1. Carbon Storage - Measuring, Monitoring and Verification

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Abstract

This paper shares the lessons learned from a portfolio of Alberta Innovates, InnoTech Alberta, C-FER and ERA supported projects related to CCUS, supplemented with experience gained from within the broader sector. This paper serves to summarize the body of knowledge developed and supported by these organizations regarding carbon storage measurement, monitoring and verification, and to recommend ways to help enable widespread use of CCUS both in Alberta and around the world. It is primarily focused on technology and knowledge development, identifying technology gaps, providing insights and recommends initiatives to develop CCUS technologies for widespread deployment to support emissions reductions targets. This paper also provides an overview of priority focus areas for future carbon measurement, monitoring and verification development.

1.1. Purpose of This Paper

This paper has been published as part of a series of papers on work completed on various aspects of Carbon Capture, Utilization and Storage (CCUS) with recommendations regarding how to advance carbon capture and storage in the future. This paper shares the lessons learned from a portfolio of Alberta Innovates, InnoTech Alberta, C-FER and ERA funded projects related specifically to carbon capture completed over the past two decades. These organizations work very closely to ensure the most efficient development and deployment of promising solutions occurs within Alberta. This paper serves to summarize the body of knowledge developed and supported by these organizations, and to identify the remaining gaps that need to be addressed with recommendations regarding how to help enable widespread use of CCUS both in Alberta and around the world. This paper is not intended to be a policy position paper, but it may be used to inform policy decisions as required. It is primarily focused on technology and knowledge development, identifying technology gaps, insights and priority focus areas for further investment to de-risk CCUS technologies for widespread deployment to support emissions reductions targets.

1.2. Introduction

An integral part of any commercial CCUS project is a detailed Measurement, Monitoring and Verification (MMV) plan. MMV spans across the geosphere, hydrosphere and atmosphere but technologies specifically designed to monitor the injected CO_2 plume itself reside in the geosphere. Alberta Innovates has contributed significantly to the development of CCUS in Alberta. For example, (Chalaturnyk, Jimenez, Bachu, & Gunter, 2005) describe the development of a generic MMV plan for monitoring acid gas injection and many of these recommendations are equally applicable to CCS projects and were carried forward into The Government of Alberta Regulatory Framework Assessment for CCS, published in 2013, which includes a statement that a CCS project “requires MMV and closure plans based on a project-specific risk assessment, and including the use of best available technologies to monitor the atmosphere, surface, ground and surface water, and subsurface” (Alberta Energy, 2013).

CCUS projects in Alberta utilize a wide variety of geophysical and geochemical technologies to demonstrate and verify containment and conformance of the injected CO_2. MMV technologies are designed and implemented in the beginning of a project and will continue throughout the duration of the project including post-closure. MMV plans are comprehensive in nature, site specific, risk based and should be flexible and adaptive to any changes that might occur during the project lifetime (Shell Canada, 2012a).

1.3. MMV Stages

During a CCS project, monitoring is generally undertaken in 4 distinct phases: baseline, operational, closure and post-closure. The purpose of baseline monitoring is to fully characterize the storage complex (reservoir and seal) in terms of containment and conformance, identify and remediate any potential integrity issues attributable to legacy wells in the storage area, determine injectivity of the CO_2, and sample and undertake sampling of groundwater systems about the base of groundwater protection. During operational monitoring, the performance of the CO_2 injection well(s) is evaluated continuously through down hole pressure and temperature gauges or optical fibre systems and the injected CO_2 plume is tracked by a broad range of geophysical, geochemical and geotechnical surveys to verify containment and conformance, or for the early identification of any loss of containment, should that occur At site closure, when the injection program has been completed, the MMV program is designed to ensure that the operator knows the distribution of the CO_2 in the storage complex, that it is contained below the cap rock seal, and that the plume is stable. For post-closure the MMV data must demonstrate that the plume is stable, that the behavior of the plume is consistent with models and that the CO_2 is permanently stored, in order for environmental liability for the site can be transferred to the government.

1.4. MMV technologies

In the following sections, we briefly summarize MMV technologies.

1.4.1. Surface seismic surveys

Seismic surveys are commonly used to delineate a reservoir suitable for injection and to monitor the CO_2 plume during the injection program. When surveys are conducted several times over a period of time, time-lapse images are created that enable the operator to map changes in the subsurface due to sequestered CO_2. While 3D seismic surveys provide exceptional imaging of the subsurface, it may be challenging for them to robustly image sequestered CO_2 and the associated pressure plumes for certain storage project where the storage formation may be quite thin relative to the wavelength of the seismic data.

1.4.2. Vertical seismic profiles (VSP)

Vertical seismic profiles are unique type of survey whereby geophones are placed downhole in a well and a source is located on the ground surface at the well, or offset from the well. VSP surveys provide detailed images proximal to the well and are designed to monitor the injection process and the location of the plume close to the well. Distributed acoustic sensing (DAS) utilizes a fibre optic cable installed in the well and an interrogator measures backscattering of light when a seismic wave intercepts this cable, yielding information on strain. In many projects that Alberta Innovates has contributed funding to, such as the Quest and the Pembina Cardium projects, VSP data has been an essential component of the MMV plan. DAS fibre also allow for continuous monitoring of reservoirs from passive seismic sources. Distributed temperature sensing (DTS) is similar to DAS, but instead of measuring strain, DTS measure temperature along the length of the fibre. DTS fibres are useful for understanding cooling effects due to the phase change of CO_2 from liquid to gas, as well as understanding well-reservoir coupling.

1.4.3. Cross-well seismic surveys

Many CCUS projects (e.g Quest, Pembina-Cardium, Weyburn) include observation wells that enable subsurface monitoring of the near-surface groundwater as well as the storage complex. When multiple wells are available, cross-well surveys can be undertaken during which a source (seismic or electromagnetic) is placed in one well and receivers are placed in the second well. Crosswell tomography uses travel times or secondary electromagnetic fields to provide high resolution imaging of the inter-well region.

1.4.4. Microseismic surveys

In this method, geophones or DAS fibre placed in injection or observation wells, and surface broad-band seismic stations are deployed to record microseismic data continuously during CO_2 injection. Any microseismicity recorded may be due to the development of fractures in the reservoir or cap rock during injection, or induced seismicity caused by displacement of pre-existing faults in the surbsurface as a result of the pressure changes.

1.4.5. Interferometric Synthetic Aperture Radar (InSAR)

InSAR is a satellite-based remote sensing technology that allows researchers to measure vertical ground displacements. InSar is particularly beneficial as it is a non-invasive technique compared to surface seismic and VSP which require extensive land use and drilling of wells. Injection of CO_2 typically displaces the ground vertically which InSAR is able to detect. This assists researchers in identifying how the CO_2 is interacting and changing the rocks within the injection zone. Near-surface tilt-meters may be used to complement InSar surveys in developing and refining a geomechanical model of the storage complex and the overburden.

1.4.6. Electrical Resistivity Tomography (ERT)

This technology monitors the change in electrical resistivity of rocks in the subsurface. CO_2 generally has a higher resistivity that the baseline pore fluids so this method will map the distribution of CO_2 in the geosphere and thus is directed towards containment monitoring. Electrodes that at are part of the ERT system can be deployed along the surface of the ground or behind casing in observation or injection wells.

1.4.7. Electromagnetic (EM) surveys

Similar to ERT surveys, EM surveys can also be used to monitor changes in electrical resistivity in the subsurface and generally will yield deeper but lower resolution data than ERT surveys. EM surveys are applicable for monitoring well integrity or loss of containment of CO_2 through cap rock faults or fractures.

1.4.8. Gravity surveys

CO_2 is a buoyant fluid and generally has a lower density than native pore-fluids, particularly brines. As CO_2 replaces brine, the overall density of the formation containing the CO_2 will decrease and this will be manifested by a change in gravitational acceleration which can be measured at the ground surface (low resolution) or within wells (high resolution). This method is most applicable for monitoring large plumes of CO_2 because the change in density when CO_2 replaces brine pore fluids tends to be small.

1.4.9. Pressure Monitoring

Pressure is a MMV property that is fundamental to all CCUS projects. Bottomhole pressure in injection wells is key to monitoring injection performance and to history match against reservoir simulations. Pressure measurements in aquifers about the storage complex are very important as an increase in pressure above zone may indicate loss of containment from within the storage complex.

1.4.10. Geochemical Monitoring

Carbon dioxide-rich (CO_2) gases are injected into lithological pore space to achieve pore space CO_2 storage on geological time-scales. CO_2 injection can also be used to improve or enhance crude oil (EOR) or natural gas (EGR) recovery from both conventional and unconventional petroleum reservoirs, many of which may subsequently be repurposed as future CO_2 pore space storage complexes.

Geochemical monitoring provides compositional and isotopic information that confirms directly the characteristics and performance of subsurface CO_2 pore space storage. Geochemical monitoring also characterizes the impacts of pore space storage and EOR activities on the storage complex and the overlying natural environments. It can be applied to a variety of project realms, within the area of the injection and storage activities that generally follow a superimposed pattern that include:

1. The storage complex, consisting of both the porous injection zone and the overlying caprock or stratigraphic seal;
2. The overlying succession of commonly water-bearing rock strata, sediments and soils, including both the groundwater protection zone and the deeper saline aquifers;
3. The vadose zone, typically occurring within the soil or tills;
4. The surface environment notably including the hydrosphere and atmosphere; and
5. The wellbore environment which normally crosscuts all of the above generally horizontally stratified environments and is generally monitored independently. In addition, the well bores provide conduits for the monitoring of surface realms during different project phases.

Temporally geochemical monitoring has four characteristic phases:

1. Prior to any CCS or EOR activities on the site, baseline studies should be performed to document the characteristics and state of the site prior to the CCS or EOR project regardless of the whether the site is “undisturbed” or affected by previous agricultural or industrial activities;
2. The site construction phase provides important opportunities to perform additional baseline studies that characterize the vertical succession using techniques not commonly employed during the construction of typical petroleum wells, such as cutting gas compositional and isotopic studies, that can provide important information regarding the initial pore space fluid composition in the subsurface succession. This information can also constrain the material and pore space characterization of the subsurface succession and the chemical and physical processes operating between the storage complex and the surface environment;
3. The operational or injection phase is typically the focus of repetitive monitoring surveys that create time series of monitoring data that indicate environmental changes associated with the performance of the EOR or CCS activities. Both CCS and EOR activities are required to operate without chemical impact on any of overlying saline aquifers, the groundwater protection zone or the surface environment. As such it is expected that, except for potential chemical reactions in the storage complex, the geochemical monitoring program should vary within the range of the

seasonal variations of the baseline study. Geochemical changes that are attributed to either a failure of storage complex containment or conformance serve as indications of unpermitted environmental impacts that would suspend or close the project prematurely; and

4. The closure or post-injection phase of the project requires continued, although less frequent, monitoring to ensure storage complex containment and conformance. In the post-closure interval the progressive decline of pressure in the storage complex and environs reduces the risk of migration beyond the storage complex into other parts of the succession.

1.4.11. Wellbore Integrity Monitoring

Wellbore integrity is an issue that that is important for all AER-regulated wells, not just those related to CCS or EOR activities. Monitoring of wellbores and their state of integrity and isolation may be required throughout the construction, operational and closure phases of CCS projects. Unlike the storage complex, wellbores are permitted, under specific conditions, to emit natural gas to the atmosphere.

Formation and groundwater monitoring are important for understanding the chemical reactions that injected CO_2 participates in with both the lithic and fluid phases in the CO_2 storage complex. This discussion is limited to reactions between the injected CO_2 and the aqueous fluids in the reservoir, as these are important for understanding both the mechanisms and amounts of CO_2 storage that are achieved, and they can also be important for the preservation of storage complex containment and conformance to engineering plan. In EOR projects there are also important physical and chemical reactions between the reservoir petroleum and the injected CO_2 are important for of the management and optimization of EOR recovery that are beyond the scope of this paper.

Although the ground water protection zone tends to occur where aquifer temperatures and pressures are low this does not mean that the infiltration of CO_2 into the groundwater protection zone can be neglected for either regulatory or environmental reasons. Groundwater monitoring is an essential part of onshore CCUS and EOR programs, where the groundwater protection zone must not be contaminated by a loss of containment of injected fluids, especially CO_2.

1.5. CCS PROJECT MMV REVIEW

In the following sections we present MMV learnings from projects that were supported by Alberta Innovates. In some cases, more recent publications are cited that present outcomes that benefitted from the initial support and addressed subsequent research and operational programs.

1.5.1. Shell Quest

The paradigm of a thorough measuring, monitoring, and verification (MMV) program is the Quest CO_2 injection facility operated by Shell and its partners, which injects approximately 1 million tonnes of CO_2 per year (Brydie, Jones, Perkins, Rock, & Taylor, 2014) at a location near Radway, Alberta. The MMV plan is comprehensive and involves surveys spanning from the preliminary stages of the project to planned post-injection monitoring. A baseline 3D seismic survey was conducted to identify a suitable site for injection, to delineate possible faults in their defined area of interest (AOI) that might constitute a containment risk, and to enable detailed characterization of the Basal Cambrian Sands Storage complex, which is the CO_2 storage formation. Monitoring surveys to establish a baseline prior to injection of CO_2 were performed in 2013 and have continued to date. The Quest MMV plan initially covered a wide range of technologies including: (Shell Canada, 2012b):

Wells: downhole pressure and temperature, DTS, DAS, well head CO_2 sensor, pressure and temperature;

- Observation wells: downhole pressure and temperature including within the Basal Cambrian Sand storage formation, and microseismicity monitoring;
- Geosphere: Time-lapse 3D VSP (3 surveys over initial years), time-lapse 3D surface seismic surveys (every 10 years), InSar surveys;
- Hydrosphere: ground water monitoring, electrical conductivity, pH, brine and CO_2 tracer monitoring;
- Biosphere: remote sensing, brine and CO_2 trace monitoring; and
- Atmosphere: CO_2 flux monitoring.

According to AER CCS tenure regulations, the MMV plan has been revised every 3 years. The Quest MMV plan was updated in 2019 (IEAGHG, 2019) and more recently by (Harvey, O'Brien, Minisini, Oates, & Braim, 2021). The Quest project has been very successful and walkaway VSP surveys have been able to clearly identify the lateral extend of the CO_2 plume within the storage complex. No microseismic events have been recorded that might indicate a potential loss of containment. Reservoir modelling and analysis of pressure data from MMV at the Quest site indicates that there is adequate storage space for the total injection target of 27 Mt of CO_2 and the project continues to inject up to 1.1 Mt of CO_2 per year.

(Brydie, Jones, Perkins, Rock, & Taylor, 2014) performed a regional baseline hydrogeological and hydrogeochemical study as part of the Quest MMV process. They re-evaluated the shallow bedrock hydrostratigraphy to define four aquifers including, in descending order, the Surficial, Oldman, Foremost and Basal Belly River Sandstone (BBRS) aquifers. They employed historic and current groundwater monitoring data to characterize the hydrologic and geochemical baseline state of these four target aquifers. The baseline determined that surficial, Oldman and Foremost aquifers exhibited both continuity and similarity such that they appear to form a single continuous aquifer. In contrast, they found that the BBRS aquifer was hydraulically and chemically isolated from the overlying three aquifer formations, within the limits of the Quest Project Sequestration Lease (SQL). They also employed the baseline characterization to define criteria that might provide early warning of a fluid or gas containment failure in the Quest storage complex.

At the Quest sequestration lease area (SLA), eddy covariance, soil gas probes, soil flux chambers, and walk-over surveys were conducted with the intention of understanding the spatial and temporal variability of CO_2 levels prior to start of CO_2 injection associated with the Quest project. These surveys are an essential baseline monitoring activity for any CCS MMV program. The result was an extensive and comprehensive dataset that characterized soil surface CO_2 flux, ambient air and soil gas CO_2 concentration and isotopic composition across the Quest sequestration lease area. The results varied both seasonally and as a function of land use and soil and vegetation coverage. Understanding the spatial and temporal variability of CO_2 levels prior to start of CO_2 injection represents an important activity of a CCS MMV program. It provides technical input to the development of such a program, but also provides knowledge for communication to and awareness of project stakeholders (e.g. landowners) regarding CO_2 levels within the atmosphere and biosphere across a SLA.

1.5.2. Weyburn-Midale Project

The Weyburn-Midale CO_2 Enhanced Oil Recovery (EOR) and storage project was launched in 2000 to increase knowledge and understanding of carbon sequestration with enhanced oil recovery (EOR) operations (IEAGHG, 2015). Alberta Innovates co-funded the development of this best practices manual for CO_2 storage. Geophysical surveys assisted in determining the distribution of the sequestered CO_2 plume and its associated pressure plume in the Weyburn field. Surface seismic surveys combined with active and passive source downhole seismic techniques were the focus in monitoring sequestered CO_2 (IEAGHG, 2015). Within the Weyburn-Midale project, five main objectives from the geophysical monitoring were established:

1) Ability to track the CO_2 plume within the main reservoir;
2) Detect any migration of CO_2 above the reservoir seal;
3) Providing constraints on perturbations in the subsurface pressure field;
4) Understand how microseismicity from injection relates to the integrity of the storage container; and
5) Ability to calibrate geological models for predictive modelling.

As reported (IEAGHG, 2015), two of the major successes of the geophysical testing at Weyburn were the results from downhole passive seismic monitoring methods used to monitor the induced seismicity at the site in relation to CO_2 injection, and the use of 3D time-lapse seismic surveys to investigate the decreases in acoustic impedance observed near the CO_2 injection wells. More recent analysis of the time-lapse surface seismic data from Weyburn are presented by (Wang Y. and Morozov, 2020). The majority of microseismic events at the site range between magnitudes -3.0 and -1.0 and were recorded close to production wells. These outcomes imply that the microseismic events were not due to injection of CO_2 but are more likely related to the production and increase flow of oil from the EOR operation.

At the Weyburn site, 3D vertical seismic profiles were also acquired. VSPs at the Weyburn site provided a high-resolution image change of the reservoir due to CO_2 injection. However, the fold coverage of the subsurface at Weyburn was low, and further VSPs only covered a relatively small area of the reservoir. Thus, the actual area imaged was low, especially compared to what would be possible with a 3D surface seismic survey.

Groundwater geochemical monitoring at Weyburn sampled and analyzed waters from more than 60 wells. Local potable wells were examined prior to CO_2 being injected in 2000 and these were sampled at six additional times in the life of the project, until 2011. Groundwater monitoring focused on key water chemistry species (SO_4, HCO_3, Na, Ca, Mg Cl and K). Groundwater quality was essentially unaffected by EOR operations at Weyburn (Whittaker, 2011) . A baseline geochemical survey and regular geochemical monitoring at petroleum wells occurred between 2000 to 2004 and between 2008 to 2010, resulting in 17 campaigns to collect wellhead fluid and gas samples. Solubility trapping, indicated by formation of H_2CO_3, began within six months after CO_2 injection began. Increased dissolved calcium and total alkalinity also increased suggesting that the injected CO_2 was reacting with reservoir carbonate minerals indicating significant ionic trapping within a year of CO_2 injection beginning. During the 10-year monitoring period significant changes in downhole pH suggested that ionic and solubility trapping occurred contemporaneously. Changes in formation brines indicated that injected CO_2 and brines were migrating from injector wells to producers. The results proved the value of geochemical monitoring as it informs the onset and time scales for injected CO_2 solubility and ionic trapping.

Similar to the geochemical monitoring at the Pembina-Cardium project, the geochemical monitoring at Weyburn provided parameters and histories of changes in formation water chemistries that inform and permit the calculation of reactive transport models that will define project storage capacity. The primary physical mechanism for CO_2 trapping and storage is phase trapping, as supercritical CO_2, although this is unlikely to persist for the 5000-year timeline of the model. Additional solubility trapping in formation water and mineralogical trapping provide about 55 per cent of the trapping capacity.

At Weyburn, soil gas measurement techniques included discontinuous single depth measurement, discontinuous depth-profile measurements, and (particularly where environmental conditions might be highly variable) continuous monitoring. A test control location (the Minard Farm) was located outside of the injection zone was used throughout the testing period. Soil gas sampling campaigns were conducted yearly between 2000 and 2006, and again in 2011. The protracted monitoring of soil gas geochemistry at the CO_2-EOR Weyburn oil field found no evidence of leakage of the injected CO_2 to the ground surface (Beaubien, et al., 2013). Soil gas CO_2 and CO_2 flux anomalies were all attributed a biogenic origin. Temporal variations in soil gas CO_2 were well-behaved whereas CO_2 flux was observed as more variable. Ratios between O_2 (±Ar) and CO_2, and between N_2 and CO_2 were found useful if CO_2 concentrations >5 per cent. He and Rn tracer anomalies were not observed associated with elevated CO_2 concentrations.

Spatial and seasonal trends and variations from both discrete sampling of soil gas (CO_2, CO_2 flux, O_2 + Ar, N_2, ^{13}C-CO_2, He, Rn, and CH_4) from continuous monitoring of soil gas sources (CO_2 and Rn) were attributed to near-surface biochemical processes (respiration, oxidation), environmental variations (moisture content, temperature, etc.), and soil properties (gas permeability, mineralogy). Soil gas CO_2 spatial distribution was unassociated with known structural features. Total precipitation was used successfully as a proxy of soil moisture content, which was an important factor controlling CO_2 production and CH_4 consumption particularly during fall sampling campaigns.

The experience of soil gas monitoring at Weyburn strongly recommended the construction of background monitoring sites, which allows for assessment of near-surface or atmospheric variables and their impacts uninfluenced by proximity to the storage reservoir. Like the Quest program, (Beaubien, et al., 2013) recommend the rapid release of baseline soil gas data to help inform local stakeholders. They noted that the potential for successfully identifying a containment failure using a soil gas program will depend on sampling density. And they recommended higher sampling density in the vicinity of specific regions of concern (e.g. well heads) compared to sparser sampling in regions of lower anticipated leakage risk.

(Watson & Bachu, 2007) used well integrity studies and statistics at Alberta acid gas disposal wells as a model for CCUS and EOR well integrity issues. Their key conclusion was that wells constructed specifically for the purpose of acid gas disposal had fewer and less serious well integrity issues than wells constructed for other purposes that were later converted to acid gas disposal wells.

Numerous activities were undertaken to observe, model and monitor well integrity in the Weyburn Project (Hawkes, Gardner, Watson, & Chalaturnyk, 2011) (Hawkes & Gardner, 2012) (Sacuta, Young, & Worth, 2015). These studies included studies of wellbore integrity, construction, cement aging, and casing corrosion and integrity. (Hawkes & Gardner, 2012) assessed the construction details and factors affecting wellbore integrity in the Weyburn–Midale field. Data from approximately 183 wells were collected from public and private sources. They found that “a good cement job” is an important step in protecting a wellbore from well integrity issues. They also recommended a need for the monitoring both surface casing vent flow [SCVF] and annular pressure, to reduce well integrity risks.

1.5.3. Pembina-Cardium CO_2-EOR Project

Surface and borehole seismic were two of the types of geophysical MMV technologies utilized at the Pembina-Cardium site, and surveys were conducted between 2005 and 2007. During this period of time, around 60,000 tonnes of CO_2 were injected into the Cardium Formation. Monitoring was done through a baseline and two 2D seismic time-lapse surveys as well as vertical seismic profiles. It was subsequently determined that vertical seismic profiles provided more coherent results. Due to the higher frequency bandwidth and high signal to noise ratio, the VSP data were able to identify the plume but one drawback is that while their vertical coverage is excellent, the lateral imaging from VSP data is restricted to the area close to the well.

Recently, however, a new approach to seismic time-lapse monitoring has been successful in identifying the CO_2 from the 2D surface seismic data (Henley & Lawton, 2021).

At the Pembina-Cardium site, the geochemical MMV sought to characterize:

1. The state of the reservoir;
2. The regional, local and site-specific setting;
3. The movement of injected CO_2 by monitoring of reservoir pressure, temperature and produced fluids geochemistry; and
4. To use these data and observations to predict the of the injected CO_2 using a reactive transport model.

Three baseline sampling campaigns occurred between February and April, 2005, essentially prior to the beginning of CO_2 injection in March, 2005 (Talman & Perkins, 2009). Geochemical monitoring data were obtained from detailed geological and reservoir characterizations constrained by oil, gas, water production and the fluid injection histories. Injected and produced gases and fluids were sampled and analyzed for a broad range of chemical and isotopic parameters including ^{13}C CO_2 isotopes. Monthly monitoring sample collection occurred between May 2005 and March 2008 to augment historical and baseline data. Among other things, this sampling characterized a change in the composition of produced waters from an a concentrated NaCl water to a diluted $Na(Cl,HCO_3)$ water in response to a water-flood program. The evolution of water samples suggested the presence of ion exchange reactions, calcite dissolution and CO_2 stripping from the oil phase.

A reactive transport model was used to infer short and long-term chemical processes in the reservoir. Models suggested that ion exchange reactions controlled the short-term water composition, with contemporaneous calcite dissolution. The models also predicted mineralogical reactions that would result in the long-term trapping of injected CO_2. Discrepancies between the model predictions and observations were employed to refine the models with the intention of improving the understanding of improving the understanding of chemical processes in the reservoir that resulted in a model of CO_2 trapping mechanism within the reservoir.

Injected CO_2 breakthrough was associated with >10 mol per cent CO_2 in a produced gas sample. This was observed in 9 of 28 wells studied. Areal distribution of inferred CO_2 breakthrough was used to define CO_2 migration directions, which varied with time. Significant geochemical differences were observed in reservoir fluids including changes in pH, alkalinity, Ca^{2+}, Fe^{2+} between the CO_2 breakthrough wells and the wells where no CO_2 was detected.

The changes in produced water composition at the Pembina-Cardium project, most notably pH, alkalinity, Ca^{2+}, Fe^{2+}, $^{\delta 13}C$ of CO_2, and $^{\delta 18}O$ H_2O, were inferred potential CO_2 migration tracers and indicators of chemical reactions between the injected plume and reservoir lithology. Results suggest that mobilization of water from previously unswept portions of the reservoir that is being contacted after injection terminated. The greatest compositional changes in produced waters occurred during active CO_2 injection with more gradual changes thereafter. In particular, pH values decreased in those wells that had CO_2 breakthrough during CO_2 injection. Baseline pH values of ~ 7.5 fell to ~ 5 during CO_2 injection but then increased to ~6.5 after CO_2 injection ended, perhaps due to lithological buffering which is likely indicated by increased, alkalinity and Ca^{2+} during the post-injection period. During the post-injection period the CO_2 concentration in produced gases decreased from >90 per cent to ~60 per cent indicating either continued CO_2 migrating away from wells or continuing CO_2 dissolution into reservoir fluids, which may be more likely considering other post-injection water chemistry changes.

Although it was one of the earliest of the CCUS or EOR projects reviewed, the continuous monitoring of the chemical and isotopic composition from produced fluids and gases at Pembina provides an unparalleled record of parameters in produced fluids and gases that were indicative of reservoir changes during and after the active injection of CO_2, which were inferred to indicate progressively greater solubility trapping of injected CO_2.

Soil gas monitoring was performed at the Pembina EOR project (Hutcheon, et al., 2016). Samples of soil gas were collected in surface flux chambers and in nine shallow gas monitoring wells all <22 m deep. Of the samples obtained contained exclusively or predominantly N_2 and O_2 generally in atmospheric proportions, but with several of the samples having detectable methane and CO_2 components. The recovered methane was interpreted to have a biogenic origin and the carbon dioxide was interpreted to be probably atmospheric.

1.5.4. Acid Gas Disposal

Acid gas disposal has been prominent in Alberta since the 1980s. In Western Canada, acid gas is permitted to be injected into depleted oil and gas reservoirs. These are considered ideal locations as many wells that were previously producing likely have extensive MMV plans already implemented. Further, the depleted reservoirs are highly studied, and seismic surveys including time-lapse analysis were likely to have already been conducted. (Chalaturnyk, Jimenez, Bachu, & Gunter, 2005) state that a monitored decision process is not simply long-term monitoring, it is a planned approach to decision making over time. Current MMV technologies for acid gas disposal are similar to MMV technologies employed in CCS projects. Technologies within the geosphere include 2D and 3D time-lapse seismic reflection surveys, VSPs and cross wellbore seismic surveys, satellite imagery of land surface deformation (such as InSAR), and reservoir pressure monitoring (Chalaturnyk, Jimenez, Bachu, & Gunter, 2005).

1.6. Gaps and Recommendations – Measurement, Monitoring and Verification

It's expected that MMV technologies will continue to develop for carbon sequestration, particularly for scale-up. At present, projects at the scale of Quest (~ 1 Mt/yr) can be developed with well-established MMV plans as detailed in Alberta Innovates reports reviewed for this white paper as well as in other subsequent publications. Geophysical and well-based MMV plans have been successful in operational monitoring and groundwater monitoring at established projects indicating that well-selected and carefully constructed CCUS storage complexes exhibit reliable containment of the injected CO_2

Currently, the Government of Alberta is investigating the concept of CO_2 storage hubs to drive scale up of CCS implementation in the Province. For large-scale CO_2 storage hubs there are gaps in MMV that need to be researched and addressed. These include a better understanding of basin-scale hydrodynamics of aquifers to ensure that pressure and CO_2 plumes from possible adjacent hubs do not interfere with each other, characterization of seals on a regional basis, and how to implement MMV plans at a large spatial scale, including groundwater programs, observation wells and surface geophysical surveys.

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