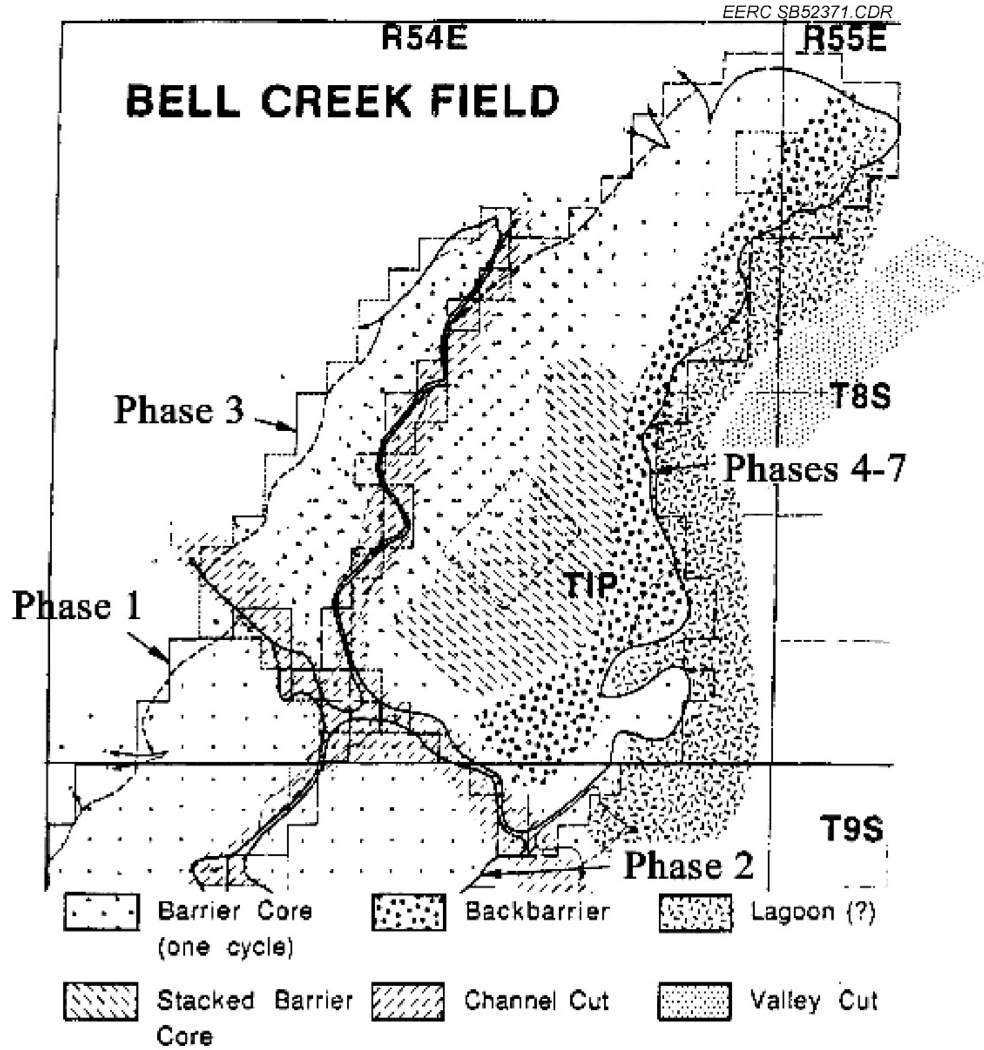

Figure 2-5. Map illustrating geological interpretation of permeability barriers in the Bell Creek Field. CO_2 EOR Phases 1–7 are labeled on the map; Phases 8 and 9 (to the south) are not shown (Burnison and others, 2017b).

The general MVA approach was to prioritize verification of CO_2 containment in the oil reservoir using off-the-shelf solutions adopted from the oil and gas industry, such as time-lapse seismic (Hamling and others, 2017). MVA activities at Bell Creek was focused on testing and developing more sustainable (i.e., cost-effective, low-footprint, and low-impact) methods for collecting data. The results of the MVA program implemented at Bell Creek are far too many to discuss in this report; therefore, only a few key results from geophysics-based verification strategies employed at Bell Creek, representing MVA practices not already mentioned in this report, are highlighted in the sections that follow.

Table 2-1. Bell Creek MVA Strategic Plan Summary

Activity Description	MVA Type	Frequency		Target Structure/Area	Primary Purpose
		Preinjection	Injection		
Surface Facilities					
Mass Flow Calculations	A	NA[1]	Continuous, real time	Flowmeters installed at flow line termini	Flow line monitoring and accounting method
Near-Surface					
Surface Water Flux Analysis	M	Periodic sampling at each location starting prior to Phase 1	Periodic sampling at each location	Eight sampling locations	Surficial waters monitoring
Soil Gas Flux Analysis	M			>100 locations around wellheads	Soil gas monitoring
Groundwater Flux Analysis	M			15 wells (stock and domestic)	Groundwater (to lowest USDW[2]) monitoring
Deep Subsurface					
Casing and Tubing Pressure Testing	M	After well completion	Periodic	Injection and deep monitoring wells	Wellbore integrity monitoring
Pulsed-Neutron Logging	V	Baselines starting prior to Phase I	Periodic	Injection and deep monitoring wells	Verification of containment in AZMI[3] and storage reservoir
Chemical Analysis of Reservoir Fluids	M	Baselines starting prior to Phase I	Periodic	Injection and deep monitoring wells	Containment in storage reservoir monitoring
Casing-Conveyed P–T[4] Gauges	M	Installed prior to injection (Phase 1)	Continuous, real time	Deep monitoring well	AZMI, storage reservoir, and wellbore integrity monitoring
Fiber-Optic Cable, DTS[5]	M	Installed prior to injection (Phase 1)	Continuous, real time	Deep monitoring well	Storage reservoir and wellbore integrity monitoring
Tracer Survey	V	N/A	Periodic	Injection and deep monitoring wells	Verification of containment in storage reservoir
3D VSP	V	Baseline over Phases 1–5 and 8	Periodic	Injection and deep monitoring wells	Verification of containment in storage complex
Time-Lapse 2D and 3D Seismic	V	Baseline in Phase 1	Periodic	Bell Creek Field	Verification of containment in storage complex
Surface EM[6] Survey	V	Baseline for Phase 3	Periodic	Bell Creek Field	Verification of containment in storage complex
K-Wave[7] Field Test	M	NA	Periodic	Injection or monitoring wellheads	Monitoring of the CO_2 plume front
SASSA	V	Baseline for Phase 4	Periodic	Bell Creek Field	Verification of containment in storage complex
InSAR[8]	M	Baseline for Phase 4	Periodic	Bell Creek Field	Supplementary data set for monitoring containment in storage complex

[1] Not applicable.
[2] Underground source of drinking water.
[3] Above-zone monitoring interval.
[4] Pressure–temperature.
[5] Distributed-temperature sensing.
[6] Electromagnetic.
[7] Krauklis wave.
[8] Interferometric synthetic aperture radar.

2.3.3.1 Time-Lapse Seismic

Time-lapse seismic surveys (2D and 3D) were most successful in verifying CO_2 containment and imaging permeability barriers and baffles at Bell Creek. Figure 2-6 provides an example of the results from a time-lapse 3D survey at Bell Creek, illustrating the plumes in the oil reservoir from the injected CO_2 at the time at which the data were obtained. The time-lapse seismic map highlights an area between Phases 1 and 2 where fluid communication was detected in one of the major permeability barriers in the field (Burnison and others, 2017b), illustrating the utility of this verification strategy.

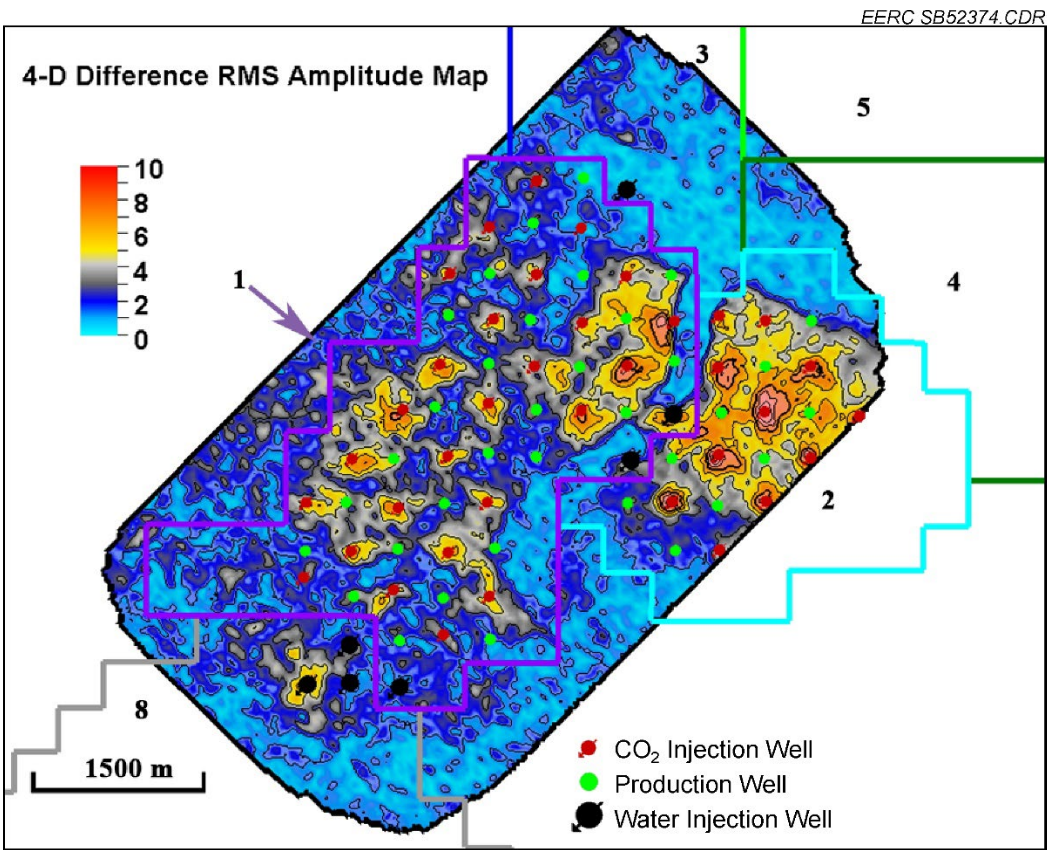

Figure 2-6. Time-lapse 3D seismic RMS (root mean square) amplitude map at Bell Creek; the distribution of the free-phase CO_2 (warmer colors) in the oil reservoir is consistent with the permeability barriers (cooler colors) identified from Figure 2-5 (Burnison and others, 2017b).

2.3.3.2 InSAR

Another commercial method, typically used for monitoring subsidence (i.e., because of fluid extraction), is InSAR. InSAR is applied in this case for measuring positive ground deformation related to the change in pressure within the oil reservoir (i.e., because of CO_2 injection). InSAR is a satellite-based method that uses high-density measurements from radar to estimate relative ground surface deformation (U.S. Geological Survey, 2018). InSAR data were analyzed for

Phase 4 of the Bell Creek project (Table 2-1) and despite challenging terrain, the processed data showed an observable difference in the cumulative ground surface deformation (millimeter scale). Historic InSAR data provided baseline surface measurements and compared with data through injection operations, as shown in Figure 2-7. The InSAR data improved the calibration of the geomechanical model developed for the Bell Creek Field and indicated that the inverted reservoir pressure information from InSAR could be used to locally constrain distributions of reservoir pressures (Reed and others, 2018). The data also provided a supplemental data set for verifying the location of pressure changes resulting from CO_2 injection in the oil reservoir.

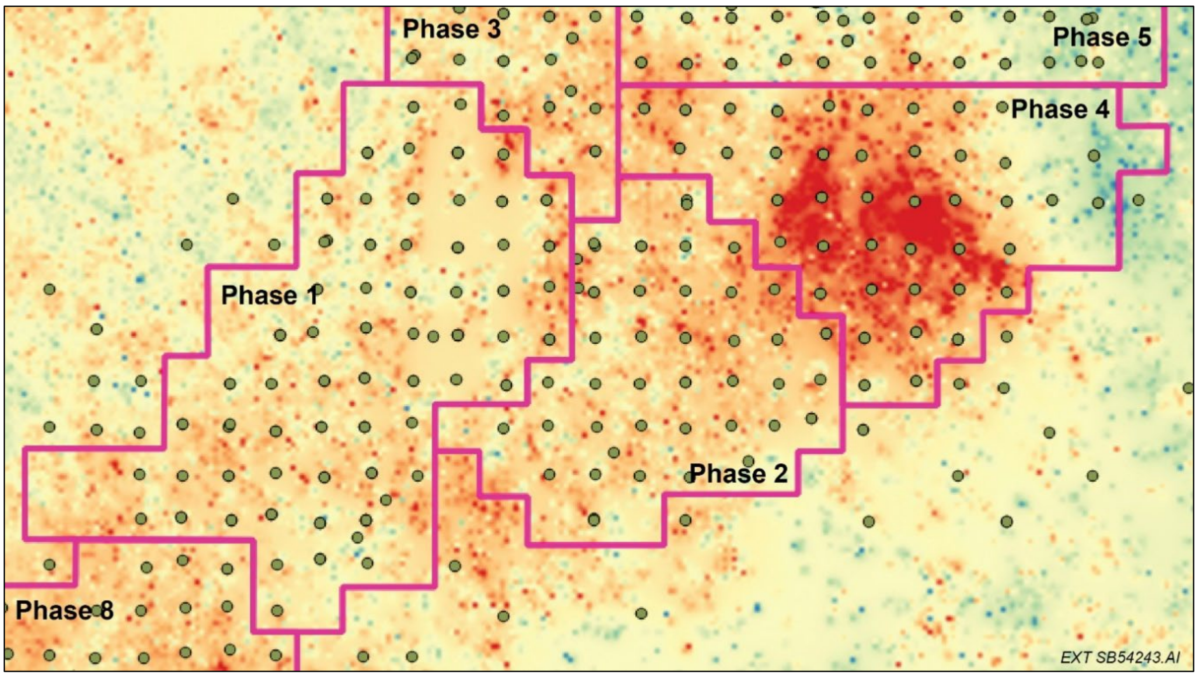

Figure 2-7. Cumulative ground surface deformation at Bell Creek after Phase 4 injection of CO_2; warmer colors indicated more positive ground surface deformation (Reed and others, 2018).

2.3.3.3 Novel MVA Strategies at Bell Creek

Two novel geophysics methods in MVA were field-tested at Bell Creek: SASSA (Burnison and others, 2017a) and the Krauklis wave (Burnison and others, 2018).

Scalable, automated, [sparse] seismic array (SASSA) (Burnison and others, 2017a) developed by the EERC provides strategic sparse monitoring of changes in CO_2 saturation. The SASSA method includes a sparse surface seismic array with a stationary or semipermanent source that can collect data autonomously at any desired frequency for incrementally verifying the location of CO_2 in a storage reservoir. Figure 2-8 provides an example of SASSA results at Bell Creek. Results from SASSA show how the data can be incorporated with dynamic reservoir

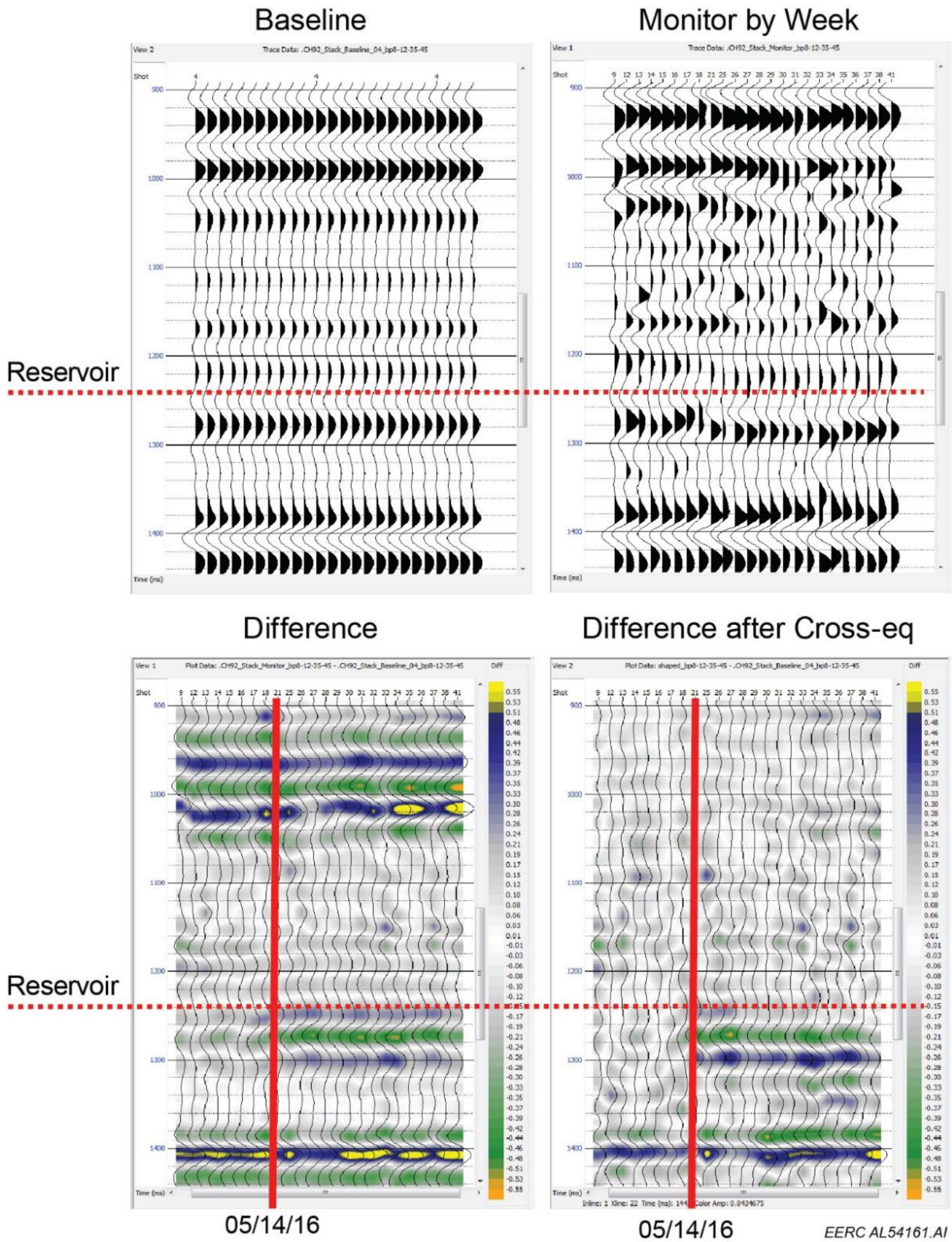

Figure 2-8. Example results of SASSA at Bell Creek.

simulations on a weekly basis to improve understanding of the CO_2 plume's migration in the storage reservoir (Richards and others, 2022). The SASSA method also successfully demonstrated a way for collecting seismic data more frequently (weekly) and sustainably (Burnison, 2017) saving on acquisition costs and maintaining a lower impact on the environment.

The Krauklis wave, or K-wave, is seismic energy that travels laterally in fluids bounded by elastic media (Burnison, 2017). The purpose of the K-wave method, which uses a wellhead-mounted source to propagate seismic energy down the wellbore and through any well perforations, is to detect the CO_2 saturation front as it migrates through the target reservoir. The K-wave method applied at Bell Creek, which was developed by Seismos, Inc. (Austin, Texas), is explained in Burnison and others (2018). Field testing at Bell Creek and modeling of seismic source energy strengths showed attenuation levels at the well perforations were higher than expected, resulting in an inability to produce a detectable signal at the receivers (Burnison and others, 2018).

2.3.3.4 Accounting Strategy at Bell Creek

EPA created MRV (*monitoring*, reporting, and verification) plan regulations under 40 CFR Part 98 "Greenhouse Gas Reporting Program," Subparts RR and UU, for reporting annual progress of and changes to CCUS projects. A primary purpose of the MRV plan is to ensure CO_2 volumes stored in the subsurface are properly accounted for to qualify CCUS projects for IRS 45Q tax credits. The MRV plan may be optional for CO_2 EOR project operators (Subpart UU) but is required for all geologic CO_2 storage permits (Subpart RR) in order to qualify for the 45Q tax credit.

EPA's MRV plan accounting procedures remain the standard for accounting practices in MVA today and are essentially a collection of equations for mass (material) balance and a set of rules specifying when certain equations must be applied (40 CFR Part 98, Subparts RR and UU). Denbury Resources, Inc. (Plano, Texas), the operator of the Bell Creek Field, has submitted MRV plan updates to EPA to receive 45Q tax credits under Subpart UU (Noël, 2018). Mass flows of CO_2 at Bell Creek are continuously monitored with surface facilities and well equipment (e.g., mass/volumetric flowmeters), and the remaining monitoring and verification strategies provide evidence to support the calculations. Figure 2-9 illustrates the percentage of CO_2 emitted from the closed-loop system in terms of relative (unitless) volumes of CO_2.

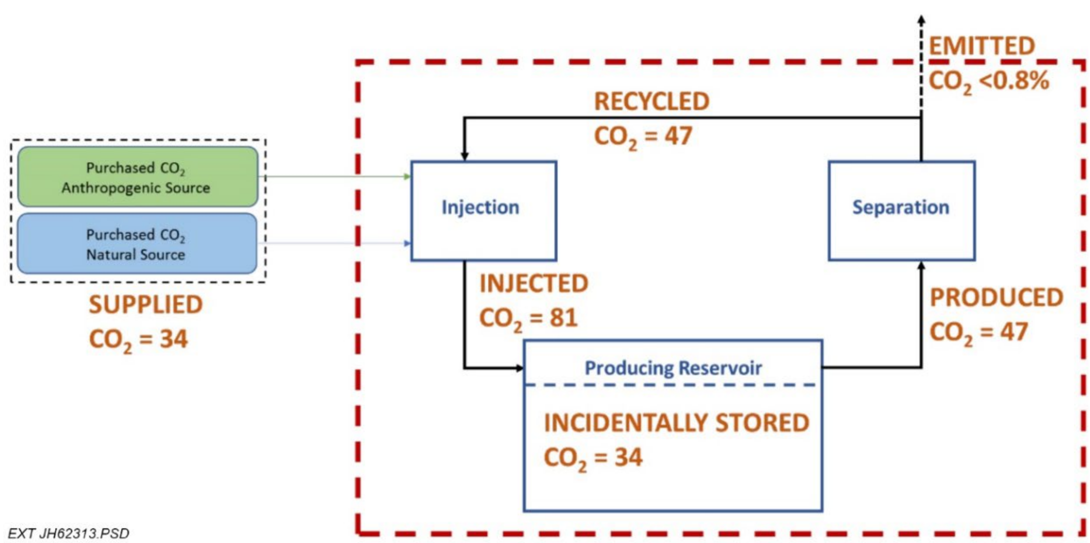

Figure 2-9. Material balance of the CO_2 accounting system at Bell Creek; unitless volumes are for illustrative purposes only (National Petroleum Council, 2019).

2.3.4 Aquistore

The Aquistore project (2009–Present), located near the town of Estevan, Saskatchewan, Canada, is a large-scale geologic CO_2 storage and demonstration project that has stored over 395,000 metric tons of CO_2 in a deep saline sandstone formation. The CO_2 is sourced from the SaskPower Boundary Dam coal-fired power plant located near Estevan along the U.S.–Canada border. Aquistore is an independent research and monitoring project managed by the Petroleum Technology Research Centre (PTRC), Regina, Saskatchewan. The central goal of the Aquistore project is to demonstrate that geologic CO_2 storage in a deep saline sandstone reservoir is a safe and workable solution for mitigating greenhouse gas emissions (Black and others, 2016). Under the PCOR Partnership Phase III program, the EERC led activities for geologic modeling and simulations and core analysis (2009–2013) that informed the MVA strategic plan (Peck and others, 2014).

The MVA strategic plan for the Aquistore project was developed and is currently managed by PTRC, with support from project partners. PTRC uses the term MMV (measurement, monitoring, and verification). The MMV plan for the Aquistore project is summarized in Figure 2-10.

Over 50 publications on the research and results of the MMV plan at Aquistore exist in peer-reviewed journals (Petroleum Technology Research Centre, 2022); therefore, discussion of MMV practices employed at Aquistore is limited to those that have not yet been introduced in this report and represent novel methods for CCUS projects in the PCOR Partnership region at the time. Such activities include 1) atmospheric monitoring, 2) piezometer and stable carbon isotope measurements from shallow groundwater wells, 3) continuous sampling and stable and radiogenic carbon isotope analyses of soil gas, 4) microseismicity monitoring with distributed acoustic sensing (DAS), 5) installation of an array of geophones and seismicity stations for seismicity monitoring, 6) reservoir fluid sampling with a novel fluid recovery system (FRS), and 7) time-lapse surface and borehole gravity surveys.

2.3.4.1 Atmospheric, Soil Gas, and Shallow Groundwater Monitoring

The Aquistore project employed a robust groundwater-sampling program, obtaining three baseline measurements from 40 existing groundwater wells that were either used for domestic purposes or owned by SaskPower and 20 groundwater wells that were drilled for the CCS project (Worth and others, 2014). All samples were tested for composition (i.e., major cations/anions and trace metals) as well as oxygen and stable carbon isotopes. Piezometers were also installed in the groundwater wells to continuously measure pressure changes within each of the shallow groundwater aquifers. Testing for isotopes in the groundwater was important for upgrading the monitoring strategy to a verification strategy, as the isotopes combined with the other geochemical analyses provide a more deterministic means of attributing source. Isotopic sampling of groundwater and soil gas samples is a recommended approach for any CCUS project, according to DOE NETL's (2017) Best Practices Manual.

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AQUISTORE MEASUREMENT AND MONITORING TECHNOLOGIES

	SURFACE	SHALLOW SUBSURFACE	DOWNHOLE INSTRUMENTATION	SEISMIC
MONITORING TECHNOLOGIES	Tiltmeters	Piezometers	Fibre-optic distributed temperature systems (DTS)	Cross-well seismic tomography
	inSAR satellite interferometry	Groundwater chemistry monitoring	Fibre-optic distributed acoustic systems (DAS)	Broadband seismography
	Electromagnetics	Soil-gas monitoring	Fluid recovery system	Permanent 650 geophone areal seismic array
	GPS	Multi-species atmospheric surveys	Pressure gauges	Time-lapse 3D seismic imaging
	Gravimeters		Temperature gauges	Continuous passive microseismic monitoring
	Inherent tracers		Pulsed neutron decay (PND) and cross dipole sonic logging	Vertical seismic profiling (VSP)
			Borehole gravity	Accurately controlled, routinely operated signal system (ACROSS)
PURPOSE OF MONITORING	Surface deformation	Ground water and soil changes	Geophysical logging to measure changes from injection	CO_2 plume location
		Near-surface atmospheric changes	Cross-well electrical and seismic tomography	Induced seismic activity
			Rock-fluid properties	Geological changes
			Reservoir fluid chemistry	

Figure 2-10. MMV plan summary for Aquistore (Petroleum Technology Research Centre, 2022).

Lessons learned from the Kerr case, in which a surface owner mistakenly claimed there was CO_2 leakage from the CO_2 EOR operation at the Weyburn–Midale oil field (Romanak and others, 2013), prompted stable and radiogenic carbon isotopic sampling as additions to measurements of soil gas flux for the soil gas program at Aquistore. Soil gas measurements were also taken continuously, creating a much more detailed background data set for future comparisons than previous CCUS projects had implemented. A total of 50 semipermanent probes were installed for the Aquistore project (Worth and others, 2014). As with the groundwater-sampling program, the soil gas-monitoring strategy was upgraded to a verification strategy with the addition of the stable and radiogenic carbon isotope data.

Atmospheric sampling was carried out for the Aquistore project to supplement the soil gas-sampling program. Equipment was mounted on a truck that conducted a drive-around survey, collecting multispecies flux measurements from the atmosphere every 10 to 20 meters of accessible road throughout the project site (Worth and others, 2014). CO_2 detection stations were also mounted on the injection wellhead to detect any leakage at the surface (Global CCS Institute, 2015). Both sampling techniques were novel methods in CCUS MVA at the time.

All publicly available reports containing information about the sampling programs discussed in this section have given no indication of CO_2 leakage at the surface.

2.3.4.2 *Seismicity and Microseismicity Monitoring*

A permanent surface seismic array, consisting of 630 geophones buried approximately 30 meters beneath the ground surface, was installed at Aquistore for 2D and 3D time-lapse seismic monitoring. A total of 50 of the 630 geophones are also capable of providing continuous passive seismicity monitoring at the project site (Worth and others, 2014). In addition, three broadband seismographs were installed at the project site (White and others, 2014). Together, these efforts provide a detection capability for events near to or as low as a magnitude of 0.6 (Stork and others, 2018).

The CO_2 injection well and deep monitoring well completed for the Aquistore project had DTS and DAS fiber installed along the lengths of the wellbores, supplementing seismicity monitoring and seismic acquisition efforts while also providing the potential for continuous microseismicity monitoring (confirmed with a 35-day test) around the near-wellbore environment (White, 2019).

Based on a review of the publications available, the Aquistore project has detected no injection-related induced seismicity (e.g., Stork and others, 2018; White and others, 2016).

2.3.4.3 *Fluid Reservoir Sampling*

Similar to what was done at the North Dakota lignite field test (Section 2.2.2), Aquistore sampled storage reservoir fluids periodically in the deep monitoring well to correlate conductivity changes with temperature and pressure changes in the reservoir obtained from permanently installed downhole gauges (Worth and others, 2017). The FRS was a downhole device specifically designed for the Aquistore project to characterize fluid compositions before and after CO_2 injection.

Figure 2-11 illustrates the effect of CO_2 on conductivity as measured in the deep monitoring well, illustrating the value of the FRS tool to provide information on the CO_2–brine interactions in the storage reservoir.

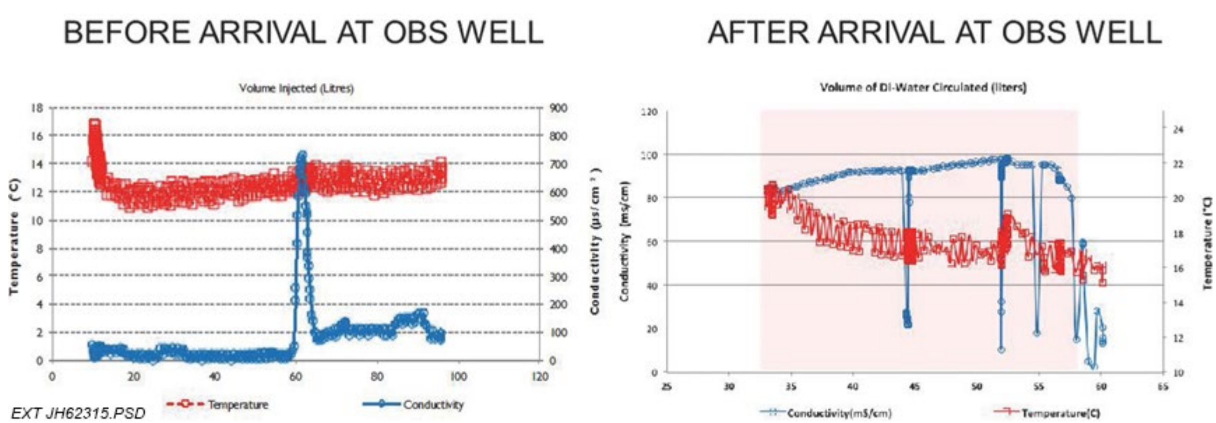

Figure 2-11. Example of how CO_2 affects conductivity in the storage reservoir, as measured in the deep monitoring well at Aquistore (Worth and others, 2017).

2.3.4.4 *Time-Lapse Gravity Surveys*

Surface and borehole gravity surveys were collected for verifying containment of CO_2 in the storage reservoir at Aquistore (Worth and others, 2014). The anticipated change in gravity response for injecting CO_2 into the storage reservoir was on the order of a few microgallons, while any out-of-zone migration would be expected to produce changes on the order of tens of microgallons. Several baseline surface gravity surveys were collected over the project site, but results were not consistent with modeled expectations. The baseline gravity response was much higher than anticipated, which was attributed to natural (seasonal) changes in groundwater levels (White, 2019). The results of the surface gravity data were limited, since the data could not be readily used to differentiate a leakage signal from "normal" injection operation conditions; therefore, a follow-up surface survey was not conducted.

A borehole gravity survey was acquired in the deep monitoring well after injection operations had begun. Because no baseline borehole gravity survey data were available, Black and others (2016) compared borehole gravity densities with openhole log densities. The results of the analysis indicated that future borehole surveys would provide useful information about density changes detected in the near-wellbore environment (White, 2019).

2.3.5 Synthesis of Phase III MVA Activities

The larger demonstration projects in Phase III required a much greater effort to design and implement the MVA strategic plans. The focus of MVA activities in Phase III was to further develop lower-cost, lower-impact, and more continuous data-sampling methods for verifying containment in the storage reservoir using both off-the-shelf and novel geophysics-based technologies.

The novel MVA activities applied at Bell Creek (i.e., K-wave and SASSA) could not verify containment of CO_2 in the storage reservoir because of technological limitations at the time, while novel activities applied at Aquistore generally met project objectives to verify containment and provide low-impact and more continuous data-sampling solutions. More continuous, on-demand data-monitoring solutions, real-time data gathering advanced during this project demonstration period with inclusion of 1) continuous soil gas monitoring at Aquistore, 2) introduction of a process-based approach to soil gas analysis for CCUS projects (Romanak and others, 2012), and 3) installation of fiber optics and buried surface seismic arrays for time-lapse seismic and passive seismicity/microseismicity monitoring at Bell Creek and Aquistore.

All the demonstration projects either incorporated the AMA (Ayash and others, 2017) or applied an equivalent set of site characterization, geologic modeling and simulation, and risk assessment activities to inform the MVA strategic plan (Peck and others, 2014). From the focus on the application of geophysics-based approaches to verify CO_2 containment, it seems that near-surface sampling and analysis techniques took a backseat until the events of the Kerr case (Weyburn–Midale, discussed in Section 2.5.1), which prompted application of more analytically robust and deterministic techniques at Aquistore (e.g., measuring soil gas and groundwater composition fluxes combined with isotopic data sets).

The demonstration projects, except at Bell Creek, did not generate (or at least not document) much information on how to develop or implement CO_2 accounting strategies. While the method of mass/material balance seems straightforward, documentation providing any justification for accounting practices is lacking. The authors of this report estimate that less than 10% of papers written on MVA reviewed, consisting of about a dozen examples, actually discuss accounting practices beyond specifying "accounting" in the term MVA. EPA's MRV plan seems to be the standard for accounting and reporting practices that have been adopted for projects in the United States. EPA MRV accounting practices are recommended as the only accounting strategy in the DOE NETL (2017) Best Practices Manual. CARB accounting requirements stipulate that project operators must quantify any leakage that is detected outside the storage reservoir *and verify the amount of CO_2 leakage*, in addition to taking corrective action (CARB LCFS Carbon Capture and Sequestration Protocol, Chapter C, Section 2.4.4 "Plume Extent Reevaluation," subsections [d] and [d][1–2]); therefore, there exists the opportunity for accounting practices to evolve and be guided by monitoring and verification strategies.

There are no documented cases in the real world where CO_2 was detected outside the storage reservoir, quantified in the subsurface, and subsequently verified for a CCUS project. If the CARB requirement for quantifying and verifying subsurface leakage is to be met with a high degree of certainty, monitoring and verification strategies will have to continue to improve toward providing more frequent, clearer, and real-time depictions of subsurface conditions. Importantly, the solution to this accounting problem will be driven primarily by the evolution of next-generation monitoring and verification strategies.

2.4 First Wave of Incentive-Driven CCS Projects in North Dakota

2.4.1 CCS Projects in North Dakota

North Dakota was the first U.S. state to receive Class VI primacy from EPA in 2018. With the expansion of IRS tax credits through Section 45Q around the same time and the introduction of other incentive programs like CARB, North Dakota was well-positioned to receive the first wave of projects from commercial companies looking to invest in CCS. As of writing this report, three Class VI well permits have been developed and approved by the regulatory authority in North Dakota, the North Dakota Industrial Commission (NDIC). The first permit was issued to Red Trail Energy (RTE) near the end of the third-quarter 2021, while two others, both belonging to Project Tundra, were issued in the first quarter of 2022. The Great Plains CO_2 Sequestration Project, the fourth Class VI well permit in the state, is currently being considered for approval by NDIC. The EERC, with its nearly 20 years of experience in CCUS research and application through the PCOR Partnership, led or co-led the development of all four permits.

Figure 2-12 provides summaries for the three projects, and Table 2-2 summarizes the similarities and differences in MVA activities at each of the project sites.

Figure 2-12. Summaries of the RTE CCS Project, Project Tundra, and the Great Plains CO_2 Sequestration Project (modified after Hamling and others, 2022).

Table 2-2. MVA Strategic Plan Summaries for the RTE CCS Project, Project Tundra, and the Great Plains CO_2 Sequestration Project

Plan		Monitoring Type	RTE Activity	Project Tundra Activity	DGC[1] Activity	Target Structure/Area
Surface Plan		CO_2 Stream Analysis	Periodic compositional and isotopic analysis of the CO_2 stream at liquefaction outlet	Periodic compositional and isotopic analysis of the CO_2 stream upstream or downstream of the flowmeter	Periodic compositional analysis of the CO_2 stream from capture facility compressors	Capture facility compressor(s) or liquefaction outlet
Surface Plan		Mass Flow Calculations (e.g., flow rates, volumes, and surface and downhole temperature and pressures)	Volumetric flowmeters and pressure gauges on surface equipment (from start to end of CO_2 flow line)	Volumetric flowmeters and pressure gauges on surface equipment (from start to end of CO_2 flow line)	Mass flowmeters and pressure gauges on surface equipment (from start to end of CO_2 transmission line)	CO_2 flow line and injection wellhead(s)
Surface Plan		Atmospheric Monitoring	CO_2 detection station at flow line riser for continuous monitoring; periodic gas analyzer sample blanks at each soil gas profile station (SGPS)	CO_2 detection station at injection wellhead and flow line riser for continuous monitoring; periodic gas analyzer sample blanks at each SGPS	H_2S detection stations for continuous monitoring installed at injection wellheads, outside wellhead enclosures, and flow line risers	Outside of wellhead enclosures and flow line risers
Surface Plan		Flow Line Leak Detection	Continuous monitoring via fiber-optic cable (DTS, DAS, DSS) buried with the flow line detectors at injection wellhead; mass balance between flowmeters at either end of the flow line, with automatic alarms and shutoffs	Continuous monitoring via fiber-optic cable (DTS/DAS/DSS) buried with the flow line; mass balance between flowmeters at either end of the flow line, with automatic alarms and shutoffs	Mass flow balance with automatic alarms and options to shut-in operations	CO_2 flow line
Surface Plan		Well Equipment Leak Detection	CO_2 detection station at injection wellhead and flow line riser for continuous monitoring; fiber-optic cable installed along the flow line riser and in the injection wellhead	CO_2 detection station at injection wellheads and flow line risers for continuous monitoring	H_2S detection stations at injection wellheads and outside well enclosures; pressure gauges and flowmeters placed at either end of the flow line	Wellsite flow line to wellhead
Surface Plan		Surface Corrosion	Periodic flow-through corrosion coupon testing of the flow line and well materials	Periodic flow-through corrosion coupon testing of the flow line and well materials	Periodic ultrasonic testing of tubing test sections installed at injection wellheads	Wellsite flow line to well infrastructure
Subsurface Plan	Wellbore	Downhole Corrosion	Periodic ultrasonic testing (material wall thickness) and monitoring packer fluid volumes in injection and monitoring wells	Periodic ultrasonic (material wall thickness) or EM testing and monitoring packer fluid volumes in injection and monitoring wells	Periodic caliper or ultrasonic testing of the injection wells; continuous monitoring of packer fluid, with constant pressure applied to tubing–casing annulus and nitrogen cushion	Downhole tubing and casing strings
Subsurface Plan	Wellbore	Internal and External Mechanical Integrity Testing	Continuous temperature data from casing-conveyed P–T gauges and DTS/DAS/DSS[2] fiber; periodic tubing–casing or casing pressure testing and ultrasonic logging in injection and deep monitoring wells	Continuous temperature data from DTS fiber (or temperature logging if fiber fails; periodic tubing–casing or casing pressure testing,	Periodic temperature logging, tubing–casing pressure testing, and ultrasonic logging in all injection wells	Well infrastructure
Subsurface Plan	Environmental	Near-Surface	Periodic sampling and compositional and isotopic analyses of soil gas (two SGPSs and multiple probe locations), shallow groundwater (two wells), and lowest USDW (two wells)	Periodic sampling and compositional and isotopic analyses of soil gas (three SGPSs), shallow groundwater (up to 18 wells), and lowest USDW (one well)	Periodic sampling and compositional and isotopic analysis of soil gas (11 SGPSs), shallow groundwater (three wells), and lowest USDW (seven wells)	Vadose zone, shallow groundwater, and lowest USDW
Subsurface Plan	Environmental	AZMI	Periodic PNL in the injection and deep monitoring wells	Periodic PNL in the injection and deep monitoring wells	Periodic PNL; digital annular pressure gauges for continuous monitoring in all injection wells	Surface-to-AZMI
Subsurface Plan	Environmental	Direct Reservoir	Periodic PNL; continuous casing-conveyed P–T gauges, and DTS/DAS/DSS fiber in the injection and deep monitoring wells; periodic pressure falloff testing in the injection well	Periodic PNL; continuous tubing-conveyed P–T gauges and DTS fiber in the injection and monitoring wells; periodic pressure falloff testing in the injection well	Periodic PNL, pressure falloff testing, and BHP/T[3] readings to confirm continuous WHP/T[4]–BHP/T correlation monitoring	Storage reservoir and dissipation intervals
Subsurface Plan	Environmental	Indirect Reservoir	Time-lapse seismic surveys with SASSA and 3D VSPs, surface gravity surveys; continuous monitoring with InSAR, DSS fiber analysis, and eight seismometers	Time-lapse 2D/3D seismic surveys and 3D VSPs; continuous monitoring with InSAR and seismometers	Time-lapse 2D seismic surveys and VSPs	Entire storage complex

[1] Dakota Gasification Company.
[2] Distributed strain sensing.
[3] Bottomhole pressure/temperature.
[4] Wellhead pressure/temperature.

2.4.1.1 *Red Trail Energy CCS Project*

RTE is a 64-million-gallon dry mill ethanol production plant located outside of Richardton, North Dakota. The plant produces approximately 180,000 metric tons of CO_2 per year from the corn feedstock-to-ethanol production process. RTE will capture and inject the 180,000 metric tons of CO_2 generated at the plant annually into a deep saline sandstone reservoir near the RTE facility over a 20-year period. The RTE CCS Project was the first approved CCS project in North Dakota. Injection operations are set to begin in the second or third quarter of 2022.

DOE, NDIC, and the PCOR Partnership have provided funding for storage site development and commercial demonstration of novel monitoring techniques, including SASSA, InSAR, passive seismicity, and DTS/DAS fiber optics, all of which were tested at some capacity during PCOR Partnership Phase III activities. A novel approach in MVA that will be tested at RTE includes DSS.

Fiber-optic cables equipped with DSS are installed in the CO_2 injection well, deep monitoring well, two groundwater-monitoring wells and CO_2 flow line. DSS data, which are obtained from additional processing of DAS, will be used to derive pressure for integration with recorded surface and downhole pressures. The data set aims to provide RTE with a real-time, continuous solution for monitoring pressures along the length of the wellbores and flow lines. Results from the MVA strategy are not yet available for discussion in this report.

2.4.1.2 *Project Tundra*

Minnkota Power Cooperative (Minnkota) operates a 734-megawatt lignite coal-fired power plant, which produces approximately 4 million metric tons of CO_2 per year. Minnkota will capture and inject that amount of CO_2 into the subsurface for a 20-year period, targeting two separate deep saline sandstone formations for permanent stacked storage.

Project Tundra is funded under DOE's Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative (currently in Phase III). Project Tundra is the first CCS project to gain approval for a stacked storage opportunity, thereby requiring two North Dakota storage facility permits for the project. The MVA plan for the stacked storage opportunity is the same as a single storage opportunity but with the addition of injection wells and monitoring wells to accommodate two storage reservoirs overlying one another. The MVA strategic plan developed for Project Tundra is also unique in that Minnkota will apply a phased approach for all near-surface monitoring efforts, meaning that as the CO_2 plume expands in the storage reservoir, the near-surface sampling and analysis program will expand in size and effort to ensure safe operations and provide evidence of containment. Figure 2-13 provides an example of the phased approach for near-surface activities.

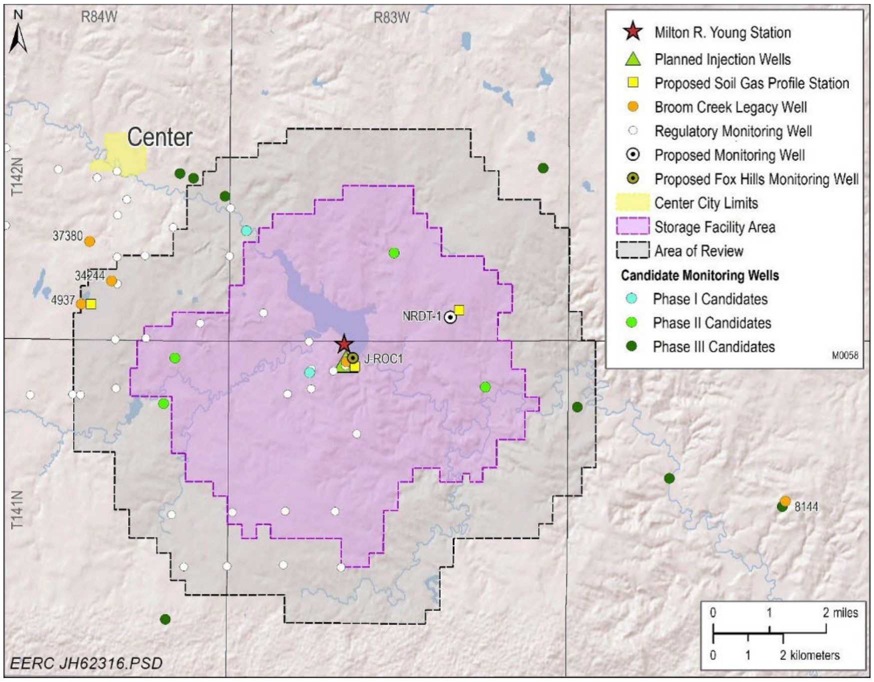

Figure 2-13. Map illustrating the phased approach to near-surface sampling for Project Tundra (Source: Minnkota's North Dakota Broom Creek storage facility permit).

The storage location, similar to the Aquistore project, also benefits from an existing groundwater-sampling program operated at the coal mine which has established historic baselines of geochemical conditions all throughout the near-surface environment.

2.4.1.3 Great Plains CO_2 Sequestration Project

The Great Plains CO_2 Sequestration Project is located near the town of Beulah, North Dakota. DGC, a wholly owned subsidiary of Basin Electric Power Cooperative, operates a lignite coal gasification plant capable of gasifying over 6 million metric tons of lignite coal per year. DGC will capture between 1.0 and 2.7 million metric tons of CO_2 annually for injection into a deep saline sandstone formation with six injection wells located near the gasification facility over a 12-year period.

The CO_2 stream has about 1% H_2S by volume, allowing a unique opportunity for atmospheric monitoring at the Great Plains CO_2 Sequestration Project site. In this case, H_2S detection quickly attributes source while avoiding quantification of a highly variable CO_2 signal in the atmosphere as means for detecting signs of leakage at the surface.

Similar to Project Tundra, DGC has benefitted from a shallow groundwater-monitoring program operated by a coal mine that supplies the feedstock for its gasification operations. Coteau Properties Company (CPC) owns and operates the Freedom Mine near the DGC facility and has drilled over 500 groundwater-monitoring wells, many of which have decades of geochemical information from the groundwater being monitored for the active mining operation.

The Great Plains CO_2 Sequestration Project site is located near an active mining operation, introducing the potential for challenges related to land accessibility and ground coupling for acquiring time-lapse 3D seismic surveys. Therefore, the project operator chose to deploy a unique geophysical approach for tracking the CO_2 plume in the subsurface for a CCS project. As Figure 2-14 illustrates, the seismic survey design involves shooting 2D seismic lines in multiple azimuthal directions (each approximately 45 degrees apart), creating a "spokes on a wagon wheel" appearance. The result is a compromise between data coverage and land accessibility concerns.

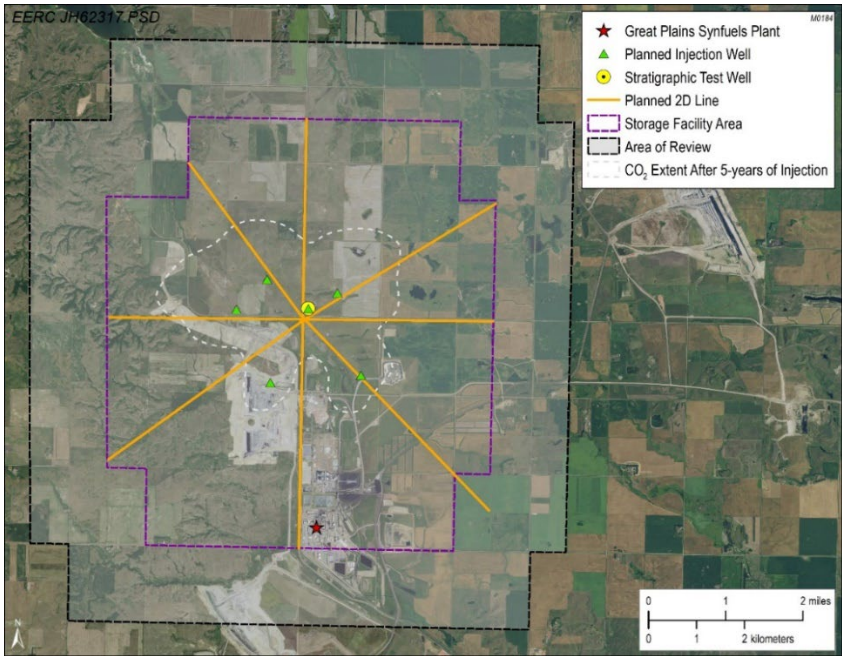

Figure 2-14. Example of a planned radial 2D seismic survey for the Great Plains CO_2 Sequestration Project (Source: DGC's North Dakota storage facility permit).

The Great Plains CO_2 Sequestration Project is also unique because there is no dedicated reservoir-monitoring well for the project. Instead, the project takes advantage of using the injection wells (up to six) to monitor early-time operations. For late-stage injection operations, the storage operator will take advantage of two existing Class I injection wells, ANG #1 and ANG #2, located south of the DGC's gasification facility (Great Plains Synfuels Plant) which currently inject wastewater into the storage reservoir (beyond the influence of the stabilized CO_2 plume boundary).

2.4.2 Synthesis of First-Generation CCS Projects in North Dakota

A clear difference between the first wave of CCS projects in North Dakota and the pilot programs and field demonstration projects completed previously under the PCOR Partnership is the overall shift in mindset from research to a commercial focus. This is expected, as the purpose of the field demonstrations was to provide a set of viable options for commercial CCUS projects, and to establish the technical foundation for the current commercial CCUS industry. Still, novel methods were introduced to the RTE CCS Project, Project Tundra, and the Great Plains CO_2

Sequestration Project. In general, the push toward implementing novel solutions arose from site-specific conditions and circumstances (e.g., active mining operations causing concerns about performing repeated seismic data acquisitions). Project partners may have also been willing to sponsor additional research at a CCS project site (e.g., SASSA and DSS monitoring at RTE), and project operators' preferences played a role as well (e.g., Minnkota chose to implement a phased near-surface sampling and analysis approach). While an overarching goal for any project operator applying for a geologic CO_2 storage permit is to have the project approved by the regulating authority, the site-specific circumstances and project operator preferences clearly drove the need for implementing new MVA practices, following after the expectations of the AMA (Ayash and others, 2017).

Despite the stacked storage opportunity for Project Tundra necessitating two North Dakota storage facility permits, the MVA strategic plan presented in both permits is identical because the same environments must be monitored over the same area with the same set of site-specific conditions. MVA activities are nearly identical too, with only the injection well and (deep and near-surface) monitoring well locations changing between plans. The overall MVA *strategy* should stay the same across all CCS projects, whether in conventional vs. unconventional or single vs. stacked storage reservoirs. Differences may arise in the MVA *practices* as site-specific conditions warrant (e.g., large differences in injection volumes and/or rates between stacked storage reservoirs or little difference in depth between stacked reservoirs).

2.5 MVA Strategies for Other CCUS Projects in the PCOR Partnership Region

The CCUS projects discussed up to this point were presented in the order in which they were developed. Two CCUS projects, which fall within the PCOR Partnership region but were not led or co-led under the PCOR Partnership, are discussed next: The IEAGHG Weyburn–Midale Monitoring and Storage Project and the Shell Quest CCS Project.

2.5.1 IEAGHG Weyburn–Midale Monitoring and Storage Project

The IEAGHG Weyburn–Midale Monitoring and Storage Project (2000–2015) was an early research program led by PTRC for demonstrating the safe and long-term storage of CO_2 in a geologic reservoir. The Weyburn–Midale oil field, located in the southeastern portion of Saskatchewan, Canada, has safely and permanently stored over 30 million metric tons of CO_2 for EOR (about 2.8 million metric tons per year) since 2000 (Sacuta and others, 2015). The research was divided into two phases. Phase I (2000–2004) involved site characterization activities, including geologic modeling and simulation work, risk assessment, and MVA strategic planning. Phase II activities (2005–2015) involved implementing a MVA strategic plan, referred to as a MMV plan for Canadian CCUS projects.

The approach to developing the MMV plan at Weyburn–Midale was to focus on geophysical and geochemical monitoring of the oil reservoir and wellbores. Table 2-3 summarizes the MMV strategic plan.

Table 2-3. MMV Strategic Plan Summary for the IEAGHG Weyburn–Midale Monitoring and Storage Project

Activity Description	MVA Type	Frequency	Target Structure/Area	Primary Purpose
Surface Facilities				
Mass Flow Calculations (flowmeter)	A	Continuous, real time	CO_2 flow line/injection wellheads	CO_2 accounting
Wellhead Pressure and Temperature	M	Continuous, real time	CO_2-Injection Wells	Leak detection near/at wellheads
Near-Surface				
Soil Gas Flux and Isotopic Analysis	V	Periodic and continuous sampling	>500 locations	Soil gas monitoring
Groundwater Flux Analysis	M	Periodic Sampling at each location	>60 wells (potable water)	Groundwater (to lowest USDW) monitoring
Deep Subsurface				
Casing and Tubing Pressure Testing	M	Periodic	Injection and deep monitoring wells	Wellbore integrity monitoring
Wellbore Integrity Logging (caliper, cement bond, and ultrasonic tools)	V	Periodic	Injection and deep monitoring wells	Verification of containment near the wellbore environment
Chemical Analysis of Reservoir Fluids	M	Periodic	Injection and deep monitoring wells	Containment in storage reservoir monitoring
Time-Lapse 3D Seismic Surveys	V	Periodic	Weyburn–Midale Field	Verification of containment in storage complex
InSAR[1]	M	Periodic	Weyburn–Midale Field	Containment in storage complex monitoring
Forward Seismic Modeling[1]	M	Periodic	Weyburn–Midale Field	Containment in storage complex monitoring
LEERT[1]	M	Periodic	Weyburn–Midale Field	Containment in storage complex monitoring
Gravity Surveys[1]	M	Periodic	Weyburn–Midale Field	Containment in storage complex monitoring
Downhole Microseismicity with Permanently Installed Triaxial Geophones	M	Continuous, real time	Weyburn–Midale Field (eight geophones installed in one vertical well)	Microseismicity monitoring
Passive Seismicity with three broadband seismometers	M	Continuous, real time	Weyburn–Midale Field	Seismicity monitoring

[1]Feasibility studies only.

Near-surface efforts to characterize CO_2 levels in the groundwater and soil gas proved to be one of the most important activities for the IEAGHG Weyburn–Midale Monitoring and Storage Project because of a landowner claiming CO_2 was leaking from the project site (e.g., Romanak and others, 2013). The sampling methodology, which included using a process-based approach for attributing CO_2 source in soil gas (Romanak and others, 2012) coupled with isotopic measurements, proved that no leakage had occurred at the site (Sacuta and others, 2015).

Time-lapse seismic provided the most useful results for locating the CO_2 plume in the subsurface. The results of the seismicity-monitoring effort were that no seismic events were detected with the broadband seismometers installed at the site (Sacuta and others, 2015). Microseismicity events, ranging between magnitudes of –3 and –1, were recorded by downhole geophones before and during CO_2 injection (White, 2009). The microseismicity events were more often located near production wells, suggesting that the events were due to production rather than injection operations (Sacuta and others, 2015).

Several geophysics-based activities, including InSAR, forward seismic modeling, long electrode electrical resistance tomography (LEERT), and gravity surveys, were considered for application at Weyburn–Midale. Feasibility studies for each of these activities indicated none of them would be successful for the project (Sacuta and others, 2015; White, 2011); therefore, all of them were excluded from the MVA strategic plan.

Results from conducting periodic wellbore integrity tests, including tubing–casing pressure tests, caliper or ultrasonic logging, and chemical analysis of reservoir fluids indicated that the wellbores and seal above the oil reservoir showed no significant signs of degradation (Sacuta and others, 2015).

A clear difference in MVA practices between CO_2 EOR projects and CCS projects discussed so far in this report is fluid sampling from the storage (or target) reservoir. This, of course, is because of the larger number of wells that may already exist for an EOR operation. Another clear difference is the amount of core and log information available to the project operator to leverage throughout the life of the project. At Weyburn–Midale, the project operator did not specify saturation logging operations (e.g., RSTs) as being part of the MMV plan, and instead, relied on time-lapse formation fluid sampling and wellbore corrosion-monitoring methods from the existing data and well set. Well penetrations into the storage reservoir are considered the number one risk to any CCUS project (U.S. Environmental Protection Agency, 2010). However, a larger number of wells can also provide opportunities to apply different MVA practices, including geochemical monitoring of the storage (oil) reservoir. Figure 2-15 illustrates the utility of acquiring time-lapse alkalinity data from the oil reservoir at Weyburn–Midale to verify conditions are not progressing too far in a direction that might cause wellbore integrity issues.

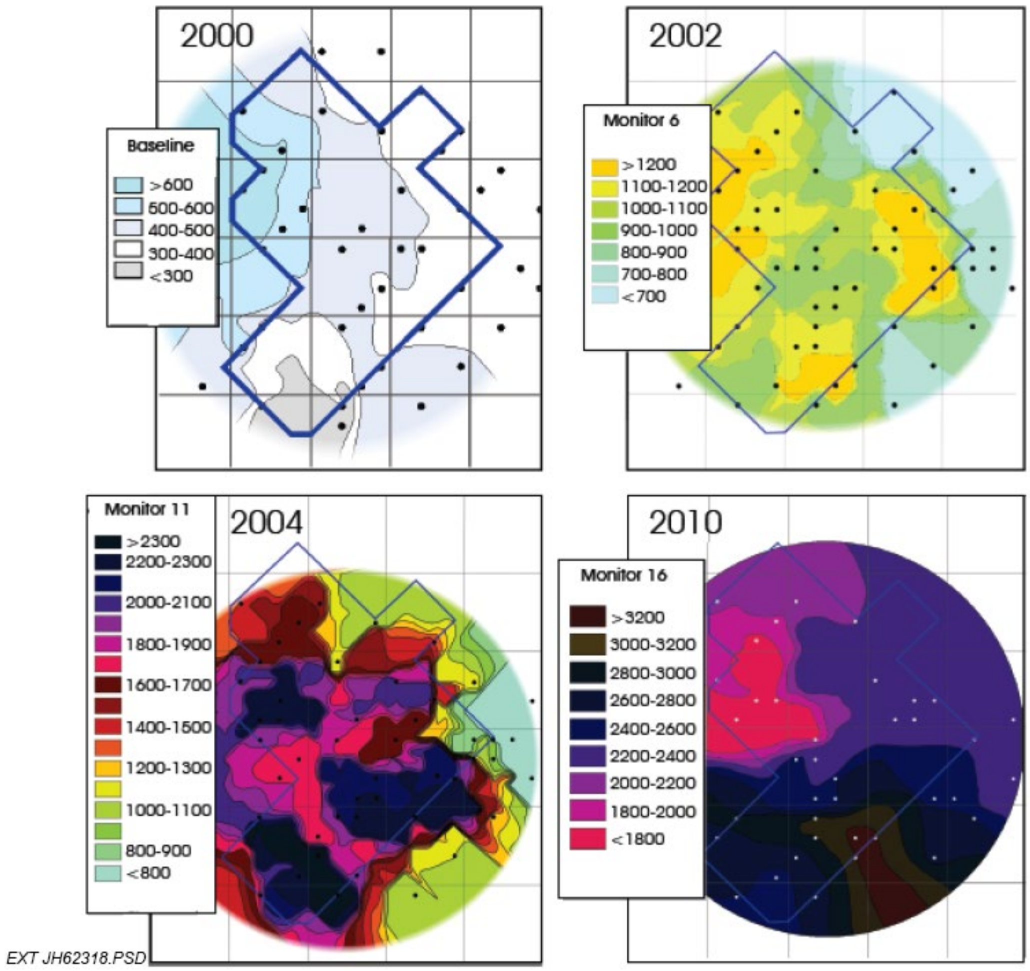

Figure 2-15. Alkalinity changes detected from geochemical sampling of the oil reservoir at Weyburn–Midale (Sacuta and others, 2015).

2.5.2 Shell Quest CCS Project

The Shell Quest CCS Project (2011–present), located near Edmonton, Alberta, has captured and injected about 6 million metric tons of CO_2 in a deep saline sandstone formation since 2015 (Shell, 2022). The CO_2 is sourced from the Scotford Upgrader located near Fort Saskatchewan, Alberta. The Scotford Upgrader is an industrial refining facility that processes Alberta bitumen to produce hydrogen. The purpose of the project is to demonstrate large-scale storage of CO_2 from an industrial source is safe and effective for mitigating greenhouse gas emissions. Site characterization and baseline data collection activities for the Shell Quest CCS Project began in 2011, and injection operations began in 2015. The project had to meet the regulatory standards for CCS created by the Government of Alberta, so the MMV plan developed and implemented in Figure 2-16 follows after the MVA framework developed by the Regulatory Framework Assessment (presented earlier in Figure 1-1). Results from the MMV strategic plan are many, most of which are not presented to keep within the scope of this report. Results of MVA activities

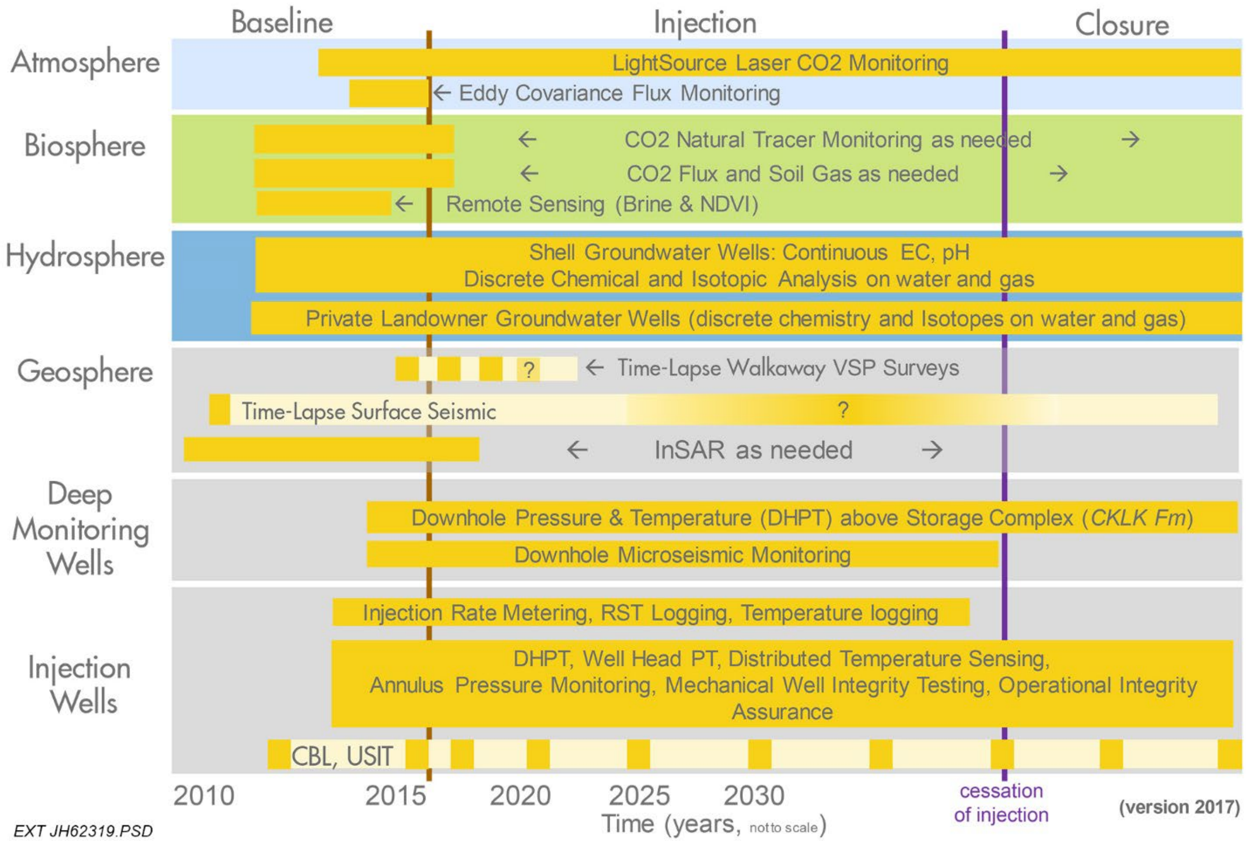

Figure 2-16. MMV plan summary for Shell Quest (Shell Canada Limited, 2017).

that were novel for the time but not previously discussed in this report are discussed. Such activities, which are limited to the atmosphere and surface environments, include 1) atmospheric monitoring with laser-based CO_2 sensors fixed on wellheads, 2) atmospheric monitoring with Eddy covariance flux towers, and 3) remote sensing to detect changes in the water and vegetation.

2.5.2.1 Atmospheric Monitoring

CO_2 levels near the injection well pads are monitored with a laser-based CO_2 gas analyzer installed in one corner and three mirrors placed at the other three corners to create a closed loop. The system is tied to weather station equipment (e.g., anemometer) to record the wind direction and speed continuously (Shell Canada Limited, 2017). To date, no surface leakage has been reported at any of the injection well pads, but the system has been successfully tested with a series of small and controlled surface releases of CO_2 (Hirst and others, 2017).

Eddy Covariance, a method which uses micrometeorological data to detect trends in the flux of atmospheric gases like CO_2 and water, was tested at the Shell Quest CCS Project (Burba and others, 2013). The method was used to collect baseline information, but the results were too variable because of site conditions and difficult to interpret; therefore, the method was not applied once injection operations began (Rock and others, 2017).

2.5.2.2 *Remote Sensing*

Radar-based satellite imagery was used during the baseline period of the Shell Quest CCS Project to characterize surface waters and vegetation with multispectral imaging analysis. The advantage of using a remote-sensing method was the spatial coverage; however, there were concerns regarding the detectability threshold of the remote-sensing technique (Bourne and others, 2014). The plan was to ground-truth the remote-sensing results with soil gas and atmospheric monitoring data. However, the remote-sensing method was not implemented after injection began. The reasoning for this appears to be undocumented but is possibly due to the fact that the instrument proved to not have a detection threshold sufficient for identifying early signs of surface leakage.

2.6 Conclusions

During Phases I through III of the PCOR Partnership, the general approach to MVA was guided by the objectives set by DOE. Each set of objectives built on the previous phase, enlarging the scope of the project and budget. An emphasis was placed on developing and testing MVA methods capable of “seeing” the migration of the CO_2 plume in the storage reservoir in Phase II. The best results for verifying the location of the CO_2 plume were produced from time-lapse seismic surveys and measurements of saturation profiles near wellbores. In Phase III, CCUS policy frameworks and landowner claims of suspected leakage provided project operators with legal objectives and criteria to guide development and implementation of MVA. With the increase in project scope and budget in Phase III, greater attention was given to site characterization, modeling and simulation, and risk assessment activities, all of which guided MVA strategic planning.

In the first wave of CCS projects covered in this report, MVA practices were primarily influenced by policy framework requirements, site-specific conditions, and project operator preferences. In general, MVA practices were selected from Phases I through III of the PCOR Partnership to fulfill policy framework requirements. The projects described in this report have demonstrated compliance with multiple policy frameworks and an overall acceptance of current approaches to MVA by permitting authorities. MVA strategies or the overall goals of MVA should remain the same across all CCS projects, while the selection and evolution of practices/methods will continue to be guided by a set of dynamic factors (e.g., policy framework decisions, site-specific conditions, technology improvements, project economics, and project operator preferences).

3.0 FUTURE DIRECTIONS IN MVA

MVA practices are evolving as research and development programs and commercial CCUS projects move forward. MVA strategic planning should be thought of with an AMA mindset, or the idea that the implementation of effective MVA activities is an iterative process that needs continual reevaluation over time. MVA practices may change (as illustrated in Figure 2-16) as site conditions and circumstances change, new results are analyzed, and models are updated.

Based on the evolution of MVA within the PCOR Partnership region, it is clear there is a continued push for more "sustainable" methods, meaning lower-cost, lower-footprint (lower-impact), and more continuous and real-time data gathering and processing. More work needs to be performed in the real-time data-processing space. Soil gas, groundwater, and even seismic can be acquired autonomously and continuously, and the raw data can be transmitted instantly via the cloud or a cell modem, while data processing is still predominantly a manual process.

Because of the requirements under CARB to quantify and verify any out-of-zone migration of CO_2 from a storage reservoir, monitoring and verification strategies may be under new pressure in the future to provide more precise and quantitative analyses of CO_2 volumes than what traditional accounting practices have required.

In addition to the above insights, recommended future work in MVA strategies includes 1) incorporating Bayesian search theory to develop deep and near-surface fluid-sampling strategies to advance rapid data interpretation and 2) integrating more detailed and quantitatively robust leakage models and hydrogeological models to justify monitoring well/site locations and produce the most efficient sampling strategies, following the principles and best practices described in Gilbert (1987).

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