PROJECT DEVELOPMENT AND PERMITTING STRATEGIES FROM THE FIRST WAVE OF GEOLOGIC CO_2 STORAGE PROJECTS IN NORTH DAKOTA

Plains CO_2 Reduction (PCOR) Partnership Initiative
Deliverable 8b

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EXECUTIVE SUMMARY

The North Dakota Industrial Commission (NDIC) has granted the first three geologic carbon dioxide (CO_2) storage facility permits (SFPs) through the state's Underground Injection Control (UIC) Class VI Primacy Program. These first landmark permits, coupled with a well-defined regulatory environment, excellent geology, and stacked storage potential of North Dakota, have resulted in the advancement of a broad range of commercial geologic CO_2 storage projects in the region. The projects being deployed include CO_2 capture from coal-fired power generation, ethanol production, and natural gas compression, processing, and generation. The lessons learned from these projects at all stages of development can be used to support future commercial development of carbon capture, utilization, and storage (CCUS) in the region.

The purpose of this report is to provide an overview of the lessons learned during the project development and permitting of the first wave of geologic CO_2 storage projects in North Dakota. These lessons learned, which have resulted in a set of recommendations and considerations for site characterization, modeling and simulations, permit preparation, communication with regulators, and community outreach, will serve as a project development guide to accelerate the commercial deployment of CCUS. These recommendations and considerations can also be used to streamline geologic CO_2 storage project development and permitting in North Dakota and can be adapted to inform the commercial deployment of CCUS throughout the United States.

Operators of the initial geologic CO_2 storage projects in North Dakota found it necessary to collect 2D or 3D seismic data and drill stratigraphic test wells to characterize potential storage sites. These data acquisition activities proved to be essential for the development of CO_2 storage permit applications, ultimately demonstrating that the storage reservoir was suitable for safe and permanent storage. Eleven stratigraphic test (appraisal) wells have been drilled in North Dakota for site characterization of geologic CO_2 storage sites since 2017. Lessons learned from the drilling, coring, testing, and logging of these wells have provided information critical to the successful development and permitting of geologic CO_2 storage projects. Additionally, learnings acquired during the review and interpretation of existing seismic data and acquisition of new seismic data have informed future efforts regarding the timing for acquisition of a new seismic survey, survey design, and seismic data processing.

Through lessons learned during the development of North Dakota UIC Class VI permits and the subsequent NDIC review and public hearing process, the Plains CO_2 Reduction (PCOR) Partnership has developed several recommendations related to:

- The application and documentation of modeling and simulation methods to address North Dakota UIC Class VI requirements, including documentation of modeling and simulation inputs, assumptions, and results; application of new methods for determining stabilized plume and risk-based area of review; and approaches for geochemical modeling and defining storage facility area.

- The use of a standardized permit template designed to address regulatory requirements that allows the information to be presented in a way that is easier for a non-subject matter expert, such as a stakeholder, to understand and allows the regulator to easily cross-reference the regulatory requirements with the permit text.

- Regular communication with regulators, which promotes transparency and streamlines the permit review process.

- Early, proactive public outreach with stakeholders to share project and activity information, ensure timely communication of project and/or regulatory developments, demonstrate transparency, and show the respect necessary to build the trust needed for community support of a geologic CO_2 storage project.

These lessons learned from the development of approved North Dakota UIC Class VI permits have been integrated with the PCOR Partnership's adaptive management approach (AMA) to generate a generalized timeline for implementing a geologic CO_2 storage project that accounts for the permitting process. This project development timeline, shown in Figure ES-1, comprises all the phases of a project including site screening, feasibility assessment, project design/permit application, regulatory review and approval of the permit, investment/construction, and operations. Despite the range of CCUS project types, each follows a similar commercial development arc and timetable that consist of common stages and decision points. While the timeline shown in Figure ES-1 is specific to the North Dakota UIC Class VI permitting process, these development stages are applicable to all geologic CO_2 storage projects, regardless of geography.

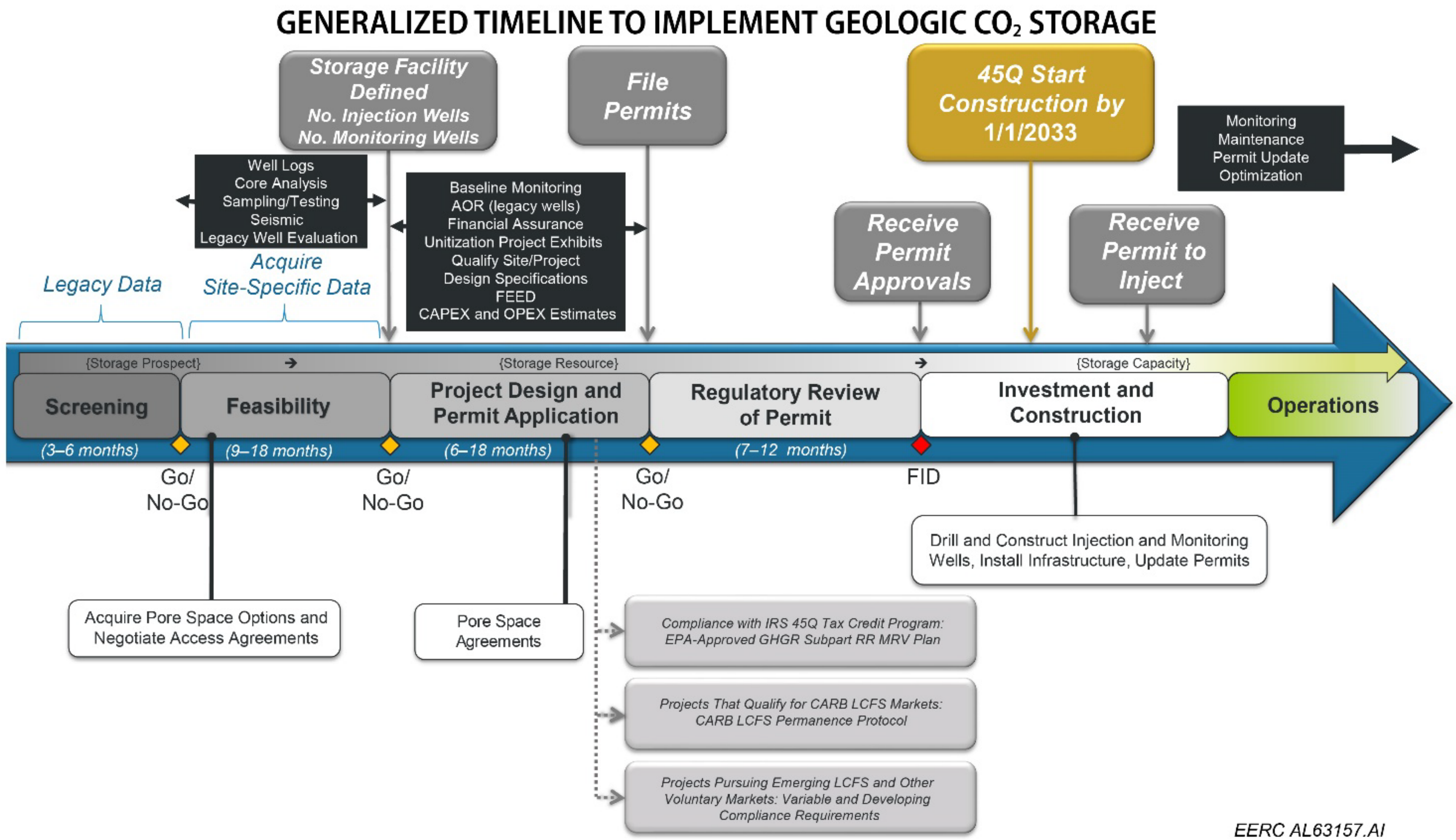

Figure ES-1. Generalized timeline for development of a geologic CO_2 storage project for states with UIC Class VI primacy.

PROJECT DEVELOPMENT AND PERMITTING STRATEGIES FROM THE FIRST WAVE OF GEOLOGIC CO_2 STORAGE PROJECTS IN NORTH DAKOTA

INTRODUCTION

The regulatory certainty of a known, well-defined permitting process is crucial to wide-scale commercial deployment of carbon capture, utilization, and storage (CCUS), beginning with securing the up-front investment required to characterize and permit a geologic CO_2 storage site. In the United States, the time and cost required for permitting a geologic storage of carbon dioxide (CO_2) project with associated underground injection control (UIC) Class VI injection have been identified as a barrier to the commercial deployment of CCUS (Connors and others, 2022a). This barrier has now been better defined and quantified, reducing the uncertainty of the permitting process and its perception as a commercial barrier, as the first commercial CO_2 storage projects have been permitted in the state of North Dakota (Connors and others, 2022b).

The North Dakota Industrial Commission (NDIC) has granted the first three geologic CO_2 storage facility permits (SFPs) through the UIC Class VI Primacy Program of the state (North Dakota Industrial Commission, 2022a). These permitted projects include the Red Trail Energy, LLC (Red Trail Energy) project located in Richardton, North Dakota, and Project Tundra, which is located 3.4 miles southeast of Center, North Dakota. Red Trail Energy is an ethanol facility that captures CO_2 from its fermentation process and has been injecting CO_2 into the Broom Creek Formation since June of 2022 (North Dakota Industrial Commission, 2021a). Red Trail Energy plans to store 180,000 tons of CO_2 per year within the Broom Creek Formation. Project Tundra[1], sponsored by Minnkota Power Cooperative (Minnkota), plans to capture CO_2 from the Milton R. Young Power Station (MRY), a large coal-fired power plant, and store an average of 4 million tons of CO_2 per year in the Broom Creek and Deadwood Formations (North Dakota Industrial Commission, 2021b).

These first landmark permits, coupled with a well-defined regulatory environment, excellent geology, and stacked storage potential of North Dakota, have resulted in a broad range of geologic CO_2 storage projects being advanced in the region. The projects being developed include CO_2 capture from coal-fired power generation, ethanol production, and natural gas compression, processing, and generation. These commercial CCUS projects in North Dakota include both the geologic storage of CO_2 in saline formations (i.e., dedicated storage), which is regulated under the Class VI UIC Program, as well as the geologic storage of CO_2 that occurs in association with CO_2 enhanced oil recovery (EOR) (i.e., associated storage), which is regulated under the Class II UIC Program.

This report provides an overview of lessons learned during project development and permitting of the first wave of geologic CO_2 storage projects in North Dakota, which are primarily dedicated geologic storage projects. This report includes a description of the key project development stages of a dedicated CO_2 storage project, the project development and permitting strategies that have been pursued during the development of approved North Dakota UIC Class VI

[1] Two SFPs are required for this project, one each for the Broom Creek and Deadwood Formations.

permits, and the lessons learned from these efforts, which have resulted in a set of recommendations and considerations for site characterization, modeling and simulations, permit preparation, communication with regulators, and community outreach. Despite the range of CCUS project types, each follows a similar commercial development arc and timetable that consist of common project phases and decision points. The lessons learned from these projects at all stages of development will serve as a project development/permitting guide to accelerate the commercial deployment of CCUS, both in North Dakota and throughout the United States.

CCUS PROJECT DEVELOPMENT

The Plains CO_2 Reduction (PCOR) Partnership, funded by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL), the Oil and Gas Research Program of the NDIC, and the Lignite Research Program, along with more than 230 public and private partners, is advancing the deployment of CCUS in the PCOR Partnership region. The PCOR Partnership region comprises ten U.S. states and four Canadian provinces in the upper Great Plains and northwestern regions of North America (Figure 1). It is led by the University of North Dakota Energy & Environmental Research Center (EERC), with support from the University of Wyoming and the University of Alaska Fairbanks. Implementing CCUS is vital for mitigating anthropogenic CO_2 emissions while allowing the full range of economic and societal benefits derived from the industries that generate the CO_2. The goal of this joint government–industry effort is to accelerate commercial deployment of CCUS throughout the PCOR Partnership region.

The PCOR Partnership has formalized an adaptive management approach (AMA) for the commercial development of geologic CO_2 storage projects (Figure 2) (Ayash and others, 2017). The use of this approach, which draws upon the collective CCUS experience and lessons learned from the PCOR Partnership, represents best practices for advancing CO_2 storage projects toward commercial deployment. At the heart of the AMA are four interactive technical elements that are necessary for any successful CO_2 storage project: 1) site characterization; 2) modeling and simulation; 3) risk assessment; and 4) monitoring, verification, and accounting (MVA) (Figure 2). These elements play a key role in gathering and assessing site-specific data that provide a fundamental understanding of the storage complex and its performance. While each of the four technical elements can provide useful data independently, integrating them through the AMA yields a streamlined, fit-for-purpose strategy for the commercial deployment of CO_2 storage. Key to this integration and resulting best practice are feedback loops that allow the results of each element to serve as inputs to the others. Each iteration of the AMA creates an improved understanding of the storage complex and thus more targeted and efficient applications of the technical elements. For the purpose of establishing an adaptive management framework, hard lines have been drawn between the technical elements of the AMA. However, in practice, the rapid and seamless interaction between the elements can blur these lines. For example, to aid in the analysis and interpretation of site characterization data, a static geocellular model is often required. While this model development is part of the technical element, modeling and simulation, it is an integral part of the site characterization effort. Likewise, much of the monitoring data collected as part of the MVA technical element can be used to inform site characterization. This back-and-forth flow of data and use of models between the technical elements continues throughout the project implementation.

Figure 1. Geographic extent of the PCOR Partnership region comprising ten states (Alaska, Montana, Wyoming, North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Missouri, and Wisconsin) and four Canadian provinces (British Columbia, Alberta, Saskatchewan, and Manitoba).

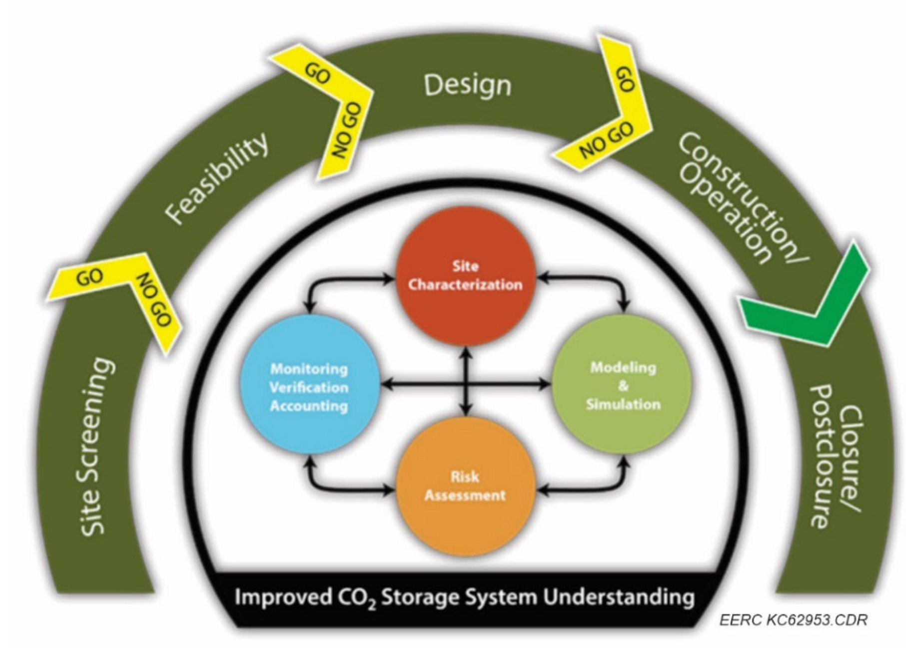

Figure 2. AMA for CCUS project implementation.

Also shown in Figure 2 are the life cycle phases of a geologic CO_2 storage project, which include screening, feasibility, design, construction/operation, and closure/postclosure. The AMA is applied during each phase of the life cycle. As part of each phase, specific questions, which are guided by technical, economic, and regulatory factors, need to be answered prior to advancing to the next project phase. Following each of the preoperational development phases of the project (i.e., site screening, feasibility, and design) are go/no-go decision points that allow the project developer to determine if advancement of the project to the next phase is warranted. The AMA provides the necessary framework to gather the data needed to answer the questions at each project phase and facilitate commercial deployment; however, the exact boundary or scope of a particular life cycle phase may vary from project to project, with the various phases potentially overlapping one another based on the perspective and needs of the individual project operators. Although some key differences exist between dedicated and associated storage of CO_2, the PCOR Partnership AMA can be used to successfully advance commercial projects in either case.

Lessons learned from the development and permitting of the first wave of geologic CO_2 storage projects in North Dakota have been integrated with the AMA to generate a generalized timeline for implementing a geologic CO_2 storage project involving UIC Class VI injection that accounts for the permitting process. This project development timeline, shown in Figure 3, expands the number of project phases shown in Figure 2 to include the permit application and regulatory review and approval of the permit application. This timeline also includes several go/no-go milestones where certain activities and considerations must be addressed before progress to the next project development stage can occur. These milestones should be used by project developers to guide decisions and reflect on how best to proceed with project development activities. While the timeline is specific to the North Dakota UIC Class VI permitting process, these development stages are applicable to geologic CO_2 storage projects across the United States.

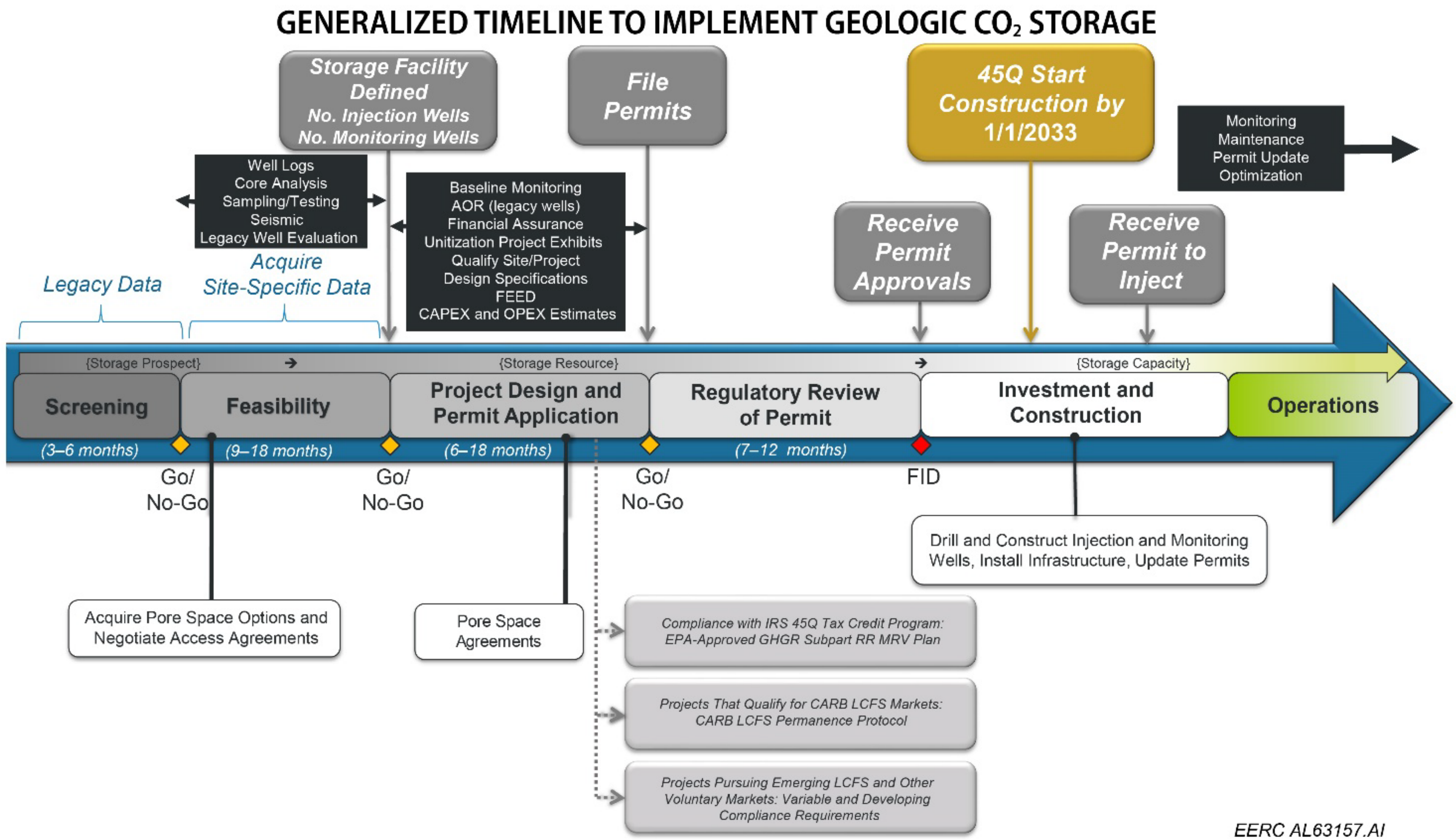

Figure 3. Generalized timeline for development of a geologic CO_2 storage project for states with UIC Class VI primacy.

While the development of the permit application and the regulatory review and approval of the application are not specifically identified in the AMA, it represents an important step to consider when developing a commercial geologic CO_2 storage project. This is especially true for projects that would like to take advantage of incentives that may have timing stipulations, such as 45Q tax credits that have deadlines associated with the start of construction and operation. The permit review and approval process may take several months or even years depending on what agency has primary regulatory enforcement authority of UIC Class VI wells and should be accounted for in project scheduling. By understanding and planning for these regulatory permitting development and review requirements and associated timelines in the early phases of project development, a potential developer can use these considerations to guide both business and technical project decisions.

Permitting considerations for a CO_2 storage project are important even at the earliest stages of project development. To avoid project delays, potential developers should be aware of UIC Class VI regulatory requirements as they proceed with the project. By understanding and planning for regulatory requirements and associated permit review timelines in the early phases of project development, a potential developer can ensure that they have the necessary data/information in hand at the time that regulatory process is initiated.

Site Screening

The first step in developing a geologic CO_2 storage project is the site screening phase. The goal of site screening is to identify one or more candidate storage sites that 1) are economically accessible to a source of CO_2, 2) have sufficient capacity and injectivity to store the total projected volume of CO_2 that will be captured and at the required rate, and 3) have the geologic structure or stratigraphy necessary to securely contain the CO_2 in the storage reservoir. This phase of the project includes the evaluation of existing data and information, which can be found in public domains as well as purchased from private entities. Detailed site screening criteria can be developed on a project-specific basis or adopted from generic guidelines (e.g., IEA Greenhouse Gas R&D Programme, 2009).

In addition to technical and economic considerations, project developers should consider legal components to site development that may preclude a project from moving forward, including land access or other regulatory hurdles related to pore space leasing and pipeline construction right-of-ways. Other important considerations include proximity to commercial oil and gas production and potential for mineral trespass as this may impact permit approval or may become the source of pore space ownership disputes. By communicating with the proper legal and technical teams, these considerations will help determine the viability of potential storage sites in a timely manner. The candidate storage sites selected for further analysis will proceed to the next project phase: feasibility. In the event that no candidate sites are identified during site screening, a no-go decision by the project operator would be warranted.

Feasibility

The focus of the feasibility phase of a project is to determine the technical and economic viability of storing CO_2 at the candidate geologic storage sites that have passed the initial screening exercise and been identified as a potential location for a commercial CO_2 storage project. During this phase, a conceptual design of the storage facility and supporting infrastructure should be developed. This conceptual design should include an estimate of the number of wells required to inject the desired volumes of CO_2 into the target injection reservoir and a preliminary estimate of the footprint of the storage facility and associated area of review (AOR). An initial evaluation of legacy wellbores within this preliminary AOR is also recommended to assess their potential to act as leakage pathways. Additionally, a review of available data should be conducted and a determination of the need to acquire new site-specific data should be made. In some cases, new data may need to be acquired during the feasibility phase of the project to select a final storage site and make a go/no-go determination, depending on the suitability of existing data and technical risks identified as part of the site screening phase.

Project Design and Permit Application

Following storage site(s) selection, a detailed design of the storage system should be developed based on the conceptual design created during the feasibility phase. The detailed design will include all necessary information for the preparation of the final project cost estimate, permitting, and construction of the facility. This phase of the project should also include the final compilation and interpretation of information and data to support the development of a UIC Class VI permit application. Among other technical details, this includes the development of geologic exhibits to demonstrate the suitability of the storage complex for safe and permanent storage of CO_2.

To finalize the design of the storage system and support the preparation of the UIC Class VI permit, modeling and simulations should be conducted to confirm the reservoir has adequate capacity to store the desired amount of CO_2; inform operational parameters including maximum wellhead and bottomhole pressures and annual injection rates; and define the pertinent project boundaries (i.e., extent of stabilized CO_2 plume, storage facility area, hearing notification area, and AOR). As part of the permit application, a detailed evaluation of existing wellbores within the AOR is also required to determine their potential to serve as leakage pathways and a basis for the development of a corrective evaluation plan to mitigate risk of leakage.

Additional supporting plans are required to demonstrate that the site will be safely operated and that controls are in place to mitigate potential leakage and perform reclamation should leakage occur. These plans include a testing and monitoring plan, worker safety plan, emergency remedial response plan, well casing and cementing program, injection well and storage operations plan, and a financial assurance demonstration plan. As part of the testing and monitoring plan, a baseline atmospheric, soil gas, and groundwater-sampling plan should be developed and implemented well in advance of the start of injection to quantify the seasonal variability of the chemical characteristics of these media (Brunson and others, 2022). A plugging and abandonment and postinjection site care plan are also required to show that the project infrastructure will be properly decommissioned in a manner that will ensure safe and permanent storage of the injected CO_2 after injection ends. The financial assurance demonstration is required to verify the proper financial instruments are in place to decommission the site, monitor postinjection site and subsurface conditions, mitigate potential postinjection leakage, and perform remediation, should a leak be discovered.

During the project design and permit application phase, projects looking to take advantage of 45Q tax credits, California Air Resources Board (CARB) Low Carbon Fuels Standard (LCFS) credits, or other emerging incentive programs should also ensure that the project design complies with the requirements of these programs. Evaluating CAPEX (capital expenditure) and OPEX (operating expenses) is also an important consideration for finalizing the project design and developing the required supporting plans for the UIC Class VI permits and incentive program applications.

Results of the project design and permit application phase of the project should inform the go/no-go decision to proceed with filing a UIC Class VI permit application.

Regulatory Review of the Permit

The regulatory review of the UIC Class VI permit application is an important step to consider when developing a commercial CO_2 storage project as the approval process may take several months or even years, depending on what agency has primary regulatory enforcement authority. The two existing UIC Class VI permits issued by EPA took approximately 3 years from the time the permits were submitted to the time of their approval (Bachtel and other, 2022). To date, in North Dakota, NDIC has demonstrated an 8-month permitting process from the time the permit application was filed with the state to the final permit approval decision (Anagnost and others, 2022). An in-depth look at the permitting review timelines for EPA, North Dakota, and Wyoming can be found in Connors and others (2022a).

Once the formal review has taken place and approval has been granted by the overseeing regulatory body, the operator can move forward with the geologic CO_2 storage project. Given the 45Q time restrictions associated with the start of construction and potential financial risks related to investing in construction prior to a site being permitted, the approval of the UIC Class VI permit typically precedes a go/no-go decision related to the final investment decision (FID) and the start of construction.

PROJECT DEVELOPMENT, PERMITTING STRATEGIES, AND LESSONS LEARNED

A number of project development and permitting lessons learned derived from the first wave of dedicated geologic CO_2 storage projects in North Dakota have resulted in a set of recommendations and considerations for site characterization, modeling and simulations, permit preparation, communication with regulators, and community outreach. These recommendations and considerations can be used to streamline geologic CO_2 storage project development and permitting in North Dakota and can be adapted to inform CCUS deployment beyond North Dakota and throughout the United States.

Site Characterization

Characterization of the surface and subsurface at a storage site is necessary to assess the feasibility of a site for safe and permanent geologic storage of injected CO_2. Additionally, site-specific geologic data are required to address many of the regulatory requirements for permitting a geologic CO_2 storage site. Site characterization activities may include the acquisition and analysis of data (e.g., installation of stratigraphic test wells, collection of seismic data, etc.) to develop an understanding of the site-specific properties and characteristics of the surface and subsurface environments. Depending on the project phase, several different types of data may be collected, including petrophysical, mineralogical, geomechanical, hydrogeological, geochemical, and others (e.g., well logs).

Operators of the initial CO_2 storage projects being developed in North Dakota outside of regions studied by the oil and gas industry are finding it necessary to collect 2D or 3D seismic data and drill stratigraphic test (appraisal) wells to characterize potential storage sites because of the lack of existing data. These data acquisition activities have proven to be essential for the development of CO_2 storage permit applications and ultimately proving the storage reservoir is suitable for safe and permanent storage.

Since 2017, the EERC has worked with commercial partners to drill 11 stratigraphic test wells in North Dakota for site characterization of dedicated geologic CO_2 storage sites (Figure 4). Additionally, the EERC and its commercial partners have acquired over 238 square miles of 3D seismic data and 101 miles of 2D seismic data in North Dakota as part of site characterization efforts for these projects. These seismic data sets include five 3D surveys, 11 2D lines, and two 2D source test lines, also shown in Figure 4. Existing 2D and 3D seismic data were also licensed to support site characterization and inform acquisition parameters for new seismic surveys. These site characterization activities have yielded several lessons learned regarding coring, wireline logging, and geophysical data collection and analysis.

Coring

The deep saline formations in North Dakota identified as viable candidates for dedicated CO_2 storage are the Inyan Kara, Broom Creek, and Black Island–Deadwood Formations (Glazewski and others, 2015, Peck and others, 2014; 2020, Sorenson and others, 2009) (Figure 5). To date, over 8500 ft of 4-inch whole core has been collected in North Dakota from the Inyan Kara, Broom Creek, and Black Island–Deadwood Formations and their associated upper and lower confining zones for the purpose of CO_2 storage. The lessons learned from core collection and analysis include the benefits of viewing core in the field, determining proper pump rates while coring, understanding the limitations of sidewall cores, characterizing secondary sealing formations and pressure dissipation zones, determining the coring assembly run length, and assessing the risk of hole stability and washout with saltwater drilling fluid.

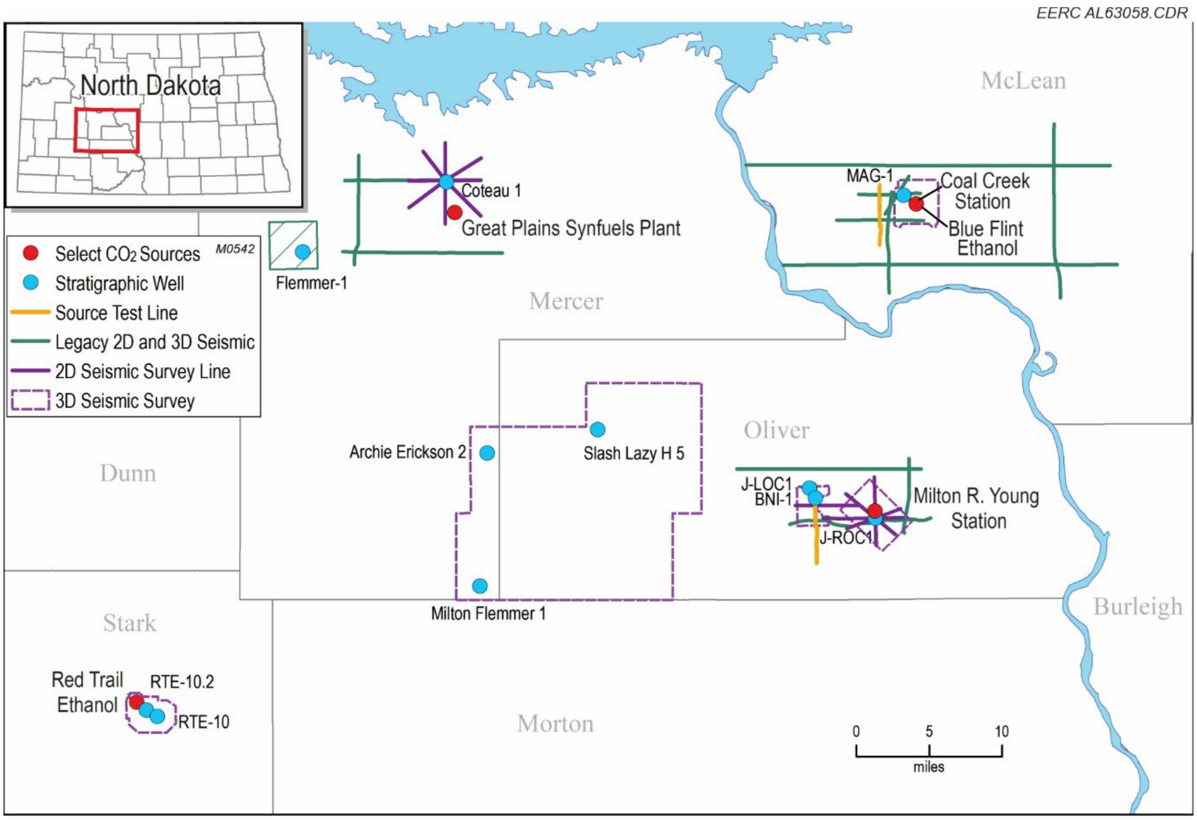

Figure 4. Map of the stratigraphic test wells drilled and seismic data licensed or acquired, to date, for characterization of geologic CO_2 storage sites in North Dakota. It should be noted that an additional source test and several 3D seismic surveys, which have also been acquired to look at the development of CO_2 EOR projects in the Cedar Creek Anticline, are not included on this map (North Dakota Industrial Commission, 2022b).

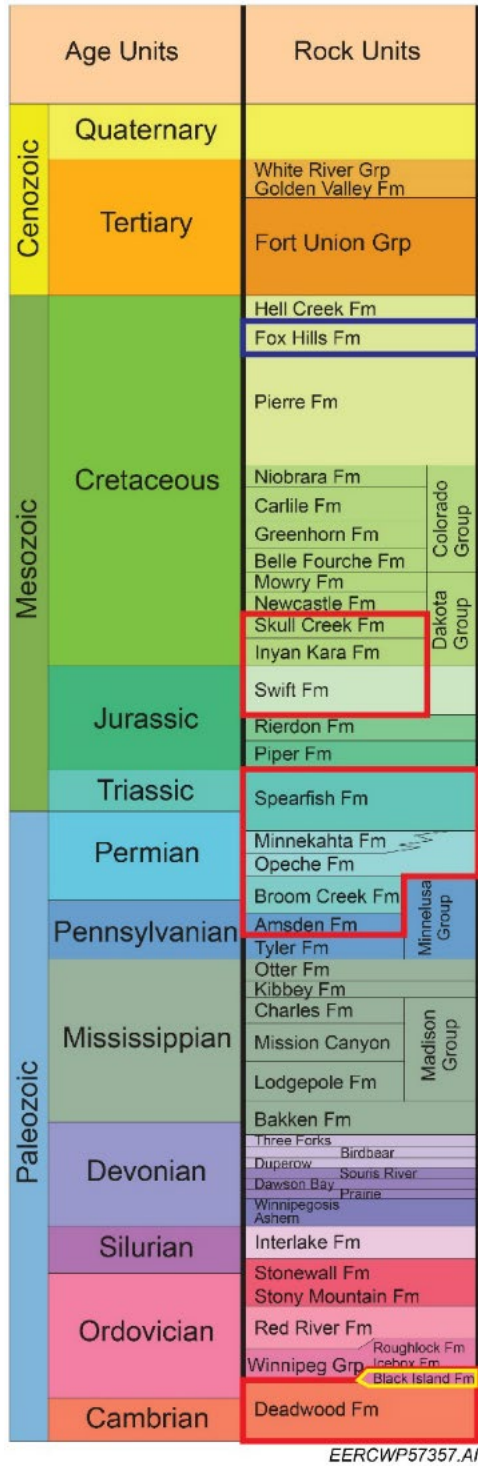

Figure 5. Stratigraphic column showing the Inyan Kara, Broom Creek, and Black Island-Deadwood Formations and their associated confining zones (boxes outlined in red). The box outlined in blue indicates the deepest underground source of drinking water, the Fox Hills Formation.

In areas with sparse data, site-specific core data are necessary to demonstrate that the potential injection zone has the capacity to store the desired amount of CO_2 and to demonstrate the upper and lower confining zones have sufficient properties to act as a seal. The characteristics measured and described from core to assess the suitability of the storage complex and address regulatory requirements include porosity, permeability, mineralogy, ductility, rock strength, and capillary pressure. The EERC recommends whole core collection for characterizing the injection zone and upper and lower confining zones because analysis of sidewall cores is limited. Sidewall cores are more prone to being chipped or fractured while being collected and transported. Chipped or fractured core are unsuitable for analysis of porosity, permeability, and capillary entry pressure. Additionally, sidewall cores are horizontal plugs, and vertical orientation is needed to perform multistage triaxial testing on core plugs to evaluate ductility and rock strength. In the absence of triaxial testing, alternative methods such as generation of a 1D mechanical earth model (MEM) using log data would be needed to address regulatory requirements. As a 1D MEM is a more indirect means of deriving ductility and rock strength, additional justification may need to be included in a permit application to support the use of this methodology.

If acquiring whole core, NDIC recommends acquiring at least 50 ft of core from the upper and lower confining zones. If 50 ft is not achievable because of operational challenges, it must be shown that the upper or lower confining zone rock that was collected has the characteristics of a cap rock. Therefore, during field operations, being able to view the core on-site and determine how much upper and lower confining zone rock was collected and the lithology of that rock is critical. Half-moon aluminum inner core barrels or the ability to cut open the inner core barrels on location provides a first look at the core collection (Figures 6 and 7). Sidewall cores, while not ideal, may be a backup option if drilling conventional core is unsuccessful because of operational challenges or if conventional core is available from a nearby well.

Figure 6. Top: Half-moon liner system that allows viewing of the core at the rig site (Reservoir Group, 2022). Bottom: Field photo of core collected from a stratigraphic test well using the half-moon liner system.

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Figure 7. EERC field operations crew viewing core from a stratigraphic test well drilled near the Minnkota-owned Milton R. Young Power Station.

If transitioning a stratigraphic test well to a UIC Class VI injection well is planned, ensuring adequate core collection (sidewall or whole core) from the reservoir and upper and lower confining zone is necessary as the North Dakota UIC Class VI regulations require that core be collected from injection wells. Regular communication with NDIC is important if operational challenges are encountered during the coring of a stratigraphic test well to ensure compliance with regulations and the ability to permit the well as a UIC Class VI injection well.

CARB LCFS requires characterization of secondary confining zones and pressure dissipation intervals above and below the injection interval. If applying for CARB LCFS carbon credits, CARB authorities may require the collection of core samples (conventional or sidewall) with full analyses from secondary confining zones and upper and lower pressure dissipation intervals.

Operational lessons learned from drilling and collecting core include observations related to core run length and drilling fluid. The EERC compared core recovery percentages from three stratigraphic test wells that use a combination of 40-, 80-, and 120-ft coring assemblies. All three wells were drilled using saltwater gel-based mud. All three core assembly lengths had comparable recovery percentages: 1) Coring with 40-ft core runs resulted in an average of 94.8% returns; 2) Coring with 80-ft core runs resulted in an average of 97.6% returns; and 3) Coring with 120-ft length resulted in core recovery of 93.95% returns. The low return rate for the 120-ft coring runs was a result of washouts in the poorly cemented sand intervals in the reservoir. Returns were improved by lowering the flow rate and the rate of penetration while coring. From an operations perspective, the main difference is cost. Using a longer core barrel assembly greatly reduces rig time and overall drilling cost.

The drilling fluids used for the stratigraphic test wells were invert (oil-based) drilling mud and saltwater gel (water-based). Invert is the drilling fluid of choice for many operators in the Williston Basin throughout the vertical portion of the wellbore. In some cases, when it comes to core analysis for effective permeability, saltwater gel-based drilling fluid has an advantage compared to oil-based mud. Wettability is a controlling factor affecting permeability, which in turn affects injectivity. Effective permeability can be reduced if the wettability of a rock surface is changed from water-wet to oil-wet. In a water-wet system, oil-based drilling fluid can change the system from water-wet to oil-wet (El-Sayed and others, 1999). Despite the positives of core analysis, invert drilling fluid is recommended if coring deep formations like the Deadwood Formation in the Williston Basin. This conclusion is based on data from four stratigraphic test wells that targeted the Deadwood Formation for characterization. Two of those wells were drilled with invert mud, and two were drilled with saltwater gel mud. The two wells drilled with invert mud had better hole stability while drilling, coring, and logging and were subjected to less extensive wash outs. Even on shallower wells drilled with saltwater gel, hole stability leading to wash outs in portions of the wellbore affected the quality of the advanced well log suite and resulted in higher uncertainty in the petrophysical analyses conducted using the logs.

Logging and Downhole Testing and Sampling

Through evaluation of the regulatory requirements and recommended best practices for site characterization, the EERC developed a recommended list of log suites to acquire for a dedicated CO_2 geologic storage site (Table 1). Appendix A expands on the reasoning and justification behind each of these recommendations. The recommended suite satisfies the UIC Class VI well construction requirements and positions CO_2 storage projects for future monitoring during operation and postoperational phases of the project.

The lessons learned from logging and performing downhole testing and sampling in the 11 stratigraphic test wells resulted in recommendations for a spontaneous potential (SP) alternative, tips for modular formation dynamics tester (MDT) formation pressure measurements, and the value add from nuclear magnetic resonance (NMR) and geochemical logs.

Spontaneous Potential

North Dakota Administrative Code (NDAC) Section 43-05-01-11.2 requires that before installation of the long-string casing in a Class VI injection well, an SP log must be run. The SP log requires a conductive mud (water-based) for an accurate measurement. However, NDIC has accepted equivalent or better logs from an oil-based drilling environment. The density porosity log is an acceptable alternative to the SP log in oil-based mud, which provides information about the pore volume of the formations.

Table 1. Recommended Suite of Well Logs for UIC Class VI Wells

OH[1]/CH[2]	Log
	Surface Section
OH	Triple combo (resistivity, density, porosity, GR[3], caliper, and SP)
OH	Acoustic compression and shear (dipole sonic)
CH	CCL[4]-ultrasonic log–VDL[5]–GR–temperature log
OH/CH	**Long-String Section**
OH	Triple combo (resistivity, density, porosity, GR, caliper, and SP (if using conductive mud); GR run to surface (0')
OH	NMR
OH	Spectral GR
OH	Capture spectroscopy
OH	Dipole sonic log (compression and shear waves)
OH	Acoustic, electric, or optical borehole imaging
OH	Fluid sampling
OH	Formation pressure testing
OH	Stress testing
OH	Sidewall cores (as a backup option ***if*** whole core fails)
CH	CCL–ultrasonic log–VDL–GR–temperature log

1 Openhole.
2 Cased hole.
3 Gamma ray.
4 Casing-collar locator.
5 Variable-density log: ultrasonic log for radial cement bond.

Modular Formation Dynamics Tester

Collecting formation fluid from the injection zone and measuring the total dissolved solids (TDS) is a requirement for all UIC Class VI injection wells; however, the method for formation fluid collection is not specified. Throughout our involvement with CO_2 storage projects, formation fluid has been collected in multiple ways, i.e., via MDT Saturn Probe on wireline, drillstem test (DST), or perforation/swabbing. The NMR log has improved the selection of formation fluid-sampling points by providing permeability (based on Schlumberger–Doll research and Timor Coates models) and pore-size distribution. Regardless of method, the acquisition of the fluid sample should always be attempted in a high-permeability zone.

Nuclear Magnetic Resonance

Another regulatory component of the UIC Class VI Program is to acquire in situ reservoir pressures within the confining zone. Several unsuccessful attempts to collect fluid samples from the confining zones in multiple stratigraphic test wells have demonstrated that obtaining a fluid sample from the confining zone using an MDT is not feasible because the fluid is immobile because of the low permeability and porosity of the confining zone. The MDT tool utilizes a large-diameter probe to test both the mobility and the reservoir pressure. The probe was unable to draw down fluid or collect a viable formation pressure measurement in the confining zones because of low to almost-zero permeability. The absence of the mobile fluids provides further evidence of the confining zone properties. NMR logs were used to support these interpretations and demonstrate the immobility of the formation fluid in tight, low-permeability confining zones. The NMR tool can be used to identify intervals with small pore space and low permeabilities.

Geochemical Logs

Another lesson learned through wireline logs is the importance of geochemical logs, such as the elemental capture spectroscopy (ECS) for petrophysical analysis. As mentioned previously, logs were heavily affected by washouts in several wells, resulting in high uncertainties in petrophysical analysis results. To overcome this challenge, additional effort was made to process and edit logs using multilinear regression to predict bad data intervals. This type of additional effort can add time and cost to a project. Another challenge in the petrophysical analysis of the storage formations is related to the complexity of the reservoir resulting from the presence of multimineral components (e.g., illite, muscovite, kaolinite, chlorite, smectite, quartz, calcite, dolomite, anhydrite, pyrite, and K-felspar–plagioclase). Geochemical logs provide critical information in quantifying reservoir mineralogy and swelling clay volumes that affect CO_2 injectivity. These logs are also used to establish correlations with XRD/XRF (x-ray diffraction/x-ray fluorescence) core analyses.

Geophysical Surveys

Although acquisition of geophysical data is not a specific requirement of the North Dakota regulations, geophysical data are an important tool for addressing regulations related to site characterization and deriving information about the subsurface structure and geologic heterogeneity. Seismic is the go-to geophysical method for site characterization over large areas. As part of site characterization for CO_2 storage sites in North Dakota, 2D and 3D seismic data were used to characterize structure, assess interwell heterogeneity, confirm lateral continuity of the injection zone and confining zones, identify potential fluid migration pathways in the confining zones, and optimize injection well placement. Results of the processed and interpreted 3D seismic data were used to enhance and refine 3D geologic models. The newly acquired 2D and 3D seismic surveys will also serve as baseline data sets for time-lapse seismic monitoring of the injected CO_2.

The lessons learned from implementation of reflection seismic methods for development of geologic CO_2 storage projects in North Dakota fall into the following categories:

- Review of existing data
- Timing of survey acquisition
- Site-specific survey design
- Source tests in areas around reclaimed surface coal mines
- Seismic data processing routines to meet site characterization needs

Review of Existing Data

As part of initial site-screening efforts, it is important to determine if seismic data have been acquired at or near the site previously and if they are available to license through seismic data brokers. There are several online resources to interactively determine if data are available for licensing. Where available, existing seismic data are a great tool for site-screening, providing information to aid the interpretation of regional structure. Existing data can also be used to inform the design parameters of a new seismic survey. In some cases, these available seismic data may be suitable for site characterization purposes, alleviating the requirement for the acquisition of new seismic data. Reprocessing existing seismic data represents a best practice that ensures the latest processing algorithms are applied to produce high-quality data.

Prior to licensing existing seismic data, it is important to perform a quality check (QC) of the data to determine if acquisition parameters are appropriate for imaging the subsurface and proposed storage reservoir. If available, previewing the data is an additional step in the QC process for gaining a high-level understanding of the data quality as well as the suitability of the data to meet the project objectives. In addition to evaluating data quality and acquisition parameters, the location of the existing seismic data relative to the proposed storage site and existing wells with available sonic log data should be considered. The ability to tie the seismic data to a nearby well with sonic log data is necessary to accurately identify the formations of interest within the seismic data.

Timing of Survey Acquisition

If the acquisition of new seismic data is required, it is important to determine the appropriate stage in the project development to acquire the data. Seismic data are often a critical path item for geologic CO_2 storage project development as they are used to confirm that the confining zone is free of transmissive faults, which may act as fluid migration pathways, and that the injection and confining zones are laterally continuous.

Evaluating site-specific seismic data prior to drilling a stratigraphic test well can reduce the risk of this investment by helping to identify any fluid migration pathways or stratigraphic pinch outs within the storage complex that may impact the suitability of the site for CO_2 storage. Acquiring seismic data prior to drilling can help to optimize the placement of the well by identifying relatively thick, good-quality reservoir intervals. However, placing the well in a location with optimal reservoir characteristics based on seismic interpretation may result in the well being located on the edge of the seismic survey, requiring additional baseline seismic data to be acquired for future monitoring purposes. Alternatively, choosing a stratigraphic test well location prior to designing a seismic survey allows for optimization of the seismic survey design to acquire baseline data for future monitoring of the injected CO_2 plume, assuming the stratigraphic test well is transitioned into an injection well. Additionally, if a stratigraphic test well is drilled and logged prior to acquiring seismic data, log data will be available to support seismic processing and interpretation workflows.

To meet the start-of-construction deadlines to secure 45 Q tax credits, some operators have drilled stratigraphic test wells prior to acquiring site-specific seismic data. In these cases, initial site-screening work was conducted to evaluate the technical risk associated with potential faults in the region, which included site-specific and regional review of data for understanding the depth of the target injection horizon in relation to the basement, reliance on the interpretation of existing regional seismic data, and a review of published studies related to structural characterization.

Another lesson learned related to the timing of seismic surveys is landowner relations. Developers of geologic CO_2 storage sites in North Dakota have taken extra steps to be good stewards of the land within and around project sites. In doing so, these projects have established good, long-term relationships with both landowners and tenants. More specifically, project developers have made accommodations and worked around planting and harvesting seasons for crops to minimize any inconvenience to landowners or their tenants. Typically, seismic surveys are conducted year-round and landowners are just compensated for crop damage; however, the surveys conducted as part of geologic CO_2 storage projects in North Dakota targeted late fall to early spring to avoid crop damage. In the rare instances where seismic acquisition activities could not wait until after harvesting was complete, operators worked with seismic contractors to minimize crop damage by designing survey lines to be along section lines, reducing traffic to foot traffic only, or moving source and receiver locations. For example, during muddy conditions, operations were paused until fields dried out or, in some cases, source locations were omitted to minimize any damage to fields and roads. Additionally, the layout of sensors and acquisition of source points were coordinated with landowners to minimize damages and inconveniences. These modifications to acquisition schedules included acquiring only source points at certain locations in the survey when the ground was frozen, delaying equipment layout in some areas until late crops were harvested, modifying the acquisition schedule to minimize shutdown time needed for a local gun club shooting range, and removing sensors from certain units during hunting season.

This focus on stewardship was one of the key considerations for survey planning and execution across the geologic CO_2 storage projects and often outweighed survey schedules and survey cost when making decisions. Operators will likely be acquiring seismic data at least once every 5 years as part of their monitoring plans, so it is important during these initial characterization surveys to be good stewards and build relationships that ensure landowner cooperation for future surveys. Additionally, landowners within the seismic survey area are likely to be the same landowners (pore space owners) within the storage facility area, making future cooperation even more critical to the success of the project.

Site-Specific Survey Design

A key lesson learned regarding survey design was consideration of land use. Land use is an important variable to consider when determining survey placement and survey type. Surface obstacles played a large role in designing seismic surveys for geologic CO_2 projects conducted in North Dakota as several were collected around active and reclaimed surface mines, industrial facilities, and waterbodies (i.e., cooling and settling ponds, dams, and naturally occurring waterbodies).

Because of surface obstacles at some sites, 3D seismic surveys were not feasible. In these cases, 2D seismic lines or a network of 2D seismic lines were used to characterize the depth and thickness of formations of interest. These 2D seismic data sets were used to determine the presence or absence of structural features such as faults and assess their impact on shallower target injection zones such as the Broom Creek and Inyan Kara Formations and their associated confining zones (Figure 5). Benefits of acquiring 2D seismic lines are that they can be oriented to avoid obstacles, placed along section lines to minimize impact to cropland, and are a cost-effective means to collect regional data to help characterize the extent of formations of interest beyond the project area and identify regional structural features.

While 2D lines were sufficient to evaluate shallower horizons, the EERC observed that optimally designed 3D seismic surveys are needed to map basement structure and reservoir heterogeneity. Deep basement faults and fractures should be studied for their potential to act as pathways for fluid migration and sources of seismicity during injection operations. Additionally, 3D seismic data are necessary to characterize heterogeneity and integrate with geologic modeling and reservoir simulations to accurately predict the movement of injected CO_2 in the subsurface and to define the storage facility area for permitting. For formations with geologic features that may act as preferential permeability pathways, such as channels that are likely to control the migration of injected fluids, high-quality 3D seismic data are necessary for predicting plume extents. For sites where acquiring 3D seismic for site characterization is not feasible, the monitoring plan should be developed to include more frequent acquisition of data to track the movement of the CO_2 plume, confirm the plume behaves as predicted, and reevaluate the storage facility and AOR boundaries.

In areas with several surface obstacles that limit the placement of source and receiver points for a 3D seismic survey, there are strategies to minimize the impact of these limitations on the data quality. 3D surveys can be designed to minimize areas with low data coverage (low fold) caused by areas where coverage of source and receiver points is reduced. This reduced coverage includes no permit areas, active mine areas, waterbodies, or other infrastructure. Careful design of the source and receiver layout in adjacent areas can help minimize these low-fold areas. Processing techniques such as 5D interpolation can be applied to help fill in low-fold areas; however, while this technique provides better imaging and data quality, it does not make up for the lack of offset coverage in the low-fold area. Data quality issues and migration artifacts associated with these low-fold areas should be considered during interpretation.

Another recommendation for designing a new 2D or 3D seismic survey to characterize a geologic CO_2 storage site is to use preliminary injection well locations and estimates of CO_2 plume size to inform the size and placement of the seismic surveys. Including preliminary well locations and predicted plume size will also help to optimize the coverage for monitoring surveys to confirm predictions based on reservoir simulation studies.

Source Testing Near Surface Mines

A primary concern for sites around reclaimed surface mines is the uncertainty in the quality of seismic data acquired in areas where the near-surface had been disturbed by previous mining and subsequent reclamation activities. In these areas, source and receiver tests can alleviate some of that uncertainty. The low-quality results of a 2D seismic line acquired by the EERC in 2017 over a reclaimed surface coal mine near MRY validated this concern. The 2D line was acquired using a 850-lb-weight drop. Although this acquisition system had been previously used to image sandstone reservoirs at depths of up to 6000 ft, the data from this survey revealed significant attenuation of the seismic signal as indicated by a lack of direct signal arrivals and visible reflections after image stacking. This attenuation was likely due to the 2D survey being conducted across reclaimed mine land that had over 80 ft of near-surface fill. The nature of the acquired data highlighted the need to better understand the impacts of reclaimed mine land on seismic signal attenuation. To that end, a seismic source test was conducted at the same site in fall 2019 to assess the feasibility of acquiring 3D seismic data over reclaimed mine land and to determine what type of seismic source was needed.

The source test involved evaluating vibroseis parameters by varying energy levels, bandwidth and sweep lengths, and a range of dynamite charge weights and shothole depths at two test sites, one on reclaimed mine land and the other on unmined land (Figure 8). Signals from dynamite shots at depths of 20 ft or more below the reclaimed interval were less affected by the reclaimed interval than data from shallower dynamite shots and data from the vibroseis trucks (Figure 9). Results of the source test indicated that the collection of quality 3D seismic data over reclaimed mine land to image deep targets of interest (>9600 ft below the surface required) required dynamite shots with 11-lb charges placed at a depth of at least 20 ft below the reclaimed interval.).

A 3D seismic survey near MRY was subsequently acquired using dynamite shots placed 20 ft below the reclaimed mine layer. Over the survey area, the reclaimed mine area ranged from 65 to 220 ft below the surface. The drilling of shot holes for a 6.5-mile 3D seismic survey comprised 606 shot locations required over 6 weeks. While dynamite was recommended for site characterization purposes, vibroseis trucks could be used for future monitoring surveys to reduce survey time and cost. Results of the source test indicated that vibroseis trucks are sufficient to acquire reflections from the deep target of interest, but the frequency of the data is band-limited. Results showed frequencies above 40 Hz were significantly impacted for data acquired with sources on the surface or within the reclaimed mine layer (Figure 9).

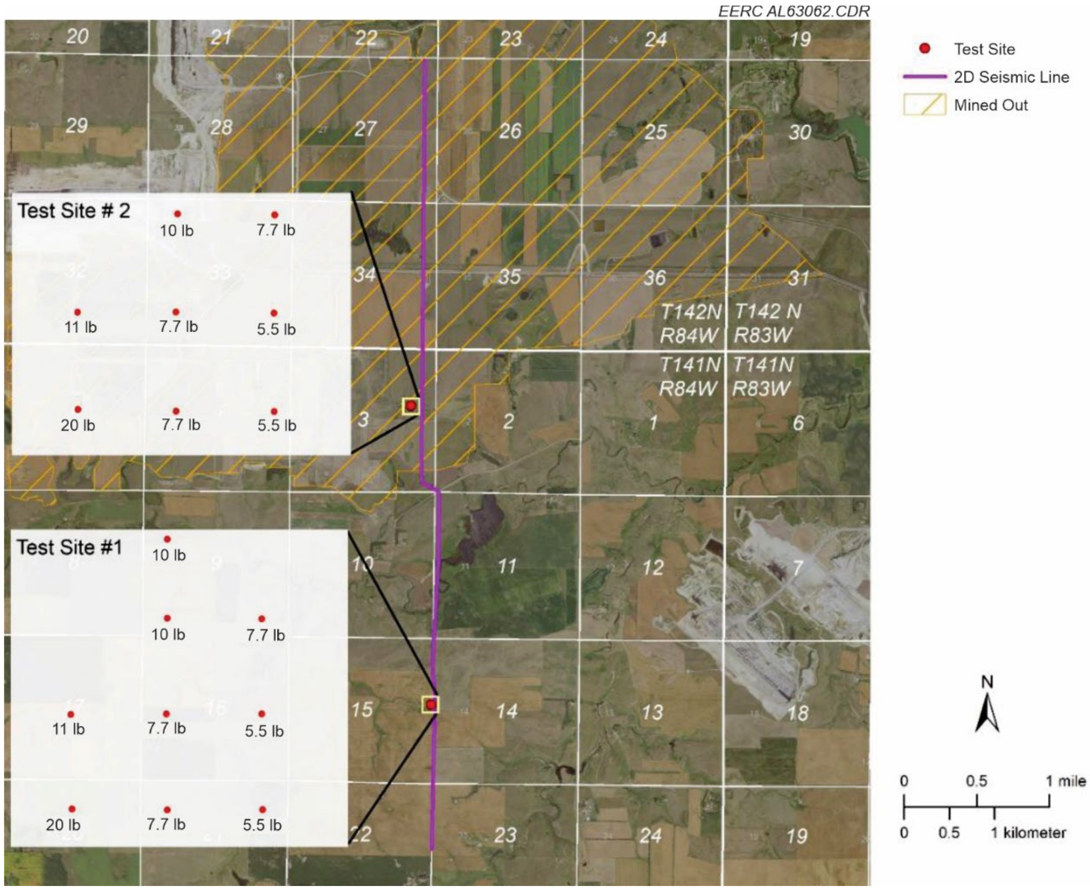

Figure 8. Map showing the seismic source test configuration.

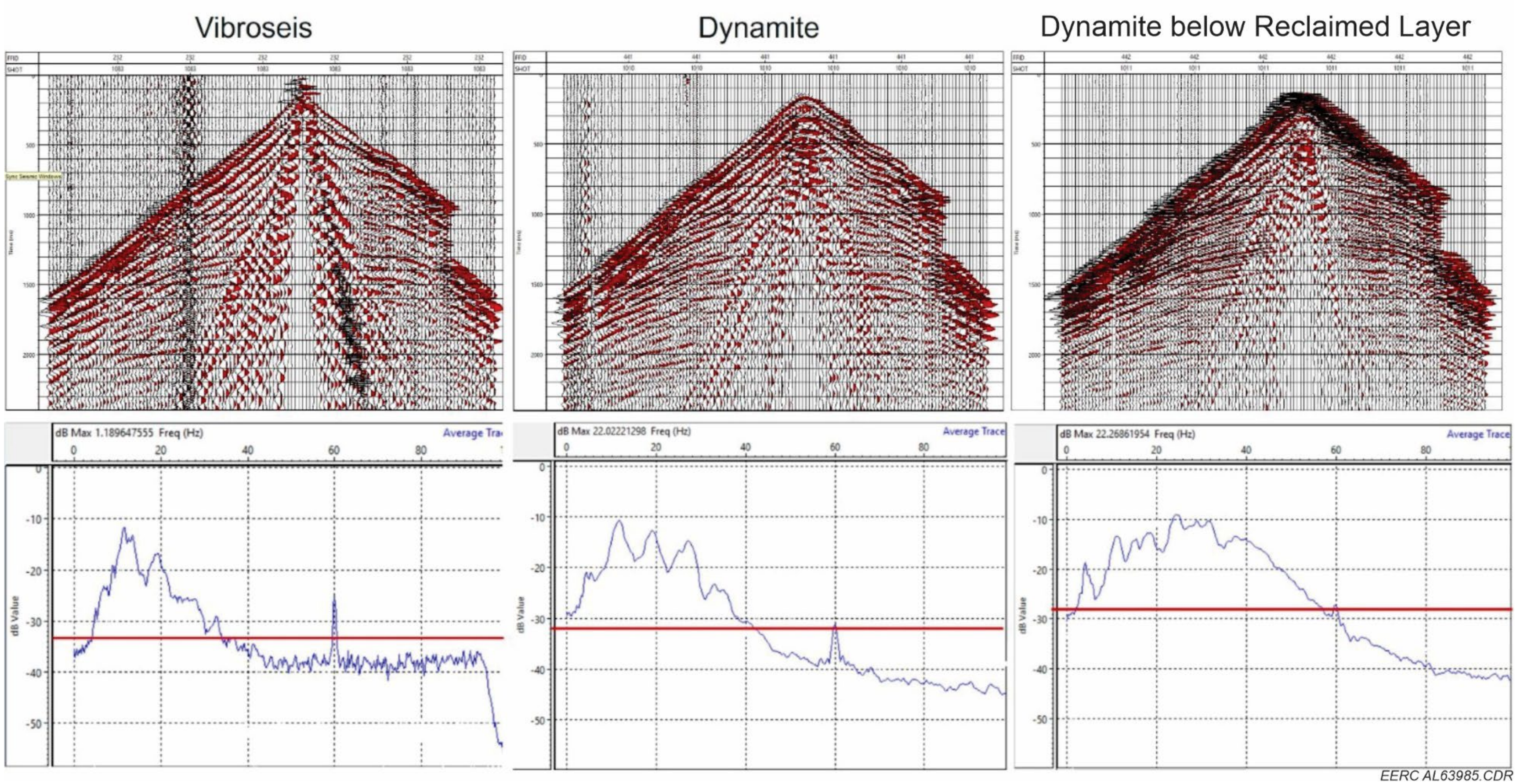

Figure 9. Scaled shot gathers from the source test and associated frequency spectra. The left panel was acquired using two vibroseis trucks with a 30-second sweep. This shot location was on reclaimed mine land, and the shot gather displayed is a stack of two sweeps. The middle panel was acquired using a 5.5-lb dynamite shot at 90-ft depth, which was estimated to be within 5 ft of the bottom of the reclaimed mine layer. The right panel was acquired using a 5.5-lb dynamite shot at 120-ft depth approximately 25 ft below the reclaimed mine layer. The figure includes a cutoff showing relative usable frequency range of 20 dB down from dominant frequency (red line)—clearly showing best bandwidth using dynamite below the reclaimed mine layer (right panel).

Seismic Data Processing

When processing or reprocessing any existing or new seismic surveys, the EERC found it helpful to have regular meetings with the seismic processing company. Processing routines and parameters were regularly reviewed to ensure the chosen parameters provided the best imaging solutions that focused on the zones of interest and adhered to project objectives. Processing was conducted using an iterative approach where the EERC performed initial interpretation on preliminary stacks and gathers and provided feedback to the processing team. One example of this iterative approach was requesting targeted multiple attenuation on the Precambrian basement after initial interpretation of a 3D seismic data set indicated potential structural features in the basement that correlated to deformation in the formations of interest. While this interval was below the lowest formations of interest and not the focus of initial noise and multiple attenuation, having a clearer picture of structural features in the basement helped with interpretation of the features at the boundary between the Precambrian basement and overlying sedimentary units.

Modeling and Simulations

Data collected from geologic cores, well logs, and seismic surveys were incorporated into petrophysical analysis, geologic modeling, fluid-flow simulations, and geochemical modeling for the geologic CO_2 storage projects in North Dakota that are permitted or in the project design and permit application phase. Site-specific data were combined with existing well data and seismic surveys to construct a geologic model of the storage reservoir. The geologic model was used to simulate CO_2 injection to determine the wellhead and downhole pressure response resulting from CO_2 injection. The simulation results were used to determine the expected CO_2 injection capacity, the CO_2 plume and pressure plume extents throughout injection and postinjection, AOR, and the postinjection stabilized CO_2 plume extent. Simulation results were also used to inform the testing and monitoring plan.

This section describes the lessons learned from the modeling and simulation efforts conducted to address North Dakota Class VI regulatory requirements including expectations of the regulators for model review and documentation of modeling and simulation inputs, assumptions, and results. This section also includes recommendations for the application of new methods for determining the stabilized CO_2 plume and risk-based AOR and defining the storage facility area as well as recommended approaches for geochemical modeling.

Model Review

Prior to the submission of the first SFP application, the EERC held working sessions with NDIC to discuss the industry-standard modeling and injection simulation methods that would be used by operators in developing SFP applications. These discussions included a review of the types of files that would be generated and the different software packages that would be used. NDIC used this information as a resource to develop a workflow for its review of SFP applications and supporting ancillary data, including model files. To verify inputs and results produced from modeling and simulation of CO_2 injection, NDIC requires the SFP applicant to supply the simulation model files as part of the application.

To aid NDIC's verification of the inputs and results from geologic modeling and numerical simulations, it is important for the SFP application to document how modeling and simulations were conducted. Inputs and assumptions used to construct the geologic model and parameters and constraints used to complete numerical simulation of CO_2 injection need to be documented and supplied to the regulator.

Additionally, while not required by regulations, NDIC has requested information on any sensitivity testing that was performed as part of the simulations of CO_2 injection that are included in the SFP application.

Stabilized CO_2 Plume and Storage Facility Area

As part of the SFP application in North Dakota, the operator needs to define a storage reservoir boundary, or storage facility area, beyond which CO_2 will not migrate during injection or postinjection site care period. The duration of the postinjection site care period is dependent on the time it takes the CO_2 plume to stabilize, i.e., no longer migrate, which must be demonstrated by the operator as a prerequisite for the closure of the site by NDIC. The predicted extent of the stabilized plume is used as a basis for defining the storage facility area. Since few commercial-scale geologic CO_2 storage projects have operated for a sufficient period to observe CO_2 plume extents at the end of operations or following the cessation of injection, both CO_2 plume migration and subsequent stability rely upon predictions based on geologic modeling and numerical reservoir simulations.

Several numerical reservoir simulations have been conducted by the EERC to evaluate the migration of CO_2 injected into the Broom Creek Formation at several sites in North Dakota. These simulations predict that the CO_2 plume will continue to slowly migrate updip within the formation after injection ceases. To determine when migration of the plume ceases, the EERC simulated the area of the CO_2 plume at 5-year intervals over the course of a 100-year postinjection period. For each 5-year time step, the CO_2 plume area, change in CO_2 plume area, and derivative of the area with time were calculated from the model grid cells.

The 3D storage reservoir contains multiple geologic model layers. For calculating the CO_2 plume area, the storage reservoir layers were projected onto a 2D plane to express the CO_2 plume extent in map view. Any x–y map view grid cell that included a single cell thickness of >5% CO_2 saturation (anywhere in the z domain) was included within the plume boundary. The CO_2 plume extent is defined as >5% CO_2 saturation, after the findings of Whittaker and others (2004), White and others (2014), and Roach and others (2014, 2017). The authors from these studies showed their geologic models and time-lapse 3D seismic data, developed for CO_2 EOR projects in Saskatchewan, Canada, had high sensitivity to intervals where CO_2 saturation was between 5% and 10% in the reservoirs and 6–13 m in thickness. Because seismic data may only detect saturated areas of greater than 6-m thickness, this approach represents a conservative view (overestimate) of the measurable size of the CO_2 plume. An alternative to a >5% saturation cutoff would be to use fluid substitution modeling to derive a site-specific cutoff.

In general, scenarios evaluated to date predict the CO_2 plume will continue to migrate one or two model grid cells updip every 5 years. An exception to this was observed for one of the scenarios, which predicted that the plume would stop migrating at 90-years postinjection. Based on these modeling and simulations results, the EERC recommends using the derivative of area (dA/dt) metric presented in Harp and others (2019) to determine the stabilized plume boundary. Using this method, the CO_2 plume is defined as stable when the rate of change in area over time levels off. A detailed discussion of this approach can be found in Regorrah and others (2022).

A buffer between the stabilized CO_2 plume and the storage facility area boundary is established to ensure the CO_2 plume never crosses the storage facility area boundary. Operators have typically drawn this buffer at a distance of approximately ½ mile from the stabilized CO_2 plume, squaring it off to the nearest quarter section or land tract to simplify legal descriptions of the storage facility area for pore space leasing purposes (Figure 10).

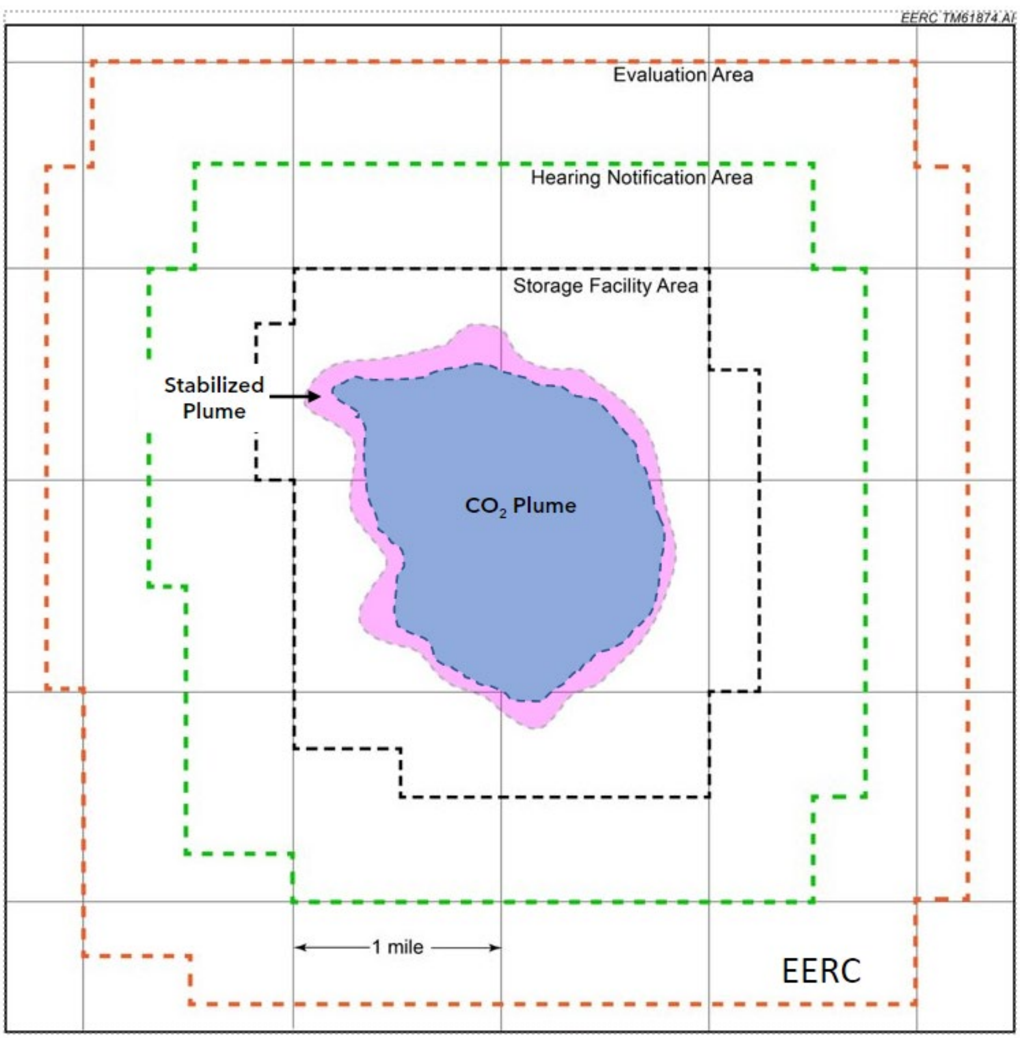

Figure 10. Map showing conceptualized boundaries of a storage project, including the CO_2 plume at the end of injection (blue area), the stabilized plume (pink area), the storage facility

area, the hearing notification area, and the evaluation area (AOR) for a geologic CO_2 storage project.

Risk-Based Area of Review

EPA guidance (U.S. Environmental Protection Agency, 2013) for delineation of the AOR includes several computational methods for estimating the pressure buildup in the storage reservoir in response to CO_2 injection and the resultant areal extent of pressure buildup above a "critical pressure," which is defined as the pressure that could potentially drive higher-salinity formation fluids from the storage reservoir up an open conduit to the lowermost USDW. The methods described by EPA for estimating the AOR under the UIC Class VI regulations were developed assuming that the storage reservoirs would be in hydrostatic equilibrium with overlying aquifers. However, in the state of North Dakota, and around the United States, some storage reservoirs are already overpressurized relative to overlying aquifers and thus subject to potential vertical formation fluid migration from the storage reservoir to the lowermost USDW, even prior to the planned storage project. Consequently, applying the assumed-equilibrium methods of EPA to these geological situations essentially results in an infinite AOR, which makes regulatory compliance infeasible (Burton-Kelly and others, 2021).

Several researchers have recognized the need for alternative methods for delineating the AOR for locations that are already overpressurized relative to overlying aquifers. For example, Birkholzer and others (2014) described the unnecessary conservatism in EPA's definition of critical pressure, which could lead to a heavy burden on SFP applicants. In response to this situation, the EERC published a peer-reviewed research article in the Greenhouse Gases Science and Technology Journal entitled "Risk-Based Area of Review Estimation in Overpressured Reservoirs to Support Injection Well Storage Facility Permit Requirements for CO_2 Storage Projects" (Burton-Kelly and others, 2021). This manuscript presents an alternative risk-based reinterpretation of this EPA framework that would allow for a more realistic assessment of the AOR while ensuring protection of drinking water resources. This risk-based definition of the AOR was incorporated into the two SFP applications that have been approved in North Dakota

Geochemical Modeling

North Dakota UIC Class VI regulations require a study that addresses the potential chemical reactions between injected CO_2 and the rock material and formation fluids of the reservoir and confining zones (upper and lower). Baseline mineralogical and fluid chemistry data obtained through sampling and subsequent analyses prior to injection are needed to evaluate these potential rock–fluid–CO_2 interactions, which may cause changes in injectivity and storage capacity and changes in the properties of injection/confining zones. Baseline geochemical data can also be used as a basis for comparing geochemical monitoring data collected during injection and/or postinjection periods for the purpose of evaluating the occurrence of geochemical interactions as a result of the CO_2 injection.

Geochemical reactions induced by CO_2 injection can be investigated through laboratory experiments or geochemical modeling and simulation tools or both. Laboratory experiments are instrumental in understanding short-term effects of CO_2 on subsurface rocks and fluids such as pH change of the formation fluids resulting in the acidification of the formation fluids, subsequent changes in the anions and cations present in the fluids, and dissolution of carbonates following CO_2 injection. However, the longer term effects of interaction with CO_2 need to be evaluated over a longer period of time, which cannot be realistically examined through laboratory experiments. On the other hand, geochemical modeling and simulations are powerful and cost-effective tools capable of providing a better understanding of the long-term interactions of CO_2 with the rocks (such as precipitation of secondary minerals) and fluids and rock properties such as porosity and permeability that ultimately define the storage capacity and injectivity (Xu and others, 2004).

Computer modeling and simulations are the recommended approach for investigating potential geochemical reactions of CO_2 in injection and confining zones to address the UIC Class VI requirements. For the permits approved to date, the EERC used Computer Modelling Group's (CMG's) GEM, a compositional fluid flow and reactive transport simulator, to investigate geochemical reactions within the reservoir zone. GEM is capable of simulating the extents of the reactions that occur in the reservoir in 3D, allowing users to develop the most accurate representation of the reservoirs. In addition, the inventory of the injected CO_2 among the different trapping mechanisms in the injection reservoir can be evaluated using GEM. This inventory is important for monitoring and accounting for the injected CO_2, which is information of interest to many stakeholders. However, one drawback of this kind of numerical investigation, one that couples fluid flow with reactions using 3D reservoir models, is that it can be computationally expensive.

The more chemical components that are considered in the geochemical evaluation using CMG's GEM modeling and simulation, the more costly the numerical computation will be and the more likely it is that it will experience numerical convergence problems, possibly delaying progress of the project. Hence, prior to performing geochemical modeling and simulation, a careful review of the injection stream data and the composition of its minor components should be conducted, followed by a decision regarding the simplification of the stream composition by eliminating some or all the impurities that would have no effect on the geochemical reactions but would facilitate a faster numerical computation. Typical impurities found in the CO_2 stream from sources such as power plants or ethanol plants include water vapor, nitrogen, hydrogen sulfide, and oxygen. EERC experience and guidance are that the CO_2 injection stream impurity components such as oxygen and hydrogen sulfide should be used as inputs for geochemical simulation as oxygen may cause some geochemical reactions involving iron-bearing minerals and hydrogen sulfide that may increase the acidity of the rock fluids. However, impurities such as water vapor and nitrogen can be removed to simplify the injection stream composition for modeling and simulation as these components are considered more inert and neutral from a geochemical perspective and their effects on the injection zone could be insignificant.

To investigate geochemical reactions within the confining zones, the EERC recommends using PHREEQC modeling software, which considers 1D fluid flow coupled with geochemical reactions. The main reasons for using PHREEQC instead of GEM for the confining zones is that PHREEQC allows CO_2 to enter the system by molecular diffusion process. Due to the low permeability, CO_2 is not expected to penetrate far into the confining zones. However, PHREEQC uses a molecular diffusion process, which permits the CO_2 to more freely enter the confining zones as compared to what is anticipated at an actual storage site. This allows for a more conservative (worst-case scenario) evaluation of the potential negative impacts of geochemical reactions on the competency of the confining zone from geochemical reactions. In addition to this conservative feature of PHREEQC, the EERC also recommends taking a conservative approach when selecting inputs and parameters to use regarding the upper confining zone, e.g., overestimating the CO_2 exposure level as compared to the expected amount or using CO_2 stream compositions with higher than anticipated percentages of reactive impurities such as O_2.

Permit Preparation

NDIC does not have specific guidelines or a template for SFP applications. Therefore, the EERC developed a proposed SFP template, which is publicly available, through a state-funded research project (Connors and others, 2020). The structure of the EERC template was constructed using the North Dakota UIC Class VI regulations as a guide. Through lessons learned with each SFP submittal, the template has evolved over time to reflect feedback from regulators and address the unique aspects of the individual projects.

The template consists of three main components: the main body of the permit application provided in a report format, appendices with ancillary information, and a SFP regulatory compliance table. The main body of the SFP template is a report that contains the information needed to address regulatory requirements of North Dakota. This report starts with an overview of the project and summary of the permit followed by sections that detail the site characterization findings, data, and supporting information needed to give a full picture of the project. The information in these sections is grouped together based on subject matter and does not necessarily follow the same order that the requirements appear in the regulatory code. This report-style format was selected because it provided a structure and flow in which descriptions about technical topics such as data collection or anomalies in data sets could be described in greater detail. This report-style format is beneficial as it allows the information to be presented in a way that is easier for a non-subject matter expert, such as a landowner or other stakeholders, to understand.

While there are benefits to this report-style format, one of the biggest drawbacks is that it makes it more difficult for the regulator to review and determine if all the regulations have been met. Therefore, the SFP regulatory compliance table included at the end of the SFP application template was designed for the regulator to be able to easily cross-reference the regulatory requirements with the report text. An example of the SFP regulatory compliance table is provided in Figure 11. As shown, it provides the following information: 1) the permit item, 2) reference to the specific regulatory code that addresses the permit item, 3) the specific requirements of the regulatory code, 4) a summary of the actions that need to be taken to address the regulatory requirements, 5) the section and page number of the main text of the permit application that addresses the regulatory requirements, and 6) a description of the figures and tables in the permit application that support the permit application. This template has been used for all the permits submitted and approved to date in North Dakota. Feedback received from NDIC has noted that this compliance table has made the review of the permit more straightforward and less time-consuming.

As of September 2022, the EERC has assisted with the preparation of five UIC Class VI SFP applications in North Dakota. Through permit development and the subsequent NDIC review and public hearing process, the EERC has noted several lessons learned related to preparing an SFP. These lessons learned are related to the following broad categories:

- Presentation of data
- Descriptions of methodology
- Addressing regulator and landowner concerns

The lessons learned for each of these broad categories are provided in the remainder of this section.

Data Presentation

Lessons learned related to presentation of data, including recommendations for how to present data, types of supporting information to include, and pitfalls to avoid, have been documented. In general, data needed to address regulations should be presented in map, figure, or table format. Presenting data in these formats, as opposed to including them in the text, makes it easier for the regulator to find and review. One pitfall to avoid when presenting data in the SFP application is to try to only present data or information in one place to minimize redundancy and to avoid reporting inconsistent values or information. Another common pitfall is consistency in units. Having a consistent unit for depth TVD (true vertical depth), MD (measured depth), or SSTVD (subsea true vertical depth) across maps, figures, and tables is helpful for the regulators to compare information. Additionally, having relevant units is something to consider. For example, reporting capillary entry pressure in terms of CO_2/brine instead of mercury air. Another recommendation for presenting data is to clarify data sources, e.g., average depth over the model area versus depth at the stratigraphic test well. Limiting map extents to show only information relevant to address the regulatory requirements is also important. While models may cover the whole basin, showing a map of the whole basin may increase the likelihood that data important to the storage facility area and AOR being permitted may not stand out and may be overlooked.

The SFPs that have been submitted to NDIC have all been over 350 pages because of the report-style format. The size of the permit applications significantly impacts the NDIC review time, and ultimately, the time it takes for a permit to be approved. Therefore, it is important to be as concise as possible when presenting the information and data necessary to meet the regulatory requirements and to only present relevant information. If necessary, more data and information can be shared with the regulators upon request.

STORAGE FACILITY PERMIT REGULATORY COMPLIANCE TABLE

Permit Item	NDAC Reference	Requirement	Regulatory Summary	Storage Facility Permit (Section and Page Number; see main body for reference cited)	Figure/Table Number and Description
Pore Space Amalgamation	NDCC 38-22-06 §3 & 4 NDAC 43-05-01-08 §1 & 2	**NDCC 38-22-06** 3. Notice of the hearing must be given to each mineral lessee, mineral owner, and pore space owner within the storage reservoir and within one-half mile of the storage reservoir's boundaries. 4. Notice of the hearing must be given to each surface owner of land overlying the storage reservoir and within one-half mile of the reservoir's boundaries. **NDAC 43-05-01-08** 1. The commission shall hold a public hearing before issuing a storage facility permit. At least forty-five days prior to the hearing, the applicant shall give notice of the hearing to the following: a. Each operator of mineral extraction activities within the facility area and within one-half mile [.80 kilometer] of its outside boundary; b. Each mineral lessee of record within the facility area and within one-half mile [.80 kilometer] of its outside boundary; c. Each owner of record of the surface within the facility area and one-half mile [.80 kilometer] of its outside boundary; d. Each owner of record of minerals within the facility area and within one-half mile [.80 kilometer] of its outside boundary; e. Each owner and each lessee of record of the pore space within the storage reservoir and within one-half mile [.80 kilometer] of the reservoir's boundary; and	a. An affidavit of mailing certifying that all pore space owners and lessees within the storage reservoir boundary and within one-half mile outside of its boundary have been notified of the proposed carbon dioxide storage project;	Red Trail Energy (RTE) has identified the owners (surface and mineral); in addition, no mineral lessees or operators of mineral extraction activities are within the facility area or within one-half mile of its outside boundary. RTE will notify all owners of a pore space amalgamation hearing at least 45 days prior to the scheduled hearing and will provide information about the proposed CO_2 storage project and the details of the scheduled hearing. An affidavit of mailing will be provided to the North Dakota Industrial Commission (NDIC) to certify that these notifications were made.	
			b. A map showing the extent of the pore space that will be occupied by carbon dioxide over the life of the project;	**1.0 PORE SPACE ACCESS – Page 1-1** North Dakota law explicitly grants title of the pore space in all strata underlying the surface of lands and waters to the overlying surface estate, i.e., the surface owner owns the pore space (North Dakota Century Code [NDCC] Chapter 47-31-Subsurface Pore Space Policy). Prior to issuance of the Storage Facility Permit (SFP), the storage operator is mandated by North Dakota statute for geologic storage of carbon dioxide (CO_2) to obtain the consent of landowners who own at least 60% of the pore space of the storage reservoir. The statute also mandates that a good faith effort be made to obtain consent from all pore space owners and that all nonconsenting pore space owners are or will be equitably compensated. North Dakota law grants NDIC the authority to require pore space owned by nonconsenting owners to be included in a storage facility and subject to geologic storage through pore space amalgamation. Amalgamation of pore space will be considered at an administrative hearing as part of the regulatory process required for consideration of the SFP application (NDCC § 38-22-06(3) and -06(4) and North Dakota Administrative Code [NDAC] § 43-05-01-08(1) and -08(2)). RTE has identified the owners (surface and mineral); in addition, no mineral lessees or operators of mineral extraction activities are within the facility area or within one-half mile of its outside boundary. RTE will notify all owners of a pore space amalgamation hearing at least 45 days prior to the scheduled hearing and will provide information about the proposed CO_2 storage project and the details of the scheduled hearing. An affidavit of mailing will be provided to NDIC to certify that these notifications were made. The identification of the owners, lessees, and operators that require notification was based on the following, recognizing that all surface owners also own the underlying pore space per North Dakota law, which vests the title to pore space in all strata underlying the surface of lands to the owner of the overlying surface estate (NDCC Chapter 47-31): • A map showing the extent of the pore space that will be occupied by CO_2 over the life of the project, including the storage reservoir boundary and 0.5 miles (0.8 kilometers) outside of the storage reservoir boundary with a description of pore space ownership, surface owner, and pore space lessees of record (Figure 1-1). • A table identifying all pore space (surface) owners, each owner's mailing address, and a legal description of pore space landownership (Table 1-1). • A table identifying each owner of record of minerals and each mineral lessee of record (Table 1-2). Note: All surface owners and pore space owners and lessees are the same owner of record, and there are no operators of mineral extraction activities within the storage facility area.	Figure 1-1. Storage Facility area map showing pore space ownership.
			c. A map showing the storage reservoir boundary and one-half mile outside of the storage reservoir boundary with a description of pore space ownership;		Figure 1-1. Storage Facility area map showing pore space ownership.
			d. A map showing the storage reservoir boundary and one-half mile outside of its boundary with a description of each operator of mineral extraction activities;		Table 1-2 showing mineral ownership and lessees
			e. A map showing the storage reservoir boundary and one-half mile outside of its boundary with a description of each mineral lessee of record;		
			f. A map showing the storage reservoir boundary and one-half mile outside of its boundary with a description of each surface owner of record;		Figure 1-1. Storage Facility area map showing pore space ownership.
			g. A map showing the storage reservoir boundary and one-half mile outside of its boundary with a description of each owner of record of minerals.		Table 1-1. Owners, Lessees, and Operators Requiring Pore Space Hearing Notification

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Figure 11. Example page from the SFP regulatory compliance table from the Red Trail Energy SFP application (North Dakota Industrial Commission, 2021a).

Descriptions and Justification of Methodologies

NDIC has requested several pieces of information that are not specified in the regulations during the permit review and public hearing process. Including this requested information in subsequent permit applications has streamlined the permit review process and shortened the public hearings. The additional information requests have included descriptions of how data were acquired or calculated, explanations of any anomalies in the data presented such as bull's-eyes on structure maps caused by gridding algorithms used, and justification or supporting evidence for why the operator believes the data/information and methods used to obtain it are sufficient to meet the regulations. For example, when calculating fracture pressure using a 1D MEM as opposed to determining it through field tests, NDIC has requested tables of the input data, equations used in the calculations, and references to published studies to justify the use of the methodology. For new methods, such as the risk-based AOR, to be accepted by NDIC, the EERC had to demonstrate the validity of the method through peer-reviewed publications and the conduct of webinars with NDIC staff. Examples of requests from NDIC for inclusion of additional information in the permit have included sensitivity analyses, reservoir pressure maps at different time stamps during the injection and postinjection period, and information about CO_2 phase state in the reservoir (free, dissolved, trapped).

Another consideration when presenting data and information in a SFP application is to ensure that a thorough review of existing studies has been conducted. Any data and/or information presented that may contradict, change, or modify an existing body of knowledge need to be justified. One example of this is formation extent. Recent stratigraphic test wells drilled in North Dakota show the extent of the Broom Creek Formation being farther east than in published studies. NDIC requested that the EERC show what data were used to make this interpretation (Figure 12).

Addressing Regulatory and Landowner Concerns

While NDIC and the public have an opportunity to provide feedback on the permit at the public hearing and make additional requests for information throughout the project development process, it is important in meetings with regulators, landowners, and other stakeholders to understand their concerns about the project and, if possible, address them in the permit application when practical to do so. Addressing any known concerns in the permit or being prepared to address concerns at the public hearing will help expedite the review and approval process and, ultimately, increase the likelihood that the permit is approved.

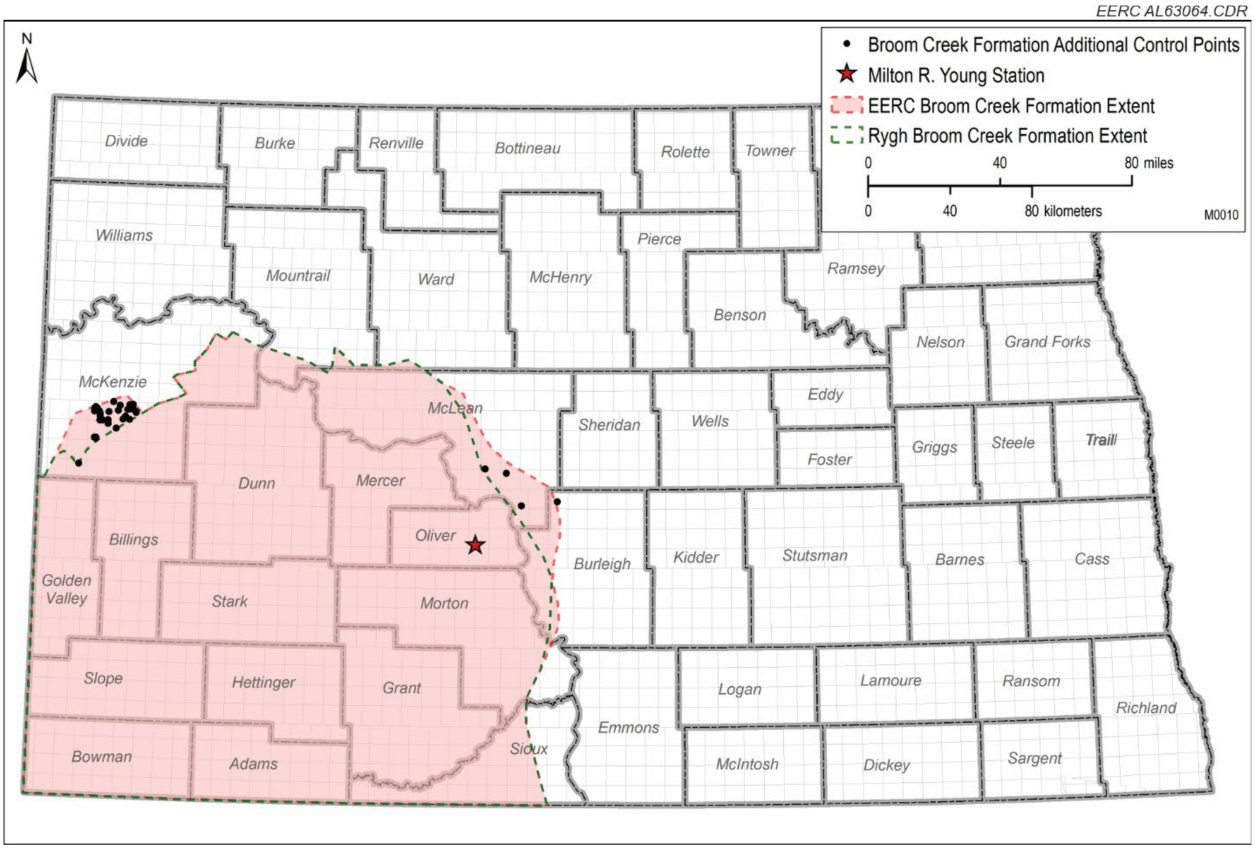

Figure 12. Areal extent of the Broom Creek Formation in North Dakota (modified from Rygh and others [1990]), showing a comparison between the interpreted extent found published in previous studies and the EERC-interpreted extent in addition to the new wells used to support the EERC's interpretation (North Dakota Industrial Commission, 2021b).

Communication with Regulators

The timely approval of a geologic CO_2 storage project relies heavily on open lines of communication between the operator and regulatory body. Meetings should be conducted with local, state, and federal regulatory bodies early in the process to promote transparency and communication. It is recommended to meet with local and state regulatory bodies, even if primacy lies at the federal level. Through these discussions, regulators may express concerns related to the project site or project design that should be addressed in the site characterization, modeling, AOR evaluation, and design efforts presented in the SFP application.

The project team should work with the permitting authority by conducting pre-application meetings to better understand the permitting process and learn of specific questions/concerns related to the project several months prior to the official permit submission. A pre-application meeting with the regulator and project team has proven to be extremely valuable to discuss the project in its early planning stages. Through pre-application meetings, regulators can help ensure a clear path forward prior to the submission of an application or permit. Pre-application meetings provide the opportunity for developers to introduce the project and answer questions from governing entities. Timelines for public hearings should also be discussed at pre-application meetings. State and federal rules often require a public comment period; therefore, project developers should ensure adequate time is available to address such comments and provide any required supplementary information to address them.

Keeping interested regulatory bodies up to date and engaged throughout project development can prevent critical delays in the permitting timeline. For example, efforts during site characterization may require discussion with regulators to make real-time decisions related to data collection because immediate variances may be required to ensure its acceptability for inclusion in the permit. Additionally, if projects are intending to use new data collection approaches, data analysis techniques, or modeling and simulation methods that are novel or unique to the project, it would be beneficial to introduce the concept to regulators prior to using such techniques. It is prudent for project developers to ensure regulations are adequately addressed prior to the introduction of any new or novel approaches. Not doing so may result in regulators rejecting the new or novel approach during the review of the permit, at which point collecting alternate data or analysis may be very challenging.

Community Outreach

Public perception is an aspect that can make or break any first-of-a-kind effort, regardless of how technically and environmentally sound it may be. Early, proactive public outreach with stakeholders has been a key to the success of the geologic CO_2 storage projects that have been permitted in North Dakota. Sharing project and activity information and communicating to convey understanding, demonstrate transparency, and show respect to community stakeholders were critical elements to building the trust needed to secure community support for the geologic CO_2 storage projects. At the heart of these efforts was providing concise, accurate, and easy-to-understand information that responded to stakeholder needs. The goal is to engage stakeholders and create an environment that allows them to make informed community decisions regarding the project.

Maintaining the trust of the community is crucial to the success of the project. Operators looking to capture and store CO_2 are usually large components of local economies and depend on local workforce or goods, e.g., corn feedstock, to operate. For this reason, showing transparency and providing opportunities for community information-sharing are vital to the sustainability of their business as well as the development of their geologic CO_2 storage projects.

Outreach should start at the early stages of a project as site characterization activities such as drilling wells, conducting seismic surveys, and collecting soil, gas, and water data are very visible activities that often require access to privately owned land. Positive relations with local landowners are a critical component to the success of any project field activities and, ultimately, the overall project development. In North Dakota, surface landowners also hold the pore space rights needed for permanent geologic CO_2 storage; therefore, building and maintaining positive relations with these stakeholders is important for implementation of geologic CO_2 storage projects. Face-to-face interaction with landowners, when possible, or direct contact via telephone provides an opportunity for trust- and relationship-building as well as opportunities for landowners to express concerns, receive immediate answers to questions, and provide feedback.

In addition to landowner outreach, engaging and providing information to the general public, local and state regulators, and the media are important for maintaining transparency and gaining public acceptance of the geologic CO_2 storage project.

Recommended practices for geologic CO_2 storage project outreach efforts include the following:

- Keep messages consistent across all target audiences.
- Messaging should be proactive and reactive, meaning the information shared with the target audiences should be adapted based on feedback received regarding message clarity.
- Share information with all stakeholders in advance of any field activities; the greater the visibility, the more broadly the information should be shared.
- Provide ample opportunities for stakeholder questions to be heard and answered.
- Anticipate questions and concerns and have responses ready.
- Ensure all individuals engaged with project development understand anticipated concerns and how they are being addressed.
- Prepare press packets for every action that may be of interest to any third-party stakeholder.
- Develop good relationships with the broadcast and printed media.
- Consider multipurpose uses of outreach materials (provide resource conservation and message consistency).
- Treat every encounter as a chance to make a good impression.
- Provide regular updates (e.g., newsletters, press releases, etc.) on activity status and progress to landowners, local officials (e.g., city councils, county commissions, etc.), and state regulators.

In general, messaging needs to help audiences understand how the technology is being safely implemented, and every encounter with the public—positive or negative—has the potential to gain additional support of the project if handled with sincerity and professionalism. Encounters can occur anywhere, anytime, ranging from planned events (e.g., an open house) to casual conversation (e.g., local café, gas station, etc.). Given the close-knit rural communities that are often near the project sites, encounters are rapidly shared among community members. Concerns to date that have been raised centered on human safety, groundwater and environmental protection, clarity and disclosure regarding the process and its permitting, transparency as the process moves forward, and the trustworthiness of the project team and regulatory oversight. Outreach activities provide an opportunity for community members to learn about the project and be heard, often revealing important concerns that must be addressed if these first-of-its-kind facilities are to be commercially accepted in the community.

Outreach activities conducted to date have included broad regional engagement and focused engagement with target audiences, including local and regional officials, landowners, and the community. The outreach efforts have required interaction with various stakeholders where value was provided through a dedicated and systematic outreach effort. Outreach activities were a coordinated effort that involved 1) the project technical team, 2) partner outreach beyond the technical team (e.g., the operator's employees and board members, EERC employees, and other project partners), and 3) external outreach (e.g., local/regional officials, landowners, etc.).

The engagement strategies used to reach target audiences comprise three categories: 1) in-person, one-on-one conversations, and small group presentations; 2) mass communications via mailings, traditional print and broadcast media, social media, and Internet interactions; and 3) indirect engagement through community activities. Within each category, strategies were customized for specific audiences and the objective of the communication. Open house and board meeting settings, as well as interactions with governmental stakeholders, often facilitated one-on-one and small group engagement. Open houses were advertised publicly in regional newspapers, using flyers posted by local businesses, digital signs, and word of mouth. Landowners, local and state officials, and local science teachers were also sent invitations.

As part of the outreach efforts, outreach material including, but not limited to, fact sheets (general project or activity-focused), posters, infographics, press releases, and bulleted talking points were disseminated. Outreach materials development involved preparing information necessary to understand the basics of CCUS technologies and the specific geologic CO_2 storage project activities. Of particular focus was translating jargon and technical information into verbiage both familiar and relevant to the audience.

Outreach material was regularly provided to local officials at local county and city commissioners' meetings to disseminate widespread information more effectively and efficiently into the communities throughout the various project development phases. At these meetings, commissioners received an informational packet containing a project fact sheet and relevant activity-specific frequently asked questions (activities FAQs) or fact sheets, presenter(s) business card(s), and, when applicable, an open house invitation and activity timeline. Similar packets with a press release were prepared for media. In advance of each appearance, the outreach team developed talking points highlighting current status and future activities, relevant dates, pertinent results, and any critical information to be conveyed. Commissioners expressed appreciation for information in advance of activities.

NDIC, a crucial stakeholder for geologic CO_2 storage projects in North Dakota, also received copies of the informational packets following each meeting. As the state regulatory entity overseeing all subsurface activity in North Dakota, NDIC is the permitting authority for North Dakota's geologic CO_2 injection and storage program (North Dakota Industrial Commission, 2013) and is recognized as a "go-to source" by media for information of this type. Supplying DMR with up-to-date information regarding the project and public engagement 1) generated more efficient future meetings and 2) ensured NDIC was aware of project progress and information in advance of potential media inquiries. Therefore, not only were good relations maintained, but the interaction also provided for the accurate dissemination of project progress and information.

Outreach efforts also included finding opportunities to be proactive in providing information and engaging with area journalists. Developing relationships with local journalists and those within the energy "beat" is crucial to ensure that accurate information about the project gets to the public. Technical projects can be difficult to portray accurately in the media because they cannot be easily boiled down to a sound bite or short article. A general rule of thumb in media relations is that if they do not receive the information from the project contact, they will find it from somewhere else, and it may be inaccurate or outdated. In developing relationships with journalists, the project benefits most from a communications team that is helpful to media contacts in accomplishing their jobs. Each journalist assigned to reporting on the project has different needs in understanding the project based on their goals and experience. For example, an energy reporter for a trade publication may be well-versed in writing about geologic CO_2 storage. A journalist for a general publication covering diverse topics may need more context to aid in understanding the topic. Proactively developing relationships with local journalists establishes a communication channel for media to get accurate information from the project team.

Establishing relationships with influential media in the area facilitates dissemination of accurate information. Having relationships with media reduces the likelihood of misinformation because the reporters come to the source for clarification on key facts. In addition, having those relationships establishes a communication channel to address misinformation as soon as possible. Print and broadcast media in the project area included local, county-size, and statewide components.

To date, feedback from targeted audiences has been generally neutral to positive, and overall, interactions have been constructive. Engagement activities have proven to be crucial for maintaining good relations with local communities and landowners within the project area, which in turn helped expedite pore space leasing. Projects in North Dakota to date have been able to lease well over the minimum requirement of 60% of the pore space for their projects with several projects leasing over 95%, which is a good indication of their reputation in the communities and the trust they have developed with landowners during the development of their project.

SUMMARY OF RECOMMENDATIONS

A set of recommendations has been developed from the lessons learned during project development and permitting of the first wave of geologic CO_2 storage projects in North Dakota. The set of recommendations shown below may be used to streamline geologic CO_2 storage project development and permitting in North Dakota or adapted to inform CCUS deployment throughout the United States.

Project Development

- Become aware of regulatory and incentive program requirements and timelines (e.g., permit review and approval process) early on in project development to ensure the necessary data are acquired, the project design is compliant with regulations, and all project/regulatory deadlines are met.

Site Characterization

- Drill a stratigraphic test (appraisal) well to acquire site-specific core data for site characterization and to address regulatory requirements.

- Evaluate seismic data prior to drilling a stratigraphic test well or injection well to lower the investment risk.

- If planning to transition the stratigraphic test well to a UIC Class VI injection well, ensure the required data (e.g., openhole and cased-hole logs, core, and fluid samples) are acquired and that the well design is compliant with Class VI regulations.

- Regularly communicate with the UIC Class VI regulator if operational challenges are encountered during coring, logging, or sampling to ensure compliance with regulations and the ability, if desired, to permit the well as a UIC Class VI injection well.

- Collect whole core from the stratigraphic test well, as geomechanical analysis of sidewall cores has its limitations.

- View core in the field to determine how much of the upper and lower confining zones was collected and that the lithologies have good confining characteristics (e.g., low permeability and lack of faults or fractures).

- Use a longer core barrel assembly when coring the stratigraphic test well to reduce rig time and overall drilling cost.

- Use invert drilling fluid for drilling a stratigraphic test well to prevent washouts.

- Acquire a nuclear magnetic resonance (NMR) log to address confining zone in situ fluid pressure requirements and to serve as an alternative of SP when using invert drilling fluids.

- Acquire geochemical logs to help quantify reservoir minerology and swelling clay volumes that affect CO_2 injectivity.

- License existing seismic data or acquire new seismic data to identify potential fluid migration pathways in the confining zone and confirm lateral continuity of the injection and confining zones.

- Evaluate the quality of existing seismic data to determine suitability for site characterization or inform the design of new seismic surveys.

- When feasible, acquire 3D seismic data to assess lateral heterogeneity of subsurface formations and optimize injection well placement.

- When acquisition of 3D seismic data is not feasible because of surface constraints, acquire a network of 2D seismic lines.

- Acquire a seismic source test prior to acquiring seismic data over reclaimed mine land to alleviate uncertainty in the quality of seismic data.

- When planning and conducting seismic surveys, consider land use and work to minimize damages and inconveniences to landowners and to help ensure landowner cooperation for future surveys and pore space access.

- Use preliminary injection well locations and estimates of CO_2 plume size to inform the size and placement of seismic surveys.

- Have regular meetings with the seismic processing company to review survey parameters and ensure the best imaging solution is deployed.

Modeling and Simulation

- Document how modeling and numerical simulations were conducted, as well as the inputs and assumptions used in the UIC Class VI permit application, to provide regulators with the information they need to review the model and simulations.

- Use the derivative area with respect to time (dA/dt) with a 5% saturation cutoff (or a site-specific saturation cutoff derived from fluid substitution modeling) as a metric to determine the stabilized plume boundary.

- Square off storage facility area boundary to the nearest quarter section or land tract to simplify legal descriptions of the storage facility area for pore space leasing purposes.

- Use a risk-based method to determine the AOR for those instances where the storage formations are overpressured prior to CO_2 injection.

- Use modeling and simulation methods to address regulations related to evaluation of geochemical reactions and their impact on injectivity and confining zone competency.

Permit Preparation

- Ensure the permit application is structured in a way that facilitates its review by the regulator and allows for a comprehensive determination that all of the regulations have been met.

- Present data needed to address regulations in a map, figure, or table format where possible to make the information easier to find and review.

- Only present data or information in one place to minimize redundancy and avoid reporting inconsistent values or information.

- Use consistent units and terms throughout the permit.
- Clarify data sources.
- Limit map extents to focus on information relevant to address the regulatory requirements.
- Be as concise as possible and present only relevant information when presenting information and data necessary to meet the regulatory requirements.
- Ensure a thorough review of existing studies has been conducted and any data and information presented that may contradict, change, or modify an existing body of knowledge can be explained and justified.
- If possible, address relevant known concerns from the regulators, landowners, and other stakeholders in the permit application to expedite the permit review and public hearing process and ultimately increase the likelihood of permit approval.

Communications with Regulators

- Meet with local, state, and federal regulatory bodies early in the project development process to promote transparency and communication.
- Work with the permitting authority by conducting pre-application meetings to better understand the permitting process and answer questions related to the project prior to the official permit submission.
- Introduce and discuss any new data collection approaches, data analysis techniques, or modeling and simulation methods that are novel or unique to the project to regulators prior to using such techniques.

Community Outreach

- Engage landowners, nearby communities, the general public, local and state regulators, and the media by providing information and periodic updates on project activities to demonstrate transparency and foster public acceptance of the geologic CO_2 storage project.
- Start community outreach early in the project development process.
- Keep messages consistent across all target audiences.
- Messaging should be proactive and reactive, meaning the information shared with the target audiences should be adapted based on feedback received regarding message clarity.
- Share information with all stakeholders in advance of any field activities; the greater the visibility, the more broadly the information should be shared.

- Provide opportunities to answer questions from the stakeholders.
- Anticipate questions and concerns and have thoughtful and well-developed responses ready in advance.
- Ensure all individuals engaged with project development understand anticipated concerns and how they are being addressed.
- Prepare press packets for every occasion.
- Develop good relationships with both printed and broadcast media.
- Consider multipurpose uses of outreach materials (provides resource conservation and message consistency).

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APPENDIX A

RECOMMENDED UIC CLASS VI LOGGING AND CORING PROGRAM

North Dakota Class VI Logging Program

Well Name	Logging Program				
	Well Logging	Depth Intervals	Purposes	NDAC Code	Justifications
			Surface Section		
OH	Triple combo (resistivity, density, porosity, gamma ray [GR], caliper, and spontaneous potential [SP])	Entire hole section.	Quantify variability in reservoir properties such as resistivity and lithology. Identify the wellbore volume to calculate required cement volume.	43-05-01-11.2-1-b(1)	This log is required by the North Dakota Industrial Commission (NDIC) under well construction requirements.
OH	Acoustic compression and shear (dipole sonic)	Entire hole section.	Identify mechanical properties including stress anisotropy. Provide compression and shear waves for seismic tie-in and quantitative analysis of the seismic data.		The log will provide information to generate 1D mechanical earth model (1D MEM) and the ability to properly tie in the seismic results and reduce uncertainty in interpretation and inversion of seismic data.
CH	CCL-ultrasonic log–variable density log VDL–GR–temperature log	Entire hole section.	Identify cement bond quality radially. Detect if cement channels exist. Evaluate the cement top and zonal isolation.	43-05-01-11.2-1-b(2)	This log is required by NDIC under well construction requirements (e.g. Isolation Scanner from Schlumberger).
			Long-String Section		
OH	Triple combo (resistivity, density, porosity, GR, caliper)	GR: total depth (TD) to surface; others: entire hole section.	Quantify variability and reservoir properties within the interest zones. Provide inputs for enhanced geomodeling and predictive simulation of CO_2 injection into the interest zones to improve test design and interpretations. Identify the wellbore volume to calculate required cement volume. Select formation test intervals and well completion intervals.	43-05-01-11.2-1-c(1)	This log is required by NDIC under well construction requirements.
OH	Nuclear magnetic resonance (NMR)	Entire hole section.	Interpretation of reservoir permeability and determine the best location for formation fluid sampling depths, packer setting depths, and stress testing depths. NMR and formation testing data combined provide enhanced permeability evaluation, fluid identification, and fluid contacts.	43-05-01-11.2-1-c(1)	Irreducible water saturation, free fluid, capillary-bound and clay-bound fluid is estimated from NMR. Pore size distribution also helps identify rock type.
OH	SP (If using water-based mud [WBM])	Entire hole section.	Lithology: identify clays that could affect injectivity and water quality.	43-05-01-11.2-1-c(1)	The SP log is required by NDIC under well construction requirements if using water-based mud (WBM), but a density porosity log (triple combo) can be used in place if using oil-based mud (OBM).
OH	Spectral GR	At a minimum, entire cored section plus 200' above and below.	Lithology: identify clays that could affect injectivity and core/log correlations.	43-05-01-11.2-2	This log provides refined information on reservoir rock properties, like clay content and permeable/nonpermeable formation. This information is important in describing the storage reservoir's mechanisms of geologic confinement characteristic with regard to preventing migration of carbon dioxide beyond the proposed storage reservoir.
OH	Capture spectroscopy (CS)	At a minimum, entire cored section plus 200' above and below.	Analyze mineralogical and elemental yields of the formations, both interest zones and their cap rocks, by detecting elemental concentrations achieved by measuring the captured spectrum of a variety of elements.	43-05-01-11.2-2	This log enhances mineralogical and geochemical reservoir analysis, similar to techniques used for special core analysis. Spectroscopy is especially beneficial for analyzing complex reservoirs with laminated beds, for correlation between wells, and for determining mineralogy. This log is beneficial when collecting data in a new area but is unnecessary to run on every well.
OH	Acoustic compression and shear (dipole sonic)	Entire hole section.	Identify mechanical properties including stress anisotropy. Provide compression and shear waves for seismic tie-in and quantitative analysis of the seismic data.	43-05-01-11.2-1-c(1)	The log will provide information to generate 1D MEM and the ability to properly tie-in the seismic results and reduce uncertainty in interpretation and inversion of seismic data.
	Borehole imaging	350' above the top of the caprock, the entire injection zone, and 350' below the top of the underlying rock.	Quantify if fractures exist in the storage formation(s) and confining layers to ensure safe, long-term storage of injecting CO_2 in ( ). Quantify sealing quality of confining layers.		This is required by NDIC under well construction requirements as a fracture finder log. This log provides the information needed to describe the storage reservoir's mechanisms of geologic confinement characteristic (e.g. Quanta Geo from Schlumberger).
OH	Fluid sampling	Selected intervals in the injection zones.	Collect [ ] one-gallon reservoir fluid samples [ ] in ( ) for testing of potential fluid and mineralogical reactions between injected fluid chemistry, formation fluid chemistry, select step-rate test fluid chemistry, and formation mineralogy that could affect injectivity. Collect reservoir pressure tests [ ] to establish a pressure profile and mobility.	43-05-01-11.2-2	A fluid sample is required by NDIC under well construction requirements. The MDT with Saturn Probe from Schlumberger collects a fluid sample during openhole logs as well as pressure and temperature profile. A fluid sample can also be collected by DST or swabbing.

North Dakota Class VI Logging Program

Well Name	Logging Program				
	Well Logging	**Depth Intervals**	**Purposes**	**NDAC Code**	**Justifications**
OH	Formation pressure testing	Selected intervals in the caprock and injection zones.	Collect reservoir pressure tests [ ] to establish a pressure profile and mobility.	43-05-01-11.2-3	This log provides the reservoir pressure, mobility, and temperature information. This information is important as inputs for reservoir simulation to establish initial reservoir condition and to calculate the formation injectivity and injection capacity. Wireline-deployed pressure-testing tool allows multiple zones and multiple testing points that provide the formation pressure gradient. Changes in pressure gradient can also demonstrate the vertical flow barriers. Formation pressure testing at the cap rock will provide a dry result or no mobility which helps justify the integrity of the cap rock (e.g. MDT from Schlumberger).
OH	Stress testing	Selected intervals in the caprock and injection zones.	Collect [ ] stress tests [ ] in ( ) for breakdown pressure, fracture propagation pressure, fracture closure pressure (minimum in situ stress) and establish injection pressure limits.	43-05-01-11.2-4-a	The stress test will provide the geomechanical properties of the interest zone and its confining zone. This information is necessary to validate the stress test results from the well and provide the justification if the project wants to propose a higher injection pressure than what is regularly used by NDIC, where the fracture gradient is ~0.7-0.8 psi/ft. Wireline-deployed stress-testing tool allows multiple zones and multiple testing points that will be used by the commission in determining the maximum allowed injection pressure of the well for a specific reservoir (e.g. MDT with mini-frac tool from Schlumberger). CARB Requirement: The CCS project operator must also discuss how the calculated fracture pressure compares with data from core tests or other wells in the area, if available.
OH	Whole cores	Selected intervals in the injection zones and confining zones.	Collect [ ]" whole core for core analysis. Depth intervals [ ] in the following formations: ( )	43-05-01-11.2-2	Whole core or sidewall cores are required by NDIC under well construction requirements to provide baseline core analysis data for relevant geologic formations.
OH	Sidewall cores	Selected intervals in the injection zones and confining zones.	Collect [ ] sidewalls cores for core analysis. One in each of the following formations: ( )	43-05-01-11.2-2	Whole core or sidewall cores are required by NDIC under well construction requirements. Sidewalls are typically only recommended as a backup option if whole core is unsuccessful in the injection zones and confining zones or if there is another well of knowledge in the storage facility area due to topical core analysis limitations.
CH	CCL–ultrasonic log–VDL–GR–temperature log	Entire hole section.	Identify cement bond quality radially. Detect if cement channels exist. Evaluate the cement top and zonal isolation.	43-05-01-11.2-1-c(2)	This log is required by NDIC under well construction requirements (e.g. Isolation Scanner from Schlumberger).

Note: OH – openhole; CH – cased hole; CCL – casing-collar locator; VDL – variable-density log: ultrasonic log for radial cement bond

North Dakota Administrative Code	43-05-01-11.2

NOTE: (Class VI Well)

1. During the drilling and construction of an injection well, the storage operator shall run appropriate logs, surveys, and tests to determine or verify the depth, thickness, porosity, permeability, lithology, and salinity of any formation fluids in all relevant geologic formations to ensure conformance with the injection well construction requirements under section 43-05-01-11 and to establish accurate baseline data against which future measurements may be compared. The storage operator shall submit to the commission a descriptive report prepared by a log analyst that includes an interpretation of the results of such logs and tests. At a minimum, such logs and tests must include:
   a. Before and upon installing the surface casing:
      (1) Resistivity, spontaneous potential, and caliper logs before the casing is installed
      (2) A cement bond and variable density log to evaluate cement quality radially and a temperature log after the casing is set and cemented
   b. Before and upon installation of the long string casing:
      (1) Resistivity, spontaneous potential, porosity, caliper, gamma ray, fracture finder logs, and any other logs the commission requires for the given geology before the casing is installed
      (2) A cement bond and variable density log, and a temperature log after the casing is set and cemented
2. The storage operator shall take whole cores or sidewall cores of the injection zone and confining zone and formation fluid samples from the injection zone and shall submit to the commission a detailed report prepared by a log analyst that includes well log analyses (including well logs), core analyses, and formation fluid sample information. The commission may accept information on cores from nearby wells if the storage operator can demonstrate that core retrieval is not possible and that such cores are representative of conditions at the well. The commission may require the storage operator to core other formations in the borehole.
3. The storage operator shall record the fluid temperature, pH, conductivity, reservoir pressure, and static fluid level of the injection zone.
4. At a minimum, the storage operator shall determine or calculate the following information concerning the injection and confining zone: a. Fracture pressure; b. Other physical and chemical characteristics of the injection and confining zone; and c. Physical and chemical characteristics of the formation fluids in the injection zone.