Monitoring Technology Ranking Methodology for CO₂-EOR Sites Using the Weyburn-Midale Field as a Case Study

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Abstract:

In a carbon dioxide (CO₂) enhanced oil recovery (EOR) operation, CO₂ is injected into a hydrocarbon reservoir to enhance hydrocarbon production. Much of this CO₂ is recycled for reinjection when the hydrocarbons are produced; however, a large amount is permanently stored in the reservoir. If a CO₂-EOR operation intends to claim CO₂ storage credit for this stored CO₂, it needs to demonstrate that the CO₂ is safely stored in the subsurface by strategically deploying monitoring technologies. For the operation to maintain profitability goals, these monitoring technologies also need to be cost-effective. If the safety of the CO₂ storage is demonstrated, the project will be classified a carbon capture, utilization, and storage (CCUS) project.

The main goal of CO₂-EOR is oil production, not CO₂ storage. Because CO₂-EOR originated as an oil production technique, the EOR process is subject to a less stringent regulatory environment than CCUS projects. These differences in the CO₂ storage accounting and the regulatory environment mean that CO₂-EOR projects need to demonstrate the long-term containment of CO₂ within the reservoir with additional monitoring in order to claim any CO₂ emission credits. Converting a CO₂-EOR project to a CCUS project requires a tailored site-specific approach. The methodology employed will differ from project to project due to differences in project risk, geology, operations history, and regulatory environment.

This paper takes the CO₂-EOR Weyburn-Midale Field (WMF) as a case study to rank monitoring strategies that may be required to shift the WMF from CO₂-EOR to CCUS. This study consisted of an in-depth review of the identified risks, the potential leakage pathways, various regulatory requirements, and the already deployed monitoring techniques. The goal was to develop a risk-, economic-, and regulatory-based monitoring technology ranking system that is suitable for the WMF. While specific to the WMF, the methodology presented here can be adapted by other CO₂-EOR operators who endeavor to demonstrate that the non-recycled portion of the CO₂ injected into the formation(s) by their project(s) is permanently stored.

Keywords:

CO₂ Sequestration, Monitoring, Well Integrity, Regulatory, CO₂-EOR

1 Introduction

The objective of the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project (WMP) was to commence follow-up research on applied technology for carbon dioxide (CO₂) enhanced oil recovery (EOR) operations that will be seeking future recognition for CO₂ storage. Between 2000 and 2012 approximately 22 million tonnes of CO₂ was injected in the Weyburn and Midale oilfields. This CO₂ was used to enhance oil production in both fields, raising oil production three-fold from pre-2000 levels. The source of the CO₂ was the Dakota Gasification Company's coal

gasification plant in Beulah, North Dakota, where the CO₂ was captured, compressed, and delivered via a 320 km pipeline to the two oilfields in Saskatchewan (PTRC, 2012b). CO₂ injection continues today and it is estimated the Weyburn-Midale Field (WMF) will end up storing over 40 million tonnes of CO₂ by the end of their production lives (PTRC, 2012b).

Building on this work, Petroleum Technology Research Center (PTRC) awarded Schlumberger Carbon Services the task of "Monitoring of CO₂-EOR Sites for Storage Integrity" as part of the Saskatchewan CO₂ Oilfield Use for Storage and EOR Research (SaskCO₂USER) project. This task is part of a larger scope of work undertaken by the PTRC and other contractors. The objective of the task was to use existing data provided by PTRC or data that are publically available to develop a method for ranking monitoring technologies for EOR projects wishing to qualify for credits for long-term CO₂ storage.

The ranking can be used to select monitoring activities with the required level of confidence to ensure management of the primary objectives of risk related to CO₂ storage including:

- Containment of the injected quantity,
- Conformance of the site to expected performance, and
- Assurance that CO₂ injection will not endanger health, safety, or the natural environment.

Using data and studies from previous phases of the WMF as a benchmark, this study reviewed various monitoring techniques available and ranked them using a cost/benefit equation with factors such as ability to reduce risk, ability to satisfy regulations, likelihood of success, cost, etc. The ranking also considered the technical performance requirements such as required procedures, sensitivity, spatial resolution, temporal resolution, and coverage. These rankings were used to select technologies, outline deployment strategies, prepare a schedule, and eliminate technologies that were considered to be less cost-effective. The ultimate goal was to tailor the monitoring technology ranking to identify technologies that are cost-effective and sufficient to satisfy emerging storage regulations.

The objective of this ranking methodology is to get the project team, expert reviewers and decision makers to ask the right questions about the costly CO₂ monitoring choices that are being made. Without a quantitative method such as this, all the project team has are separate qualitative statements such as, "Three dimensional (3D) seismic is more effective than soil gas testing, but soil gas testing is also effective and a lot less expensive to carry out so it must be more cost effective."

These statements do not actually have any value unless they can be quantified; expensive decisions are often made based on statements like this and the confusion can escalate quickly when a dozen or more technologies are added to evaluate. Furthermore, the profession of each team member biases their statements; the geophysicist will always be a champion for seismic, a hydrogeologist will always be eager to go water sampling, and a petrophysicist will want to log more wells. "He who is good with a hammer thinks everything is a nail."

The objective of the ranking method presented is to bring these different technologies together, make them visually comparable, remove any professional bias, and get decision makers to ask the right questions. Once quantitative comparisons are generated, assumptions can then be challenged by the project team. When the team looks at this objectively along with the final cost/benefit results, they are free to use professional judgement to adjust the numbers. The ranking can be upgraded automatically to be more representative. Once the team is comfortable with how well

they believe the technologies would work and understand the costs, informed decisions can be made as to which technologies to use and how to use them.

2 Site characteristics

2.1 Geological Setting

The definition of a storage complex is required by regulations. The storage complex is defined as a CO₂ injection formation, caprock formations, and any in-between monitoring formations (Table 1). In the case of the CO₂-EOR operation at the WMF, the Midale Beds are the injection reservoir and the Midale Evaporite is the caprock; these formations have been accepted by regulatory authorities. With CCUS, an additional caprock must be demonstrated to the regulator as being capable of being a final upward barrier to CO₂ migration (CCUS caprock).

Table 1: Storage Complex Formation Description

Formation Function		System	Formation
Monitoring Fm.	Storage Complex	Jurassic	Shaunavan Fm. Gravelbourg Fm.
CCUS Caprock		Triassic	Watrous Fm. The Watrous is defined as the ultimate seal for both CCUS and EOR operations
Monitoring Fm.		Mississippian	Poplar Beds, Charles Fm. Ratcliffe Beds, Charles Fm.
CO ₂ -EOR Caprock			Midale Evaporite, Charles Fm. Representing the first seal for CO ₂ migration out of the injection zone.
CO ₂ -EOR Injection Reservoir			Midale Beds, Charles Fm. The CO ₂ injection zone
Monitoring Fm.			Frobisher Beds, Mission Canyon Fm.

2.2 Site Specific Project Review

Before a monitoring technology ranking could be developed it was important to review the previous WMP work relating to risk assessment, leakage scenarios, and monitoring. The Best Practice Manual from the WMP (PTRC, 2012a) was reviewed along with the following data and results provided by the PTRC including (URS, 2010b) (URS, 2010a), (Irani, 2012) (PTRC, 2012a), (Crow, et al., 2010), (Duguid, et al., 2013), (Duguid, et al., 2014), (Hawkes & Gardner, 2013), (Cavanagh, 2013).

3 Methods

The objectives of this paper are to identify the technologies for use in monitoring and rank them in a cost/benefit analysis. This is a complicated problem and the methods to consider were categorized into 5 categories (Table 2).

Table 2: Requirements and the monitoring technology ranking approach

Requirements for a CCUS Monitoring Plan	Approach to the WMF Monitoring Ranking
Monitoring Targets	Fourteen monitoring targets were defined based on the risks associated with the WMF and are divided into containment, conformance and assurance categories. At a defined location and depth, a measurable physical property is to be measured so it can provide an indicator of compliance or non-compliance with identified risk scenarios and regulatory requirements.
Risk Areas	When ranking monitoring technologies it is important to understand the EOR operation because this is the foundation in the development of risk areas, which provides guidance on which areas require more monitoring than other areas. A method for calculating where the areas of higher risk are was developed.
Monitoring Technology Selection	The selected monitoring technologies were preliminarily selected to manage the monitoring risks identified by risk analysis.
Risk Management and Monitoring Targets	The current risk assessments were an integral component for the development of the monitoring technology ranking. The monitoring related risks were identified and monitoring technology was selected to reduce these risks.
Well Risk Assessment Methodology	This involved a review and characterization of potential leakage pathways through existing wells.

3.1 *Monitoring Targets*

In order to effectively monitor the WMF, address the risks, as well as provide the level of assurance that is needed for operating security, regulatory compliance, and public perception, the monitoring objectives have been divided into 14 monitoring targets that addresses all the specific risks (Table 3). A monitoring target is “At a defined location or depth, a measurable physical property is to be measured so it can provide an indicator of compliance or non-compliance with identified risk scenarios and regulatory requirements.” Specific monitoring targets can be grouped by the primary monitoring objective (Containment, Conformance, and Assurance). These descriptions are valuable as levels of summary to communicate how monitoring targets are being used to address risk. Assessing technologies associated with the atmosphere monitoring target were excluded at the request of the PTRC.

Table 3: Summary of monitoring targets

Primary Monitoring Objective	Monitoring Target
Containment	Well Integrity
	Caprock Integrity of the Midale Evaporite and Watrous
	Migration up into the Jurassic Fm.
	Migration up into the Lower Watrous
	Migration up into the Poplar and Ratcliffe
	Natural Seismicity And Injection Induced Microseismicity
Conformance	Plume Location and Migration in Reservoir
	Quantification for Regulatory Authorities
	Storage Efficiency and Fine Scale Processes
	Calibration of Predictive Models
Assurance	Surface Leaks: Soil
	Surface Leaks: Groundwater
	Public Assurance
	Surface Leaks: Atmosphere (excluded from this study)

3.2 Risk Areas

Because it is cost prohibitive to frequently monitor the entire EOR field with every technology, decisions have to be made as to where to best focus efforts to demonstrate containment, conformance and assurance. For a CO₂-EOR field, monitoring should be focused in areas where the most CO₂ injection has occurred. The layout of the EOR operation was used to identify risk areas, which represent areas with low to medium to high amounts of CO₂ injected. Once it is understood where most of the CO₂ injection has occurred, monitoring technologies can be better focused in these areas of highest risk. These risk areas were used to provide guidance as to where and how frequently particular technologies should be deployed. For example, once it is understood that most of the CO₂ injection has been in a small area of the EOR field, it becomes clear that running the very expensive 3D seismic over areas of low or no injection is not cost effective. Planning for the size, schedule and associated costs of the 3D seismic surveys were adjusted accordingly and was a key component of the cost/benefit ranking discussed in Section 4.4. These risk areas were also used as part of a well risk assessment methodology (Section 3.2), which is discussed in more detail in this journal in the paper titled Well Integrity Risk Assessment to Inform Containment Risk Monitoring for Carbon Capture, Utilization, and Storage (Duguid, 2016).

The WMF currently has 177 CO₂ injection wells (horizontal and vertical) associated with this EOR project. 118 of these wells currently have a record of CO₂ injection, while 59 injection wells have 0 m³ injected. No CO₂ plume location data were available so the cumulative injection masses from each injection well were used to estimate risk areas based on the amount of CO₂ injected within 500m of a CO₂ injection well. These risk areas represent an approximate aerial extent of the developing CO₂ plumes. The 500m distance was chosen based on the measurable extent of the CO₂ plume from 4D seismic data (PTRC, 2012a). A risk area category (Figure 1) was assigned to each risk area using the cumulative mass of CO₂ injected at each well (IHS, 2015). The injected masses from each well

were scored in categories between 1 (lowest mass injected) and 5 (most mass injected). Because these wells are relatively close together, some overlap of these 500m areas occurred. In these cases, the highest category score would be assigned to the overlap area.

Risk Areas

- Area 5: Greater than 900,000 tonnes
- Area 4: 540,000 to 900,000 tonnes
- Area 3: 180,000 to 540,000 tonnes
- Area 2: 45,000 to 180,000 tonnes
- Area 1: 1,000 to 45,000 tonnes

Bold well symbols and well paths represent
CO₂ Injection Wells

Figure 1: WMF Risk Areas

3.3 Monitoring Technology Selection

When selecting monitoring technologies there are many that could be applied to CO₂ storage monitoring; however, not all are technically feasible or cost-effective in the specific environmental and context of the WMF. Technologies were selected as potentially appropriate for this project and will later be ranked in a cost/benefit analysis. No single monitoring technology is capable of monitoring for all risk scenarios or monitoring targets. Each monitoring technology has its own resolution, detection limits, background values, false positives, false negatives, coverage, sensitivity, and operational costs. These technology characteristics help determine how effective a technology will be at measuring a specific parameter at a specific location. Therefore, understanding the strengths and limitations of these individual technologies is important when combining all the monitoring technology results into one unified interpretation of containment, conformance, and assurance monitoring. Each technology also has its own unique context, which may include geophysical, environmental, and social context. Selecting potentially appropriate monitoring technologies was based on expert judgment and collective experience (Table 4). The term INJ refers to injection wells while OBS refers to observation wells, which may be dedicated observation wells or existing production wells.

Table 4: Monitoring technology short description

Monitoring Technology	Monitoring Technology Description
Cement Bond Log	Measures quality of well cementing job, i.e., integrity of cement bond between tubing/casing and wellbore.
Mechanical Integrity Pressure Test (Tubing and Casing)	Involves pressurizing the space between the casing and tubing in a well to monitor for potential well integrity issues.
Multi-Finger Caliper	Monitors changes in the diameter of the tubing or casing, which may indicate well integrity issues such as corrosion or scaling.
Ultrasonic Imaging Tool	Visually evaluates the integrity of the contact between the casing and cement as well as the cement and formation for potential well integrity issues.
Downhole Pressure and Temperature Sensors (Injection Well)	The tubing mounted pressure sensors use digital piezometers to take pressure and temperature measurements at discrete depths.
Distributed Temperature Sensors	Fiber optic based system used to monitor the temperature profile along the tubing or the well casing for well integrity purposes.
Microseismic Monitoring Array: Surface or Borehole	The installation of a seismic monitoring array (surface based and/or downhole array) that will monitor for any induced microseismic events. Microseismic events are the result of pressure and stress changes in the storage formation and potentially the over- and underlying formations.
Packer Isolation Test, In-situ Stress Test	Tests the integrity of packer; digital pressure and digital dead weight gauge used to ensure highest accuracy possible.
Offset Well Integrity Investigation	Offset wells that penetrate the storage formation must meet these requirements to demonstrate well integrity.
Pressure Fall-off Test	The measurement and analysis of pressure data taken after an injection well is shut in. The results can also be used in the dynamic reservoir modeling efforts. Can detect changes in reservoir performance that might be an indication of formation damage that could be occurring such as clay migration or geochemical fluid incompatibility.
Gas Chromatograph at Injectate Source/transport Pipeline	Used to monitor impurities in the CO ₂ stream that might damage downhole well components or the formation. Monitoring should include compressor oil in the CO ₂ stream.
Formation Pressure and Temperature Sensors (in and above zone)	Continuous monitoring of formation pressure and temperature can be used to ensure that proper injection operations are maintained in the injection wells and there are no issues with well integrity. These measurements in the storage formation can be used to monitor pressure plume development and calibrate geologic models and reservoir simulations. These measurements for the overlying formations can be used to monitor for changes that may indicate CO ₂ migration through the caprock. To be installed in new wells only.
Pressure and Temperature Sensors and Flow Rate (Wellhead)	Monitors, in real time, the injection pressure and temperature. They will also quantify the amount of CO ₂ that is being injected, how much is being produced and how much is being recycled.
Pulsed Neutron Log (Injection Well)	Used to monitor changes in fluid saturation along a wellbore. It has been proven to effectively detect CO ₂ and differentiate it from brine or oil in the rocks surrounding the wellbore.

Monitoring Technology	Monitoring Technology Description
Forward Seismic Modeling	Synthetic logs, would be generated for different pressure and saturation conditions using fluid substitution. Synthetic logs used to generate synthetic seismic response for different offsets to gauge accuracy of rock physics, and to generate attributes to invert field data for pressure and saturation.
Geomechanical Modeling	Used to evaluate potential leakage pathways by analyzing well log data, seismic data, and core data to develop 3D geomechanical models for a field. These can subsequently be used to optimize drilling and production strategies.
Formation Fluid Sampling and Geochemical Analysis (Obs/Prod Wells)	Fluid samples should be taken from the target formations for geochemical analysis either from production wells or dedicated observation wells.
Arial Light Detection and Ranging	A remote sensing technology that uses a pulsed laser to measure variable distances to the Earth.
Pulsed Neutron Log (Prod Wells)	Used to monitor changes in fluid along a wellbore. It has been proven to effectively detect CO ₂ and differentiate it from brine or oil in the rocks surrounding the wellbore
3D Vertical Seismic Profile	Used to outline the horizontal and vertical plume development over time in the vicinity of the OBS and injection wells. 3D VSP data are acquired with downhole receivers and surface sources. 3D VSP surveys can be used to map large spatial areas. It is a lower resolution data type as compared to well logs but higher resolution than surface seismic surveys.
3D Seismic	Used to monitor the horizontal and vertical CO ₂ plume development over time. Used to monitor any CO ₂ accumulations that may form above the cap rock as a result of CO ₂ migration.
Full Time Monitoring Staff	WMF will require a team to manage operations, regulatory requirements, data interpretation, reservoir simulation updates etc. This team should be comprised of a multi-disciplinary team with skill sets in project management, oilfield operations, regulations, environment, geology, geophysics, reservoir engineering etc.
Monitoring and Data Management System	Using various monitoring technologies in a project of this type will generate a large amount of data consisting of many types and formats. Some of these data will be collected episodically (e.g. wireline logs and 3D seismic) and some will be continually acquired for monitoring in real time (e.g. microseismic and downhole pressure). A real time data acquisition and data management system will be required for real time data sets.
Interferometric Synthetic Aperture Radar	A satellite technology and allows for cost-effective monitoring of large areas of the surface over time. Its success is somewhat dependent on the surface reflectors at the site, and in some cases reflectors may need to be installed, if there are an insufficient number of natural reflectors already present.
Surface Gravity	Gravity surveys use the density contrast between the supercritical CO ₂ and saline formation water to map the developing CO ₂ plume.
Crosswell Seismic	Involves deploying an array of receivers in one well, a source in a nearby well, and acquiring data across the formations of interest. Resolutions on the order of one meter can be obtained, which can be valuable in mapping small scale heterogeneities in the storage formation and detailed plume movement over time through time-lapse crosswell tomography.
Long-Electrode Electrical Resistance Tomography	Downhole electrical and electromagnetic methods use the contrast in resistivity between the CO ₂ and the saline water to map CO ₂ plume development and saturations over time.
Soil Gas and Soil Gas Flux Sampling and Analysis	Designed to characterize a range of soils within the area of interest with respect to land use, soil type, sensitive receptors in the area, and the location of local groundwater wells. These sampling programs are run periodically to detect any CO ₂ that may have migrated to surface. Should provide reassurance to local landowners and the regulator that CO ₂ has not migrated to the surface.
Shallow Groundwater Fluid Sampling and Analysis	Consists of regular sampling of local groundwater production wells and dedicated monitoring wells. Groundwater monitoring is a powerful public outreach and communications tool within the surrounding community and should be managed proactively.

3.4 Risk Management and Monitoring Targets

The primary driver for the development of this ranking was the identified risk scenarios and the associated risk ratings. Several risk assessments have been completed at the WMF (URS, 2010b), (URS, 2010a), (Irani, 2012), (PTRC, 2012a). Table 5 lists each risk scenario with the risk ratings which quantify the likelihood of the scenario occurring and severity if the scenario were to occur. Risk ratings are presented on scale of 1 to 20 (1=low risk, 20=high risk). These risk scenarios were categorized into either a containment/assurance or conformance risk category.

- Containment/Assurance Risk:** The ability of the reservoir/caprock system to contain the injected quantity of CO₂ and assurance that the CO₂ injection will not endanger health, safety, or the environment.
- Conformance Risk:** Conformance of the site to expected performance, which in the case of WMF, is the reservoir's ability to store 30 million tonnes of CO₂ and to demonstrate that the CO₂ plume is behaving in

safe and in predictable ways within the reservoir. The wells uncemented to caprock risk scenario was added as a risk after review of the well integrity.

Each risk scenario requires monitoring of specific monitoring targets in order to reduce the risk of each risk scenario; Table 5 is a matrix displaying this. The “X” indicates which targets require monitoring technology to be applied to reduce risk. The “Change to Project Economics” risk is driven by finances and, therefore, cannot be reduced by monitoring.

Table 5: Risk scenarios and monitoring target matrix

			Monitoring Target												
			Containment						Conformance				Assurance		
Risk Category	Risk Scenario	Risk Rating	Well Integrity	Caprock Integrity	Natural Seismicity And Injection Induced Microseismicity	Migration up into the Jurassic Fm.	Migration up into the Lower Watrous	Migration up into the Poplar & Ratcliffe	Plume Location and Migration in Reservoir	Quantification for Regulatory Authorities	Storage Efficiency and Fine Scale Processes	Calibration of Predictive Models	Surface Leaks: Soil	Surface Leaks: Groundwater	Public Assurance
Conformance	Unable to Confirm CO ₂ in Reservoir	20							X	X	X	X			X
	Change to Project Economics	13													
	Lateral Migration out of the Weyburn Unit	10			X				X	X	X	X			X
	Premature Closure	1													
	Inadequate Source	1									X				
	Reduced Injectivity	1		X						X	X	X			X
Containment/Assurance	Well Casing Corrosion	8	X			X	X	X					X	X	X
	Well Cement Channeling	6	X			X	X	X					X	X	X
	Well Micros Fractures, Micro Annuli	8	X		X	X	X	X					X	X	X
	Wells Uncemented to Caprock	9	X			X	X	X					X	X	X
	Natural Seismicity-Fault Reactivation	1		X	X	X	X	X					X	X	X
	Natural Seismicity-Wells	1	X	X	X	X	X	X					X	X	X
	EOR Minor Faults Network	1		X	X	X	X	X					X	X	X
	Nat Seismicity-New Fractures	1		X	X	X	X	X					X	X	X
	EOR Induced P/T-Reactivation	1		X	X	X	X	X					X	X	X
	EOR Induced P/T-New Fractures	1		X	X	X	X	X					X	X	X
	EOR Induced Chemical-Fractures	1		X	X	X	X	X					X	X	X
	EOR Through Faults	1		X	X	X	X	X					X	X	X

3.5 Well Risk Assessment Methodology

Well integrity was rated as a high risk for the WMF because of the potential for injected CO₂ to migrate up wells with poor well integrity. With risk areas established (Figure 1) it becomes clear that many of the 1,424 horizontal and vertical wells in this EOR field intersect the areas of highest risk (Area 3 to Area 5) and many more do not. These wells also have a range of overall well integrity ratings based on confidential well integrity score data source that was provided by The PTRC. All wells are not equal, thus the wells needed to be ranked with a well risk assessment methodology that ranks the wells from wells with the highest risk to wells with the lowest risk. This well risk ranking is a function of the well integrity rating combined with the wells proximity to risk areas (Figure 1). From this, a visual and well list can identify which wells are within the area of the CO₂ plume and which wells are far enough away to pose little risk. This methodology can be implemented at other similar EOR operations taking into account their site-specifics attributes. A well risk assessment methodology was devised to rank each well based on its well integrity and proximity to CO₂ injection. This well risk assessment methodology is discussed in more detail in the accompanying

paper within this journal (Well Integrity Risk Assessment to Inform Containment Risk Monitoring for Carbon Capture, Utilization, and Storage) (Duguid, 2016).

4 Results

The WMF was used as a case study to rank monitoring technologies that may be used to shift the WMF project from CO₂-EOR to CCUS and therefore, making the project able to claim CO₂ storage credit. All of the recommended monitoring techniques have been evaluated with respect to addressing project risks, cost/benefit and technical applicability and were ranked within matrixes for comparison. The following sections describe how the ranking was developed. A ratio of the calculated cost/benefit was used to ultimately rank each technology as applicable to the WMF. The two criteria used to develop the monitoring benefit ranking were:

- Monitoring Technology Effectiveness Ranking
- Monitoring Targets, Risk Scenarios and Applied Monitoring Technology

The two criteria used to develop the cost ranking were:

- Monitoring Technology Schedule
- Monitoring Technology Unit Cost

4.1 *Monitoring Target Effectiveness Ranking*

Each monitoring technology was evaluated on a scale of 0 to 10 for how effective it is at monitoring each monitoring target for the presence or CO₂ (0 for no effectiveness, 10 for high effectiveness). These variables are defined as the monitoring target effectiveness ranking. The variables chosen were based on professional judgement as to how they apply to the site specific characteristics at the WMF. The numbers chosen here are site specific to the WMF and would need to be site specifically tailored to other fields. The results displayed in Table 6 are ranked as to how effective each technology is at monitoring all the necessary targets. Some technologies are effective at monitoring many targets (e.g. 3D seismic) while other technologies are only applicable to one monitoring target (e.g. cement bond log). The “Monitoring Technology Total Effectiveness Ranking” is not meant to be a method of selecting or eliminating monitoring technology at the WMF, because the project risk, cost, and deployment schedule have to all be taken into account. Its primary purpose is to challenge the assumptions the team has made and identify where the team may be biased towards particular technologies. When evaluating these technologies the monitoring technology sensitivity, baseline data sets, performance requirements, resolution, false positives, false negatives and regulatory reporting requirements were all considered. This general approach of ranking monitoring technology effectiveness was adapted from the IEAGHG Monitoring Selection Tool (IEAGHG, 2015).

Table 6: Monitoring Target Effectiveness Ranking†

		Monitoring Target Effectiveness Ranking (0 to 10 Scale)												
		Containment						Conformance				Assurance		
Monitoring Technology	Total Effectiveness Ranking (0 to 100)	Well Integrity	Caprock Integrity	Natural Seismicity And Injection Induced Microseismicity	Migration up into the Jurassic Fm.	Migration up into the Lower Watrus	Migration up into the Poplar & Ratcliffe	Plume Location and Migration in Reservoir	Quantification for Regulatory Authorities	Storage Efficiency and Fine Scale Processes	Calibration of Predictive Models	Surface Leaks: Soil	Surface Leaks: Groundwater	Public Assurance
3D Seismic	52.3		8		7	3	9	9	9	8	9			6
Pulsed Neutron Log (Injection Well)	47.7	9	9		5	5	5	5	5	8	8			3
Pulsed Neutron Log (Prod Wells)	44.6	9	9		4	4	4	4	5	8	8			3
Full Time Monitoring Staff	42.3	4	4	4	4	4	4	4	4	4	4	4	4	7
Soil Gas and Soil Gas Flux Sampling and Analysis	36.9	7	7		3	3	3		5			7	6	7
Shallow Groundwater Fluid Sampling and Analysis	36.9	7	7		3	3	3		5			6	7	7
Downhole Pressure and Temperature Sensors (Injection Well)	32.3	5	5		5	3	5	3	3	3	7			3
Formation Pressure and Temperature Sensors (in and above zone)	31.5	5	5		5	3	5	3	3	3	6			3
Microseismic Monitoring Array: Surface or Borehole	30.8		7	7				6		6	7			7
Monitoring and Data Management System	29.2	2	3	3	3	3	3	3	3	3	3	3	3	3
Formation Fluid Sampling and Geochemical Analysis (Obs/Prod Wells)	26.2		3		3	3	5	5	3	3	6			3
Pressure and Temperature Sensors and Flow Rate (Wellhead)	25.4	3			2	2	2		9	6	6			3
Pressure Fall-off Test	24.6							6	6	9	8			3
Ultrasonic Imaging Tool	21.5	9			5	5	5	1						3
Geomechanical Modeling	20.0		6	6				4		4	3			3
Offset Well Integrity Investigation	19.2	5			3	3	3					3	3	5
Forward Seismic Modeling	18.5							5	8	3	5			3
Crosswell Seismic	16.2		2		2	2	2	2	2	3	3			3
3D Vertical Seismic Profile	15.4		2		2	1	3	2	2	3	3			2
Distributed Temperature Sensors	13.1	3	3		3	3	3							2
Long-Electrode Electrical Resistance Tomography	13.1	2	4		1	1	1						5	3
Cement Bond Log	10.0	8	2											3
Mechanical Integrity Pressure Test (Tubing and Casing)	9.2	9												3
Packer Isolation Test, In-situ Stress Test	9.2	9												3
Gas Chromatograph at Injectate Source/transport Pipeline	9.2								6	3				3
Multi-Finger Caliper	6.2	5												3
Interferometric Synthetic Aperture Radar	5.4							2	2		2			1
Surface Gravity	5.4		1		1	1	1	1						2
Arial Light Detection and Ranging	3.1							1	1		1			1

† Adapted from the IEAGHG Monitoring Selection Tool (<http://ieaghg.org/ccs-resources/monitoring-selection-tool1>), modified and expanded upon.

4.2 *Monitoring Targets, Risk Scenarios and Applied Monitoring Technology*

A methodology was developed to quantify the benefit of each monitoring technology based on the technology's ability to provide monitoring for each risk scenario (Table 5). For each risk scenario, the following steps were used to quantify the monitoring benefit.

1. **Technology Selection:** Monitoring technologies were selected as potentially appropriate for measuring parameters associated with each risk scenario; measuring these parameters, reduces the impact and consequence of the identified risks.
2. **Monitoring Target Effectiveness Ranking (0 to 10 Scale):** Table 5: Risk scenarios and monitoring target matrix was cross referenced with Table 6 to identify matches. These matches represent the monitoring targets that need to be monitored and how well each technology is capable of monitoring that target. Where matches occurred, relevant monitoring target effectiveness rankings were imported for step 3.
3. **Total Effectiveness Ranking:** The monitoring target effectiveness rankings from step 2 were summed for each monitoring technology associated within each risk scenario.
4. **Risk Percent Effectiveness:** This was calculated to rank how effective each technology is at reducing a particular risk by dividing the total effectiveness from step 3, by the maximum possible value and multiplying by 100. Figure 2 and Figure 3 rank the technologies according to how well they reduce risk.
5. **Monitoring Benefit:** To calculate the monitoring benefit, each risk percent effectiveness value was multiplied by the risk rating (Table 5) as a way to weight a technology's effectiveness to the magnitude of the risk scenario's risk rating. Some identified risks pose a greater risk to the WMF than others, and in some case many times more than others. Any monitoring technology that effectively reduces higher risks will have a proportionally higher benefit to the WMF than technologies that reduce risks with low risk ratings. Table 7 shows a colored matrix representing the monitoring benefit. One will notice that the left portion of the matrix shows higher values because these monitoring technologies are effective at reducing these risks with high risk ratings. The right portion of the matrix shows low values because although these monitoring technologies may be effective at reducing these risks, the monitoring benefit is low because the risk ratings are low.
6. The above steps are repeated for each risk scenario.
7. **Total Monitoring Benefit Ranking:** After all the steps are completed for each risk scenario, the monitoring benefit for each technology across all risks scenarios was totalled. For each monitoring technology, this total monitoring benefit ranking is used as a way to quantify the benefit portion of the cost/benefit ratio (Table 9).

Figure 2: Conformance risks: monitoring technology risk percent effectiveness for each risk scenario (Short names are in Table 9)

Figure 3: Containment risks: monitoring technology risk percent effectiveness for each risk scenario (Short names are in Table 9)

Table 7: Monitoring benefit ranking and summary of the addressed risk scenarios

Risk Ranking: The range is between 1 (low) and 10 (high). Taken directly from the risk assessment				Conformance							Containment/Assurance											
				Number of Technologies applied to each risk	Unable to Confirm CO2 in Reservoir	Change to Project Economics	Lateral Migration out of the Weyburn Unit	Premature Closure	Inadequate Source	Reduced Injectivity	Well Casing Corrosion	Well Cement Channeling	Well Micros Fracs, Micro Annuli	Wells Uncemented to Caprock	Nat Seismicity-Fault Reactivation	Nat Seismicity-Wells	EOR Minor Faults Network	Nat Seismicity-New Fractures	EOR Induced PTI -Reactivation	EOR Induced PIT-New Fracs	EOR Induced Chem-Fracs	EOR Through Faults
			Benefit Rank	Monitoring Technology	Risk Rating (right) Monitoring Benefit (matrix) Total Monitoring Benefit (below)	20	13	10	1	1	1	8	6	8	9	1	1	1	1	1	1	1
1	3D Seismic	36.4	16.4		6.8				2.9	2.1	2.5	3.2			0.4	0.4	0.4	0.4	0.4	0.4	0.4	
2	Full Time Monitoring Staff	31.3	9.2		4.5		0.5	3.5	2.7	3.5	4.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
3	Pulsed Neutron Log (Injection Well)	30.1	11.6		4.8			3.1	2.3	2.7	3.5		0.4		0.3	0.3	0.3	0.3	0.3	0.3		
4	Pulsed Neutron Log (Prod Wells)	28.0	11.2		4.7			2.7	2.1	2.4	3.1		0.4		0.3	0.3	0.3	0.3	0.3	0.3		
5	Monitoring and Data Management System	20.6	6.0		3.0		0.3	2.3	1.7	2.3	2.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3		
6	Pressure Fall-off Test	18.7	12.8		5.3		0.5															
7	Soil Gas and Soil Gas Flux Sampling and Analysis	18.1						4.1	3.1	3.6	4.6			0.5	0.5	0.5	0.5	0.5	0.5	0.5		
8	Shallow Groundwater Fluid Sampling and Analysis	18.1						4.1	3.1	3.6	4.6			0.5	0.5	0.5	0.5	0.5	0.5	0.5		
9	Microseismic Monitoring Array: Surface or Borehole	18.0	10.4		5.5							0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3		
10	Formation Pressure and Temperature Sensors (in and above zone)	16.1	7.2		3.0		0.4	2.4	1.8				0.3	0.3		0.3	0.3			0.3		
11	Forward Seismic Modeling	13.6	9.6		4.0							0.0										
12	Formation Fluid Sampling and Geochemical Analysis (Obs/Prod Wells)	13.0	8.0		3.3							0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2		
13	Downhole Pressure and Temperature Sensors (Injection Well)	12.3	7.6		3.2									0.3	0.3	0.3	0.3	0.3	0.3	0.3		
14	Ultrasonic Imaging Tool	11.9						3.1	2.3	2.7	3.5		0.3									
15	Offset Well Integrity Investigation	11.0						2.9	2.1	2.5	3.2		0.3									
16	Geomechanical Modeling	10.7	5.6		3.3		0.3					0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2		
17	Crosswell Seismic	8.2	5.2		2.2									0.1	0.1	0.1	0.1	0.1	0.1	0.1		
18	3D Vertical Seismic Profile	6.8	4.8		2.0																	
19	Mechanical Integrity Pressure Test (Tubing and Casing)	5.3						1.4	1.0	1.2	1.5		0.1									
20	Packer Isolation Test, In-situ Stress Test	5.3						1.4	1.0	1.2	1.5		0.1									
21	Distributed Temperature Sensors	4.8							1.2	1.4	1.8		0.2	0.2								
22	Interferometric Synthetic Aperture Radar	4.0	2.8		1.2																	
23	Cement Bond Log	3.6							0.9	1.1	1.4		0.1									
24	Arial Light Detection and Ranging	1.6	1.6																			
25	Surface Gravity	1.2	1.2																			
26	Pressure and Temperature Sensors and Flow Rate (Wellhead)	1.0				0.5								0.1	0.1	0.1	0.1	0.1				
27	Multi-Finger Caliper	0.9						0.9														
28	Gas Chromatograph at Injectate Source/transport Pipeline	0.5				0.3	0.2															
29	Long-Electrode Electrical Resistance Tomography	0.0																				

4.3 Monitoring Technology and Temporal Resolution (Schedule)

Table 8 provides a brief description of the possible monitoring frequency (temporal resolution). The schedules here are estimated based on the minimum amount a technology should be used to provide a monitoring derived conclusion. For example, conducting a 3D seismic survey only once is insufficient to provide a reliable estimate of plume locations; however, conducting a survey every other year, may be sufficient to provide a reliable plume location. A detailed schedule was used in the calculations and a brief summary is presented here. The numbers chosen here are site specific to the WMF and would need to be site specifically tailored to other fields.

Table 8: Monitoring technology and temporal resolution (schedule)

Monitoring Technology	Frequency of use
Cement Bond Log	12 wells per year
Mechanical Integrity Pressure Test (Tubing and Casing)	12 wells per year
Multi-Finger Caliper	12 wells per year
Ultrasonic Imaging Tool	17 wells per year
Downhole Pressure and Temperature Sensors (Injection Well)	Continuous Measurement
Distributed Temperature Sensors	Continuous Measurement
Microseismic Monitoring Array: Surface or Borehole	Continuous Measurement
Packer Isolation Test, In-situ Stress Test	15 wells per year
Offset Well Integrity Investigation	Every 3 years
Pressure Fall-off Test	10 wells per year
Gas Chromatograph at Injectate Source/transport Pipeline	Continuous Measurement
Formation Pressure and Temperature Sensors (in and above zone)	Continuous Measurement
Pressure and Temperature Sensors and Flow Rate (Wellhead)	Continuous Measurement
Pulsed Neutron Log (Injection Well)	21 wells per year
Forward Seismic Modeling	Every second year
Geomechanical Modeling	Every third year
Formation Fluid Sampling and Geochemical Analysis (Obs/Prod Wells)	50 samples per year
Aerial Light Detection and Ranging	Every second year
Pulsed Neutron Log (Prod Wells)	15 wells per year
3D Vertical Seismic Profile	3 per year in early stages down to 1 per year at late stages
3D Seismic	Every second year
Full Time Monitoring Staff	Continuous Measurement
Monitoring and Data Management System	Continuous Measurement
Interferometric Synthetic Aperture Radar	Every second year
Surface Gravity	Every second year
Crosswell Seismic	3 per year in early stages down to 1 per year at late stages

Monitoring Technology	Frequency of use
Long-Electrode Electrical Resistance Tomography	3 per year in early stages down to 1 per year at late stages
Soil Gas and Soil Gas Flux Sampling and Analysis	3 per year in early stages down to 1 per year at late stages
Shallow Groundwater Fluid Sampling and Analysis	3 per year in early stages down to 1 per year at late stages

4.4 *Monitoring Technology Ranking: Cost Benefit Ranking*

Twenty nine technologies were considered for ranking. This ranking includes input from all the previous rankings discussed above and acts as an overall ranking that can be used by WMF in assessing potential monitoring technologies. A cost/benefit analysis was completed where each technology was cross plotted on a graph based on the costs versus the total monitoring benefit to the project (Figure 4). Costs were calculated for each monitoring technology as the unit cost per use multiplied by the monitoring schedule. The costs estimates do not take into account monitoring technology that is currently deployed, in these cases, the costs would be less. The cost estimate details and associated methodology are not presented here. Table 9 presents the results in rank order of the cost/benefit ratio calculations with the monitoring objectives each technology meets (conformance, containment and assurance). Monitoring technologies that plotted as high cost and low benefit are considered not feasible. Monitoring technologies that plotted as low cost and high benefit are more easily justified for the project. Monitoring technologies are classified as either:

- **Required (R);** The Saskatchewan regulatory agency specifically requires this technology.
- **Recommended (RC);** These technologies are considered to be the most effective at reducing risk and are recommend to be deployed.
- **Optional (O);** Although these technologies will be effective, it is not necessarily required to deploy them either because of their low cost/benefit ratio, because they are not required by regulations or because another technology may monitor for the same parameter more effectively.
- **Not Feasible (NF);** These technologies were determined not to be effective enough to justify the expense. Many of these technologies were determined to not be successful as per previous PTRC project experience (PTRC, 2012a).

Figure 4: Monitoring technology cost versus benefit rating (Short names are in Table 9)

Table 9: Cost/Benefit ranking of monitoring technology

Cost/Benefit Rank	Cost/Benefit Ratio	Life of Project Cost	Benefit Rating	Tech Short Name	Monitoring Technology and Solutions	Containment	Conformance	Assurance	Required (R) Recommend (RC) Optional (O) Not Feasible (NF)
1	1.78	\$1,575,000	28	PNL-PROD	Pulsed Neutron Log (Prod Wells)	Y	Y		RC
2	1.53	\$700,000	11	GEOMECH-Mod	Geomechanical Modeling	Y	Y		RC
3	1.36	\$1,512,000	21	DATA-MGMT	Monitoring and Data Management System	Y	Y		RC
4	1.24	\$1,100,000	14	SEIS_MOD	Forward Seismic Modeling	Y	Y		RC
5	1.14	\$2,646,000	30	PNL-INJ	Pulsed Neutron Log (Injection Well)	Y	Y		RC
6	1.05	\$504,000	5	MIT	Mechanical Integrity Pressure Test (Tubing and Casing)	Y			RC
7	0.63	\$1,750,000	11	WELL_INVST	Offset Well Integrity Investigation	Y			RC
8	0.44	\$4,080,000	18	Soil	Soil Gas and Soil Gas Flux Sampling and Analysis			Y	R
9	0.44	\$4,200,000	19	PFO	Pressure Fall-off Test		Y		RC
10	0.40	\$3,998,000	16	DHPT	Formation Pressure and Temperature Sensors (in and above zone)	Y	Y		O
11	0.38	\$4,770,000	18	Gwater	Shallow Groundwater Fluid Sampling and Analysis			Y	R
12	0.30	\$3,927,000	12	UIT	Ultrasonic Imaging Tool	Y			RC
13	0.29	\$10,800,000	31	STAFF	Full Time Monitoring Staff	Y	Y		O
14	0.27	\$6,731,000	18	MSEIS	Microseismic Monitoring Array: Surface or Borehole	Y			O
15	0.21	\$6,300,000	13	FFS-PROD	Formation Fluid Sampling and Geochemical Analysis (Obs/Prod Wells)	Y	Y		RC
16	0.17	\$2,760,000	5	DTS	Distributed Temperature Sensors	Y			O
17	0.14	\$2,520,000	4	CBL	Cement Bond Log	Y			RC
18	0.14	\$25,740,000	36	3DSEIS	3D Seismic	Y	Y		RC
19	0.13	\$9,425,000	12	DHP-INJ	Downhole Pressure and Temperature Sensors (Injection Well)	Y			RC
20	0.12	\$3,300,000	4	InSAR	Interferometric Synthetic Aperture Radar	Y	Y		NF
21	0.09	\$1,300,000	1	GRAV	Surface Gravity	Y	Y		NF
22	0.09	\$1,800,000	2	LiDAR	Aerial Light Detection and Ranging	Y	Y		O
23	0.08	\$6,300,000	5	PIT	Packer Isolation Test, In-situ Stress Test	Y			RC
24	0.07	\$1,260,000	1	MFC	Multi-Finger Caliper	Y			RC
25	0.07	\$780,000	1	GAS-CHROM	Gas Chromatograph at Injectate Source/transport Pipeline		Y		O
26	0.05	\$16,430,000	8	CROS-SEIS	Crosswell Seismic	Y	Y		NF
27	0.04	\$17,500,000	7	C-3DVSP	3D Vertical Seismic Profile	Y	Y		NF
28	0.04	\$2,808,000	1	WHPT	Pressure and Temperature Sensors and Flow Rate (Wellhead)	Y	Y		RC
29	0.00	\$2,730,000	0	LEERT	Long-Electrode Electrical Resistance Tomography	Y	Y		NF

5 Summary

When developing the technology ranking, it was important to give weight to the cost effectiveness of the technologies (Table 9). When examining this, with respect to the technologies that are recommended for the WMF, it is apparent that the majority of the highest ranked technologies are recommended. Pulsed neutron logging is important for monitoring changes in gas saturations over time to ensure there is no leakage to above zone formations as well as to provide history matching model data to improve the ability to predict plume behavior. This meets both the objectives of containment and conformance. Furthermore, several regulatory regimes recommend pulsed neutron logging run in both injection and production wells. Because the wells represent the most likely location of leakage risk, well integrity is an important consideration when making recommendations.

Because CCUS projects are relatively new and the monitoring details and technologies are not well understood by stakeholders, there is the requirement of implementing a CCUS Monitoring Plan that contains a level of assurance that demonstrates the CCUS project will have no adverse effects on health, safety, or the environment. To accomplish this, it is recommended that soil gas and soil gas flux sampling be conducted, as well as shallow groundwater fluid sampling with associated analysis to ensure that injected CO₂ has not migrated to surface and/or into local groundwater.

Currently, 3D seismic is the most effective technology available to image the subsurface. In the interest of containment and conformance it is recommended that a series of 3D surface seismic surveys be conducted to monitor the progression of the plume and the data used to history match the model to further improve its accuracy in predicting plume progression.

The monitoring technology ranking can aid in the creation of a monitoring plan. It affords an operator a method of objectively comparing monitoring technologies to address specific needs related to site-specific risks, regulatory regimes, and economics. This ranking was tailored to the WMF; however, it is adaptable to other CO₂-EOR fields interested in converting to CCUS. CO₂-EOR operators adapting this approach will have to adjust their approaches based on site-specific and operation-specific factors.

If this ranking is used to develop a comprehensive CCUS monitoring plan, it should be subject to regular (possibly annual) performance reviews. It is unlikely that the CCUS monitoring plan will perform exactly as expected and significant deviations from expected results will require WMF to adapt the CCUS monitoring plan in response to new information acquired. It is important to note that such deviations would not necessarily imply any failure of the storage facility to meet performance criteria. It may become clear that some monitoring technologies are not working as expected, some monitoring technologies are working better than expected, or the plume is behaving in a way that was not predicted. Change to the monitoring plan may involve:

- Individual monitoring technology deployment schedules may be increased,
- Individual monitoring technology deployment schedule may be reduced,
- Monitoring technology deployment layout may be altered,
- Contingency monitoring technology may be deployed for additional information if a primary technology indicates non-conformance.

The ranked monitoring technologies will aid operators to meet the regulatory requirements by allowing a selection of technologies that meet operational and regulatory requirements. This may allow an operator to select a minimum number of technologies deployed on a minimum schedule while still providing a reliable monitoring derived conclusion on containment, conformance, and assurance.

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