BELL CREEK TEST SITE – DEVELOPMENT OF A COST-EFFECTIVE, LONG-TERM MONITORING STRATEGY

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 11 – Deliverable D55

Prepared for:

Andrea M. Dunn

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

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Prepared by:

Barry W. Botnen
Nicholas S. Kalenze
Kerryanne M. Leroux
Ryan J. Klapperich
Kyle A. Glazewski
Daniel J. Stepan
John A. Hamling
Charles D. Gorecki

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

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EERC DISCLAIMER

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EXECUTIVE SUMMARY

The Bell Creek oil field is operated by Denbury Onshore LLC (Denbury) as a commercial enhanced oil recovery (EOR) project which provides an opportunity to improve the understanding of associated carbon dioxide (CO_2) storage that occurs as a natural part of the EOR process as well as provides a large-scale CO_2 injection site that can be used to inform carbon storage in deep saline formations (DSFs). The Plains CO_2 Reduction (PCOR) Partnership Bell Creek project, which is conducted in collaboration with the commercial project, provides a substantive opportunity for the validation of viable monitoring, verification, and accounting (MVA) strategies with applicability to both large-scale carbon storage in DSFs and associated carbon storage through EOR. In collaboration with Denbury, a 5-year research MVA program was conducted to demonstrate 16 MVA techniques with applications to geologic CO_2 storage scenarios. The program represents 1.5 years of preinjection and over 3 years of operational MVA activities coinciding with the first 3.2 million tons of associated CO_2 storage.

Every carbon storage project presents unique technical, operational, and performance conditions. However, typical monitoring criteria are likely to include demonstration of secure storage; tracking the vertical and lateral migration of fluids and pressure; improving long-term performance forecasts of storage capacity, efficiency, and utilization; informing operational improvements; and understanding of the long-term distribution and containment of injected CO_2. The research MVA program was designed to evaluate the adequacy of monitoring techniques for addressing identified technical risks common to nearly all CO_2 storage applications. An adaptive management approach (AMA) was used to integrate components of the MVA program with site characterization, modeling and simulation, and technical risk assessment. This integration provided experience and insights regarding the additional ancillary value that each demonstrated MVA technique provides to a commercial injection project.

Established CO_2 injection projects, whether via EOR or in DSFs, are expected to operate for decades. The Bell Creek project, with a significant production and CO_2 injection history, comprehensive characterization of the field, extensive MVA program, and validated robust performance forecast capabilities, now serves as an excellent representation of an established commercial-scale CO_2 injection project. Established projects are characterized by a reduction in technical risks and a resulting shift in MVA focus to guiding cost-effective performance improvements and conformance monitoring. This rare combination of features provides an opportunity to demonstrate the cost–benefit of viable long-term MVA strategies applicable to commercial carbon storage. Insights derived from the research MVA program regarding the value and limitations of MVA data integration along with the process and concepts that will be used to develop these long-term strategies are described.

The research-monitoring program conducted at Bell Creek has resulted in several key insights into cost-effective, long-term monitoring for commercial-scale CO_2 storage projects. No single monitoring technique is capable of addressing all monitoring criteria throughout the stratigraphic column from the storage complex to the surface. However, when techniques are combined into a monitoring strategy that is integrated as part of an AMA, the resulting strategy can not only address the required monitoring criteria but also provide a means of evaluating and enhancing project performance.

Techniques that avoid adverse operational or health, safety, and environmental impacts and/or possess streamlined processing and interpretation that can inform near-real-time operational decisions are preferred. Monitoring techniques that allow data to be acquired and interpreted autonomously or remotely and with minimal technical field personnel are also desirable. Techniques that can improve storage or utilization performance and can cost-efficiently complement, replace, or guide more robust but less timely solutions also hold an advantage.

A long-term, cost-effective strategy for MVA of associated CO_2 storage at the Bell Creek Field that leverages commercial data, insights provided by the research-monitoring program, and the AMA are being evaluated. Several new and established low-impact and/or high-value techniques will be demonstrated to better define specific benefits, impacts, and costs associated with MVA at an established commercial CO_2 injection site. These techniques include pulsed-neutron log (PNL) fluid saturation profiles, time-lapse seismic surveys, InSAR (interferometric synthetic aperture radar) ground deformation monitoring, produced fluid sampling, pressure/temperature, and production/injection data.

Insights provided through the Bell Creek project and investigation into a long-term monitoring plan have resulted in an ongoing field demonstration of two emerging geophysical techniques, the Krauklis seismic wave (K-wave) and scalable, automated, semipermanent seismic array (SASSA), through complementary projects. These techniques show promise for providing more cost-efficient, lower-impact, near-real-time solutions for long-term monitoring. If proven successful, these techniques will provide additional techniques compatible with long-term monitoring strategies. While the development of a long-term monitoring plan for the Bell Creek project will take into consideration specific operations and benefits to the project, the case study will provide recommendations that are expected to be broadly applicable for commercial carbon storage projects throughout the PCOR Partnership region and the wider deployment of carbon capture and storage.

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

BELL CREEK TEST SITE – DEVELOPMENT OF A COST-EFFECTIVE, LONG-TERM MONITORING STRATEGY

INTRODUCTION

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is working with Denbury Onshore LLC (Denbury) to study associated carbon dioxide (CO_2) storage at a commercial enhanced oil recovery (EOR) project at the Denbury-operated Bell Creek oil field. The Bell Creek oil field lies in the Montana portion of the Powder River Basin and is injecting CO_2 gas into the Lower Cretaceous Muddy Formation at a depth of about 4500 feet. As part of this project, the PCOR Partnership has developed a long-term monitoring, verification, and accounting (MVA) plan to validate associated storage in the context of commercial EOR operations. This plan is based on the results of 16 monitoring techniques evaluated since 2011, which includes baseline (prior to CO_2 injection) and operational (during CO_2 injection) monitoring integrated with technical risk assessment and modeling and simulation activities. CO_2 injection at Bell Creek began in May 2013, resulting in approximately 3.2 million tonnes of associated CO_2 storage as of July 2016.

Carbon storage associated with the EOR process provides an opportunity to evaluate MVA techniques applicable to many large-scale storage scenarios, including deep saline formations (DSFs). There are several important differences in the implementation of MVA between CO_2 EOR projects and DSF CO_2 projects. These include the increased complexity in implementation and evaluation at CO_2 EOR sites resulting from the use of potentially hundreds of injection and production wells. EOR operations can include injection of CO_2 and water along with production of fluids (water, oil, natural gas, and CO_2). Conversely, current saline storage projects generally involve installation and operation of only a few injection and observation wells and seldom inject anything but CO_2. EOR sites are also generally better characterized because of the availability of regional legacy geologic data and historic injection and production data. In contrast, carbon capture and storage (CCS) sites have, or can be expected to have, fewer regional penetrations and regional production or injection data but will likely have more local characterization data specific to the injection site from a variety of characterization techniques. CO_2 EOR projects must also account for the effect of various fluids with differing properties (i.e., water, oil, and gases) interacting within the targeted reservoir, a challenge not expected to be encountered by CCS in DSFs. While specific risk profiles of EOR and CCS may generally vary, the technical risks themselves along with the monitoring criteria for storage verification are generally consistent. Many of the MVA strategies developed at Bell Creek have direct application to commercial carbon capture, utilization, and storage (CCUS), whether it be associated storage via EOR or commercial storage in DSFs.

Commercial CO_2 injection and oil production operations will continue at Bell Creek beyond the current PCOR Partnership Phase III effort. Likewise, commercial reservoir surveillance of the site will continue to monitor reservoir conformance and sweep efficiency, maintain regulatory compliance, and economically and efficiently operate the commercial CO_2 EOR project. Lessons learned from the MVA activities conducted to date provide a platform for developing not only a more efficient and cost-effective long-term monitoring strategy at the Bell Creek site but provide insight and best practices that are broadly applicable to commercial carbon storage. Several key drivers for long-term monitoring techniques that can be integrated with operations can guide and improve performance and address any key technical risks or objectives of the project.

ADAPTIVE MANAGEMENT APPROACH

An adaptive management approach (AMA), as illustrated in Figure 1, was used to integrate components of the MVA program with site characterization, modeling and simulation, and technical risk assessment. This integration provided experience and insights regarding the additional ancillary value that each demonstrated MVA technique provides to a commercial injection project. For example, the majority of the MVA techniques, which were guided by technical risks driven by incomplete data, led to improved characterization of the geologic environment and/or calibration of performance forecasts. In turn, this improved understanding provided insight that guided the type, timing, and location of subsequent monitoring activities, which further improved the efficiency and value of the next round of MVA.

Over time, these iterations led to comprehensive characterization of the field and validated robust performance forecast capabilities. This approach, coupled with the established production and CO_2 injection history, resulted in a reduced risk profile and ultimately a shift in MVA focus to guiding cost-effective performance improvements and conformance and assurance monitoring. The evolved MVA focus is more in line with long-term, commercially viable MVA objectives at an established commercial carbon storage project.

Although evaluating MVA techniques at an EOR site may involve different conditions than for DSFs, e.g., near-steady-state injection pressure and monitoring multiple injection and production wells, many of the strategies developed have broad application to an array of carbon storage scenarios including DSFs. MVA strategies that improve operational efficiencies, lead to more accurate performance forecasts, and aid in optimizing MVA programs have tangible benefits to EOR projects. These impacts in terms of cost-effectiveness could result in even greater benefits for commercial CO_2 storage scenarios in DSFs that have the potential for larger subsurface footprints, larger areas of review, and longer-duration and more extensive monitoring requirements, particularly if the adoption of active reservoir management (ARM) practices employing brine extraction are considered.

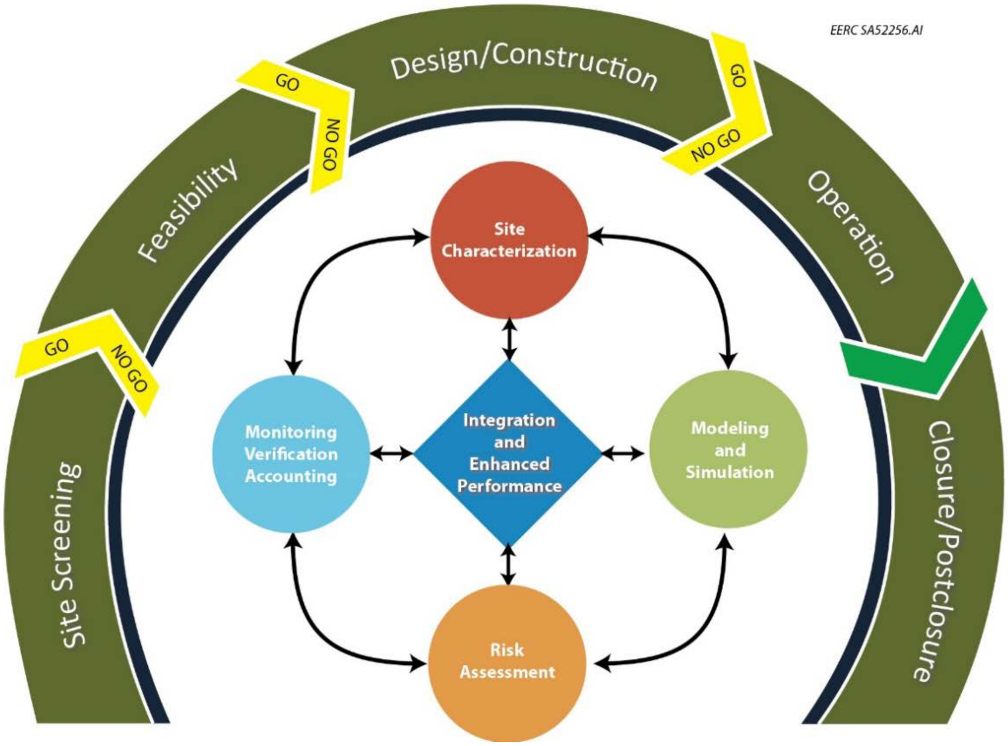

Figure 1. Conceptualized AMA to site characterization, modeling and simulation, risk assessment, and MVA as adopted at Bell Creek (Ayash and others, 2016).

MONITORING TECHNIQUES

Every carbon storage project presents unique technical, operational, and performance conditions. However, typical monitoring criteria are likely to include demonstration of secure storage; tracking the vertical and lateral migration of fluids and pressure; improving long-term performance forecasts of storage capacity, efficiency, and utilization and information to inform operational improvements; and understanding of the long-term distribution and containment of injected CO_2.

MVA of a CO_2 storage system and the overlying layers to meet these criteria requires multiple monitoring techniques (Figure 2). Initial MVA work at Bell Creek consisted of testing and validating individual monitoring techniques. The MVA program has evolved to demonstrating and validating cost-effective monitoring strategies for large-scale (>1 million tonnes per year) CO_2 injection projects (Hamling and others, 2016). These MVA strategies, often consisting of multiple monitoring techniques, provide enhanced value to other project technical activities (Figure 1) (e.g., technical risk assessment, site characterization, modeling/simulation) and can improve operational efficiency. Combined baseline and operational monitoring data using 16 monitoring techniques have been used since 2011 to enhance site characterization, improve performance forecasts, address technical aspects of the project, evaluate techniques that can account for and verify associated CO_2 storage, and improve the cost-effectiveness of MVA data acquisitions (Burnison and others, 2015; Dotzenrod and others, 2015a, b; Glazewski and others, 2016; Gorecki and others, 2014, 2015a, b; Kalenze and others, 2014).

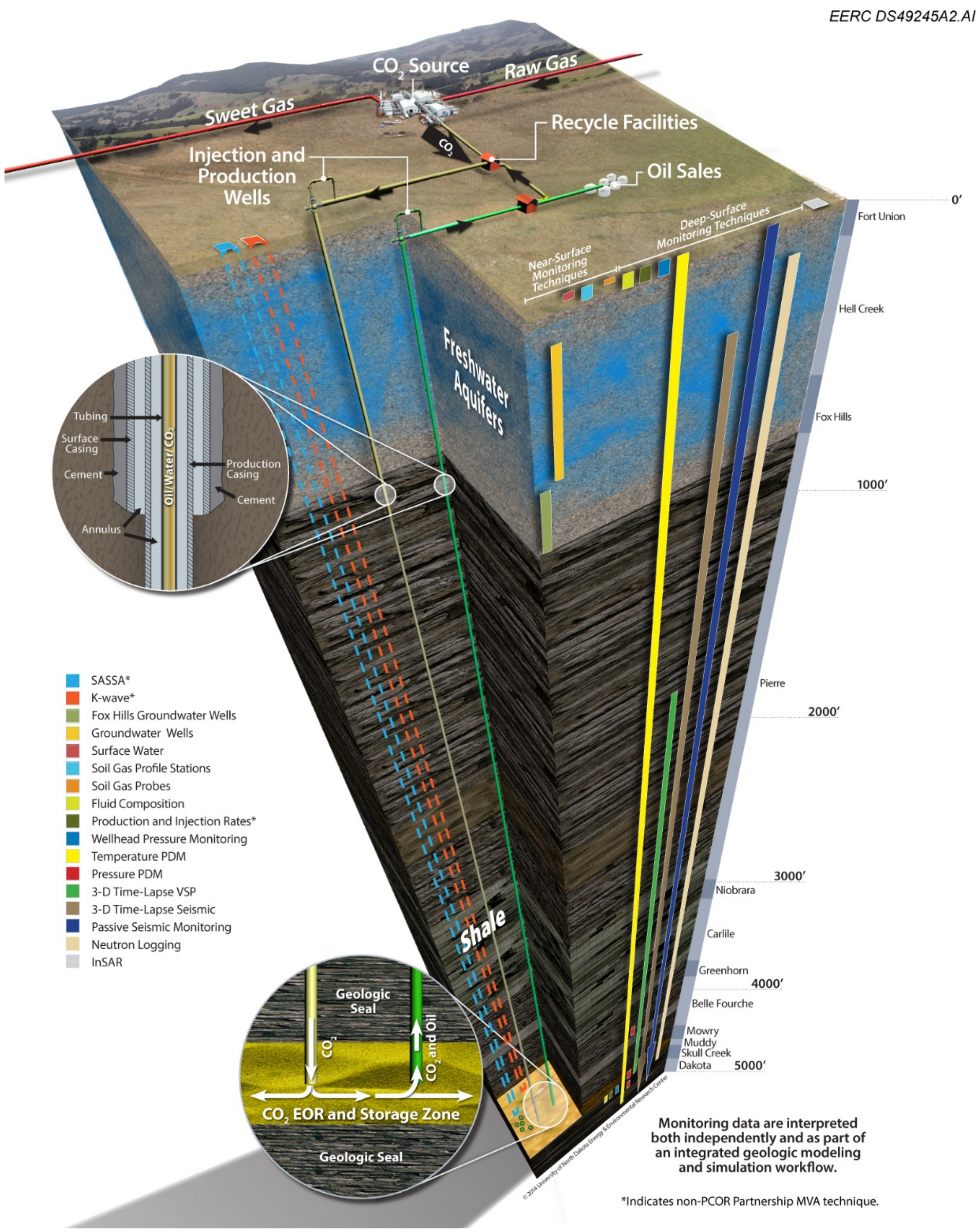

Figure 2. Stratigraphic column of the Bell Creek Field illustrating individual MVA techniques applied as part of the Bell Creek project (modified from Hamling, 2013).

The research MVA program was designed to evaluate the adequacy of monitoring techniques for addressing identified technical risks common to nearly all CO_2 storage applications. An AMA was used to integrate components of the MVA program with site characterization, modeling and simulation, and technical risk assessment. This integration provided experience and insights regarding the additional ancillary value that each demonstrated MVA technique provides to a commercial injection project.

The range of deployed MVA techniques provided a means of validating one technique against another. While each technique provided some level of value in terms of fully or partially addressing a particular monitoring criteria, the techniques that tended to provide the greatest value were reservoir surveillance techniques, which, through the AMA approach, could also inform operations and ultimately enhance project performance (Hamling and others, 2016). Table 1 provides a summary of these monitoring efforts, described further below, and how they are integrated through the AMA for a synergistic benefit to overall project efforts.

Monitoring Strategies Deployed

MVA demonstrations at Bell Creek included both assurance and performance monitoring. Assurance monitoring relates to the monitoring of areas with little to no risk (outcome expected), whereas performance monitoring utilizes techniques that enhance cost-effective operations. Near-surface MVA includes soil gas and water chemistry analyses. Fluid properties encompass volumes, pressures, and compositions of gas and/or oil streams at wellhead conditions as well as BHP data. Subsurface monitoring at Bell Creek consists of PNL surveys, a permanent downhole pressure and temperature monitoring (PDM) system, time-lapse geophysical surveys, and passive seismic monitoring. Ground deformation monitoring was also conducted using InSAR. Insights provided through the research MVA program have resulted in an ongoing field demonstration of two emerging geophysical techniques, referred to as K-wave and SASSA, through complementary projects. These techniques show promise for providing more cost-efficient, lower-impact, near-real-time solutions for long-term monitoring. Individual techniques are being evaluated to provide insight into how they can be integrated to provide cost-effective monitoring strategies for commercial carbon storage projects.

A near-surface monitoring program was developed and conducted to establish baseline (preinjection) conditions and variability of soil gas and water chemistry in the vicinity of geologic CO_2 injection that can be used in conjunction with continued assurance monitoring to ensure that CO_2 remains within the storage reservoir. The near-surface program was designed to 1) provide a scientifically defensible source of data to show that near-surface environments remain unaffected by fluid or gas migration and 2) identify and evaluate anomalies that could be indicative of an out-of-zone migration event should they occur during assurance monitoring. This program comprised three parts: sampling of surface water features, sampling of shallow groundwater aquifers, and sampling of soil gas in the shallow vadose zone. Assessment of the data collected indicated that a high degree of natural variability within these systems is possible. However, the techniques proved to generate sufficient data to both detect and attribute anomalies to natural processes within these environments.

Table 1. Summary of MVA Techniques Deployed at Bell Creek and Their Corresponding Benefits to the AMA

	Purpose and Benefits		AMA Incorporation	
Category	**Surveillance**	**Assurance Monitoring**	**Site Characterization**	**Modeling and Simulation**
Near-Surface: Soil Gas and Water Chemistry	• Naturally occurring variability of soil gas and water compositions in the near-surface environment • Provide a scientifically defensible source of data capable of monitoring for and characterizing anomalies within these environments	• Demonstrate no impact to near-surface environments Demonstrate safe/effective associated CO_2 storage	• Annual and interannual variability of soil gas and water chemistries • Near-surface environments, chemistries, and mineralogy	• Geochemical modeling • Hydrogeological modeling
Fluid Properties: Volumes, Pressures, and Compositions	• Purchase, injection, production volumes • Wellhead pressures and bottomhole pressure (BHP) data • Gas and oil sampling and analyses	• Accounting for associated CO_2 storage • Monitor for lateral migration • Demonstrate safe/effective associated CO_2 storage	• Reservoir heterogeneity • Porosity • Permeability	• History match calibration • Geomechanical and geochemical modeling and simulation
Pulsed Neutron Logging (PNL) Surveys	• Water/oil/gas saturation changes • Residual water saturation • Oil mobilization • Conformance • Storage/sweep efficiency • Guide surveillance activities (go/no go) • Vertical and lateral flow	• Monitor for out-of-zone vertical migration (accumulation zones) • Wellbore integrity monitoring • Demonstrate safe/effective associated CO_2 storage	• Structural interpretation • Reservoir and overlying strata properties • Regional variability within reservoir and overlying zones	• History match • Formation tops • Porosity • Tune and calibrate geomodel • Synthetic logs • Enhanced seismic interpretations
Permanent Downhole Monitoring (PDM) System	• Reservoir pressure/temperature • Fluid-phase behavior conditions • Aquifer support • Well testing/pressure communication • Reservoir behavior vs. injection/production rates	• Monitor for vertical pressure communication • Demonstrate safe/effective associated CO_2 storage	• Lateral and vertical zonal pressure isolation	• History match • Phase behavior and equation of state (EOS)

Continued . . .

Table 1. Summary of MVA Techniques Deployed at Bell Creek and Their Corresponding Benefits to the AMA, continued

	Purpose and Benefits		AMA Incorporation	
Category	**Surveillance**	**Assurance Monitoring**	**Site Characterization**	**Modeling and Simulation**
Seismic Surveys (3-D/4-D, surface/vertical)	• Gas saturation changes • Conformance • Areal extent of gas plume • Surveillance boundaries	• Show that out-of-zone migration, vertically or laterally, is not occurring • Demonstrate safe/effective associated CO_2 storage	• Structural interpretation • Sequence stratigraphy and depositional environment • Permeability barrier locations • Fault and fracture identification • Geomechanical properties from seismic inversion	• Refined history matching • Tune and calibrate the geologic model • Geomechanical modeling and simulation
Passive Seismic	• Source and depth of seismic emissions • Lateral or vertical out-of-zone pressure communication	• Monitor, identify, and locate induced seismic emissions vs. natural seismic events • Monitor for vertical migration to overlying accumulation zones • Monitor for fault activation • Demonstrate safe/effective associated CO_2 storage	• Variability within reservoir and overlying zones • Fault identification • Pressure communication • Correlation of events with geomechanical models	• History match • Geomechanical models • Understand stress • Calibrate • Fine-tune
Interferometric Synthetic Aperture Radar (InSAR)	• Naturally occurring deformation rates prior to the start of field pressurization • Identify swept and unswept areas of the field • Injection volumes or pressure differentials to produce measurable deformation • Evaluate injection/production performance	• Evaluate applicability as noninvasive monitoring technique to environment or EOR activities • Monitor subsurface pressure plumes over large areas • Demonstrate safe/effective associated CO_2 storage	• Deformation as it relates to CO_2 injection and/or pressure maintenance • Identify fault activation or reactivation (if present) • Identify permeability and/or pressure barriers within injection horizon	• Calibrate the geomechanical model • Validate planned time-lapse 3-D seismic monitoring surveys and passive seismic monitoring

Continued . . .

Table 1. Summary of MVA Techniques Deployed at Bell Creek and Their Corresponding Benefits to the AMA, continued

	Purpose and Benefits		AMA Incorporation	
Category	**Surveillance**	**Assurance Monitoring**	**Site Characterization**	**Modeling and Simulation**
Scalable, automated, semipermanent seismic array (SASSA)	• Movement and boundary of CO_2 front • Changes in areal extent of plume	• Track changes in plume extent with minimal data processing • Show that out-of-zone migration is not occurring • Demonstrate conformance and safe/effective associated CO_2 storage	• N/A	• Calibration of modelling and simulation • Refined history matching • Validate predictive results
Krauklis seismic wave (K-wave)	• Gas saturation changes • Movement and boundary of CO2 front between wells • Boundary surveillance • Injector/producer communication and injection pattern performance	• Track plume migration using existing wellbore infrastructure • Demonstrate conformance	• Interpretation of reservoir heterogeneity	• Calibration of modelling and simulation • Refined history matching • Validate predictive results

Metering the volume of fluid and gas injected and produced, periodic analysis of injected and produced gas and fluid compositions, and reservoir pressures provided a means to estimate associated CO_2 storage and calibrate modeling and simulation efforts (Jin and others, 2016). The compositional analysis was used to correct CO_2 storage estimates based on CO_2 content in the purchased gas stream. Accounting assumes purchased CO_2 volumes are equal to associated storage as the produced gas is captured at the recycle facility and reinjected. Hydrocarbon production rates and analysis of produced oil samples provide insights for model calibration, fluid interactions, and storage efficiency. Periodic time-lapse oil samples from select production wells are collected and analyzed to investigate shifts in molecular weight distribution, which is indicative of CO_2 interaction with reservoir fluids, allowing better assessment of fluid and gas mobility and interactions within the reservoir. Cumulative injection and production volumes of active injection and production wells, wellhead pressures, and fieldwide BHP data were integrated directly into modeling and simulation activities to improve history matching of the field. The efforts thus improved performance forecasts at Bell Creek, which further assisted in targeting future characterization and monitoring efforts through the AMA.

Time-lapse PNLs provided near-wellbore water, oil, and CO_2 saturation profiles. PNL monitoring consisted of baseline and repeat campaigns that provided information on the fluid saturation changes within the reservoir interval. Saturation changes were calculated between the baseline and repeat campaigns for select wellbores and were monitored to improve the understanding of the vertical saturation distribution in injection/production wells in addition to providing lithology and structural information for the reservoir and overlying zones. The saturation profiles helped to define geologic features within the reservoir that serve as vertical gas permeability barriers and, for assurance monitoring in overlying strata, were identified as potential accumulation zones. Overall, PNL monitoring was beneficial by effectively tracking and monitoring movement of injected CO_2, oil, and gas saturations in the near-wellbore environment, providing the ability to identify early CO_2 breakthrough and insight into fluid movement within the reservoir (Hamling and others, 2016).

A casing-conveyed PDM system was used to continuously monitor reservoir pressure and temperature. The downhole pressure and temperature data were useful as operational input to guide reservoir management decisions for acquiring subsequent MVA data and to calibrate and history-match numerical simulation. Specifically, the PDM system 1) provides continuous pressure and temperature measurements to monitor actual dynamic reservoir conditions without interfering with well-based injection or maintenance operations, 2) provides a means to correlate reservoir pressures to injection and production pressures at the wellhead, 3) identifies compartmentalization and communication within the reservoir, and 4) is applicable for multizone monitoring.

Time-lapse seismic surveys consisted of a baseline 3-D seismic survey and a 3-D vertical seismic profile (VSP) followed by repeat (monitor) 3-D seismic surveys and a repeat 3-D VSP (i.e., 4-D seismic) after injection had progressed. Difference processing and interpretation of the baseline and monitor surveys can provide images of injected CO_2 within the reservoir and between wells, but the difference can also be affected by pressure variations. 4-D seismic surveys provide a means of monitoring CO_2 migration pathways when the injected volumes and associated saturations are sufficient. Understanding the pathways can inform decisions regarding efficient management of injection and production operations to improve storage efficiency by identifying channels, geologic boundaries, gas migration pathways, and areas of the formation being bypassed by injected CO_2. They also provide assurance monitoring as means of monitoring strata overlying the reservoir for unintended CO_2 migration.

Passive seismic (or microseismic) monitoring employed a permanently installed 50-level geophone array in a wellbore. The geophones detect tiny seismic emissions caused by pressure changes resulting from CO_2 or water injection as the reservoir expands or relaxes. Events that could result from injection activities activating nearby faults are also detectable if they were to occur. Passive seismic monitoring helps determine the location of these events and provides a means to distinguish seismic events originating in the field from regional seismic activity. At Bell Creek, no events indicating fault activation have been recognized in the data as is expected based on geomechanical analysis of the area.

InSAR satellite data were processed for a baseline and operational monitoring period at Bell Creek. InSAR provides ground elevation data that can detect subcentimeter elevation changes that, in part, result from pressure changes in the subsurface. Ground elevation measurements from InSAR data have the potential to detect changing reservoir pressure conditions by observing the deformation at the overlying surface (Glazewski and others, 2016). Historical and operational data sets are processed from satellite data, with the goal of investigating naturally occurring ground deformation rates prior to and after the start of pressurization of the Bell Creek oil field. InSAR has the potential to identify heterogeneity, pressure compartmentalization or barriers, and pressure distribution within with the reservoir. The InSAR monitoring technique can ultimately be integrated with the AMA as a no-impact method of assessing subsurface pressure changes over large areas. Interpretation of these data sets is ongoing, although initial results show promise.

SASSA uses data from a single fixed seismic source fired periodically into a sparse surface array to monitor discrete points in the reservoir (Burnison and others, 2015). During injection, as the CO_2 front moves through the formation past monitored reflection points, differencing the time lapse data allows a means of determining when the CO_2 front has moved past the monitored reflection points. This could eventually provide the ability to recognize and act on changes observed to be occurring in the reservoir in near-real time. The provision of incremental information from SASSA is anticipated to offer an advantage compared to traditional time-lapse seismic methods that are acquired over larger time intervals. Traditional seismic methods also encompass challenges such as high operation costs and large impacts to the survey area due to the receiver and source locations required.

The K-wave offers operators a practical way to track CO_2 movement, providing insight into preferential fluid flow pathways and storage efficiency. Source and receiver wells are assigned systematically to create a network mesh of crosswell transit time coverage within the reservoir. After creating a baseline K-wave data set, the mesh can be repeatedly monitored to correlate observed changes in K-wave transit times to the actual CO_2 flood front movements in the field. K-wave allows operators to identify and act before CO_2 migrates toward unintended locations. Repeat sessions can be used to assess the speed of CO_2 advance and to judge the effectiveness of actions taken to manage the system.

Monitoring Within the AMA

PCOR Partnership activities at the beginning of the Bell Creek project consisted of site characterization, which began with collection of existing geologic and operational data. These data fed into initial geologic modeling efforts, thus improving the understanding of the Bell Creek Field. As the project progressed, additional data collected through site characterization or MVA activities enhanced the understanding of the field and the pertinent data were fed directly into the geologic models. The Bell Creek project provides a means to look at how characterization, MVA techniques, and modeling/simulation can be combined into an adaptive strategy for improving each of these components. As more information was acquired and the field better characterized, the ability to both forecast and monitor performance improved. Not only does the work conducted at Bell Creek allow for better prediction of long-term performance, but it also gives flexibility to look at how a wide range of hypothetical operating scenarios would likely affect performance at this and other injection sites.

The identification and assessment (qualitatively or quantitatively) of the potential technical risks that are relevant to the storage project are completed early in a project's development and refined over time as more characterization, operational, and monitoring data become available. The risk profile evolves based on increased knowledge and implementation of monitoring and/or remediation strategies (Hamling and others, 2015). The Bell Creek project includes a significant CO_2 injection history, well-characterized field, extensive MVA program, and validated robust performance forecast capabilities and serves as an excellent representation of an established commercial-scale CO_2 injection project. This stage of development is characterized by a reduction in technical risks and transition of the MVA focus to guiding cost-effective performance improvements and conformance monitoring.

COST-EFFECTIVE, LONG-TERM MVA

The goal in developing a long-term strategy for commercial-scale storage is to identify techniques that can optimally monitor CO_2 effectively, efficiently, and economically. Throughout the evolution of MVA at Bell Creek, the PCOR Partnership assessed the monitoring techniques deployed for the most benefit. Based on these experiences, the following criteria were derived for long-term monitoring applicable to commercial storage projects: demonstration of secure storage; tracking the vertical and lateral migration of fluids and pressure; improving long-term performance forecasts of storage capacity, efficiency, and utilization; informing operational improvements; and understanding of the long-term distribution and containment of injected CO_2.

Integration of Monitoring Techniques

Several MVA techniques were found to provide synergistic benefit when integrated, i.e., generating results that can build upon one another to develop a more thorough understanding of reservoir performance and CO_2 storage. For example, the PNLs have provided point data sources for measuring CO_2 saturation, while the 4-D seismic program provided a more qualitative assessment of CO_2 saturation over a geologic volume (Figure 3). With access to both of these data sets, the PCOR Partnership used PNL-measured CO_2 saturations to calibrate and better understand

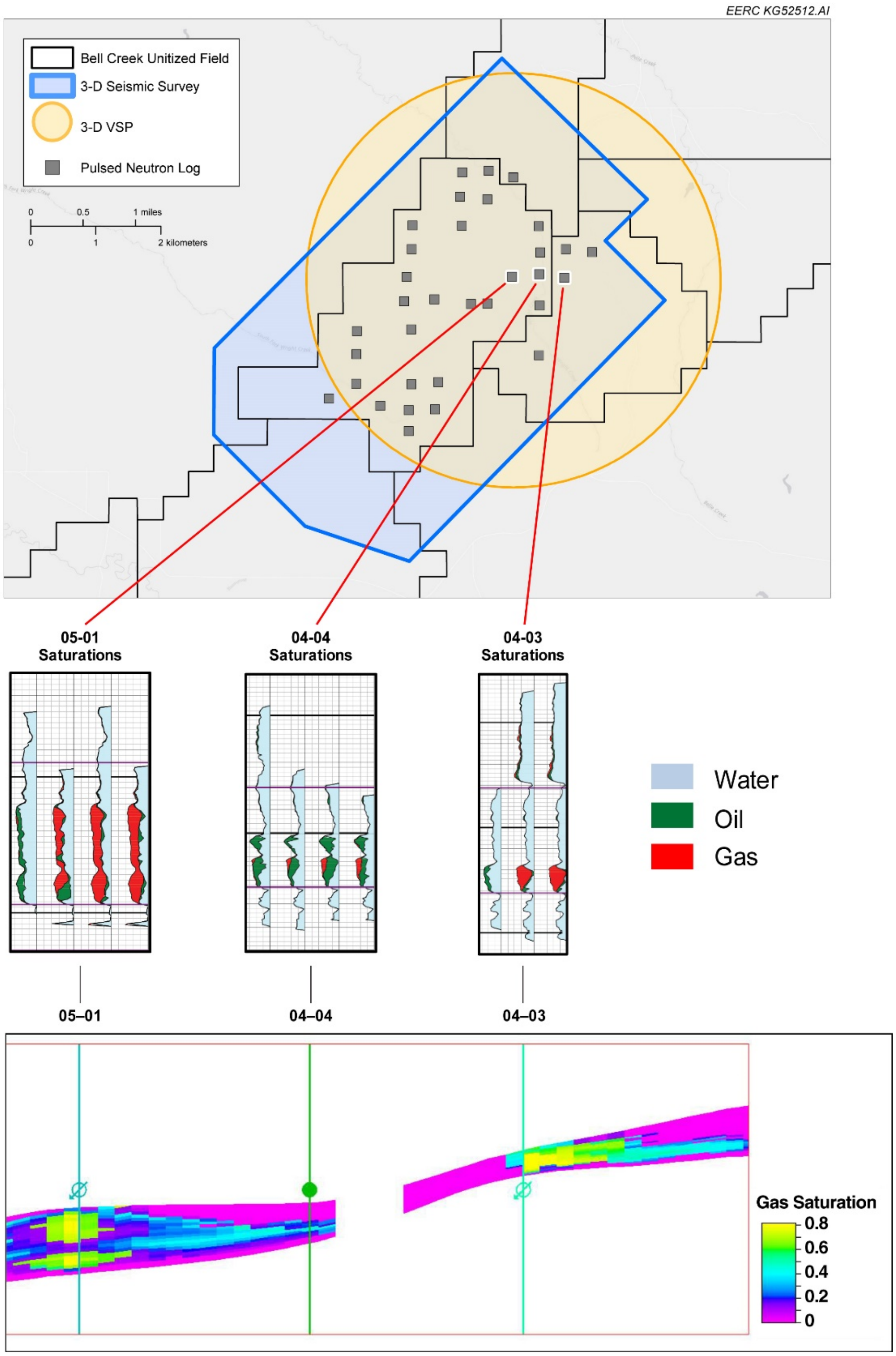

Figure 3. Several repeat PNL surveys were conducted in the field to evaluate changes in fluid composition within those wells and correlate the results with seismic data from the same location. Pictured are three repeat PNL surveys from two injectors (05-01 and 04-03) and one producer (04-04). Colored regions in the logs show changes in distribution with respect to fluids within these wells. The results of the surveys are then correlated with simulation outputs (bottom image) to improve modeled results (Hamling and others, 2016).

the 4-D seismic difference (Figure 4) by correlating the seismic pressure responses to the CO_2 saturation data as measured by the PNL surveys. This allows for better predictions and assessments of the storage resource throughout the reservoir (Hamling and others, 2016).

In addition, the integration of key monitoring techniques, such as PNL and seismic data acquisition, not only proved to be advantageous in assessing CO_2 distribution in the reservoir, but they also enhanced several components of the AMA at Bell Creek. For instance, PNL saturation data were integrated with injection and production volumes and simulation model performance forecasts to provide an indicator of when CO_2 saturations were likely sufficient to image with other seismic methods. Subsequently, a time-lapse 2-D seismic line was used to confirm that CO_2 saturation within the reservoir had indeed reached a level that could be imaged with a time-lapse 3-D seismic survey. Although the 3-D seismic survey required more significant resources, processing, and acquisition than a 2-D seismic survey, value is derived because this technique enables a 3-D understanding of injected CO_2 (e.g., distribution morphology, preferential fluid flow pathways, and containment within the field and zone of interest), thus further contributing to site characterization (Burnison and others, 2016).

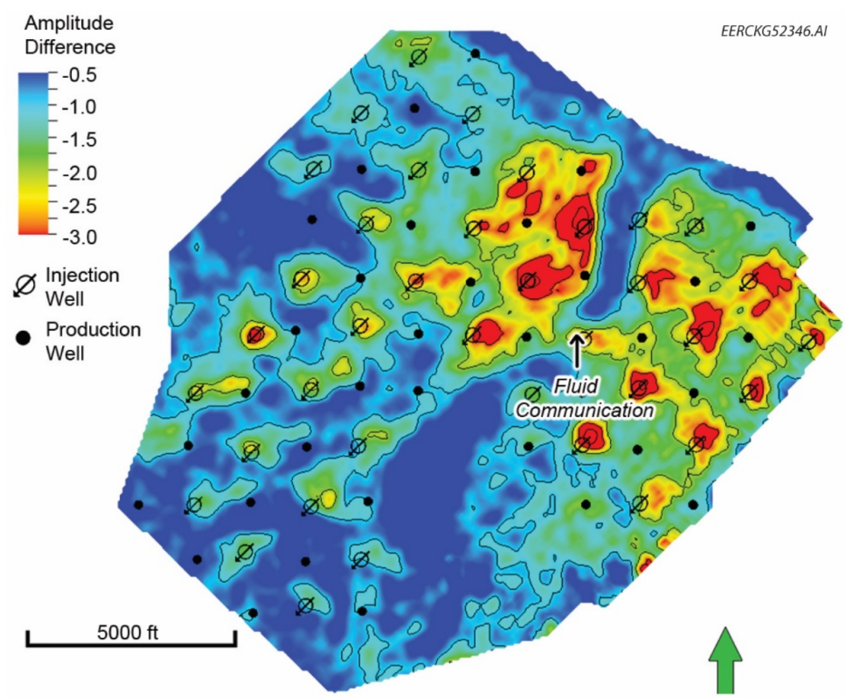

Figure 4. Bell Creek CO_2 EOR project time-lapse (4-D) seismic amplitude difference map. The warmer colors indicate regions that have experienced greater change in CO_2 saturation from the baseline seismic survey. The CO_2 response outlines a permeability barrier and fluid communication between the eastern and western portions of the seismic image (Hamling and others, 2016).

Bell Creek Long-Term Monitoring Strategy

While the MVA techniques and strategies employed at Bell Creek provided a means of wholly or partially addressing one or more monitoring criteria, the most cost-effective strategies tended to be those that provided a means of enhancing project performance through the AMA (Hamling and others, 2016). The insights gained from these analyses has led the PCOR Partnership to transition to demonstrating long-term, commercially viable monitoring strategies broadly applicable to carbon storage in a well-characterized and established field injecting CO_2. Techniques that result in no adverse operational or health, safety, and environment (HSE) impacts and possess streamlined processing and interpretation which can inform near-real-time operational decisions are preferred. Those that can be acquired and interpreted autonomously or remotely and with minimal technical field personnel are desirable. And those techniques that can improve storage or utilization performance and can cost-efficiently complement, replace, or guide more robust but less timely solutions hold an advantage.

Monitoring techniques favorable to a long-term monitoring strategy at Bell Creek include oil hydrocarbon analyses, PNL surveys, seismic surveys, and InSAR. These techniques have been deployed and assessed to fit a majority of the criteria determined necessary for long-term monitoring. The benefits will be further augmented by integration of results into the planning and interpretation of individual techniques as well as integration through the AMA into the other equally important technical activities (i.e., site characterization, risk analysis, and modeling/ simulation) of the EOR and associated CO_2 storage project at Bell Creek.

The SASSA and K-wave techniques, two non-PCOR Partnership techniques concurrently being assessed at Bell Creek as separate but complementary projects, may be considered for long-term monitoring as well. As detailed previously, both techniques are novel methods for MVA applications that investigate CO_2 plume movement with the potential to yield faster results (at near-real time) at lower costs with less impact to operations and the environment than conventional surveys to lead to actionable decisions. Should assessment of these techniques also prove favorable to a long-term monitoring strategy at Bell Creek, they may be included for further evaluation of cost-effective viability of commercial CCS and CCUS applications.

CONCLUSIONS AND NEXT STEPS

The monitoring program at Bell Creek is currently evolving from a research-monitoring effort, where an abundant suite of selected near-surface and subsurface techniques were investigated, to a more commercially viable long-term MVA approach. As results from deployment of these techniques were assessed, knowledge of the Bell Creek site was significantly improved through AMA efforts. Experiences also showed that monitoring techniques could operate in a complementary manner, where a particular technique may be used for planning future deployments to optimize results or to validate results from other deployed monitoring techniques.

The long-term strategy for monitoring at Bell Creek thus focuses on techniques that optimally monitor CO_2 effectively, efficiently, and economically. Subsurface MVA techniques have proven to offer the most benefit for long-term monitoring, particularly at the Bell Creek site, with integration of key robust techniques showing a synergistic effect with regard to assurance monitoring.

Insights derived through the Bell Creek project indicate that preferred techniques are those that avoid adverse operational or HSE impacts and/or possess streamlined processing and interpretation that can inform near-real-time operational decisions. Monitoring techniques that allow data to be acquired and interpreted autonomously or remotely and with minimal technical field personnel are also desirable. Techniques that can improve storage or utilization performance and can cost-efficiently complement, replace, or guide more robust but less timely solutions hold an advantage. These include, but are not limited to, oil hydrocarbon analyses, PNL surveys, seismic surveys, and InSAR. Other potential techniques such as the complementary, concurrently deployed SASSA and K-wave may also be considered. This long-term monitoring strategy will also provide value to the overall AMA, such that all strategic technical activities will ensure performance in an efficient and a cost-effective manner.

Execution and assessment of the developed long-term monitoring strategy will determine the technical viability of using the techniques identified to verify, validate, and quantify the storage of CO_2 within the target reservoir. Technical viability will be determined by quantifying the costs and benefits of each individual technique as well as the integration of techniques for potential synergistic effect. The AMA will also be used to determine the commercial viability of the combined long-term modeling and monitoring efforts for the Bell Creek site.

The objective of Task 11 – Postinjection Modeling and Monitoring is to develop long-term monitoring and modeling strategies based on the knowledge developed from the Bell Creek project. This report, Deliverable (D) D55, examines the results of a 5-year operational monitoring program deployed at the Bell Creek Field and the benefits derived from integration of MVA data into an AMA. Activities in Task 11 will incorporate these identified relationships between MVA and AMA with strategic field tests designed to demonstrate long-term monitoring approaches for commercial projects with established injection. Results will be used to develop long-term monitoring approaches that will be evaluated to enumerate specific strengths, limitations, costs, and their ability to address specific technical risks common to commercial carbon storage projects. Relevant findings and best practices resulting from this assessment will be presented in the final deliverables of Task 9 (D51: "Bell Creek Test Site – Best Practices Manual – Monitoring for CO_2 Storage and CO_2 EOR," due October 2017) and Task 11 (D73: Bell Creek Test Site – Monitoring and Modeling Fate of Stored CO_2 Progress Report," due January 2018).

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