SCS ENGINEERS

SCS TECHNICAL BULLETIN

APPLYING LESSONS LEARNED FROM MUNICIPAL SOLID WASTE AND COAL COMBUSTION RESIDUALS TO THE DEVELOPMENT OF TESTING AND MONITORING PLANS FOR CO_2 STORAGE PROJECTS

March 1, 2023

EXECUTIVE SUMMARY

Under the United States Environmental Protection Agency's (USEPA) Underground Injection Control (UIC) Program, Class VI injection wells are constructed for the purpose of permanently sequestering supercritical (i.e., highly compressible fluid without distinct solid and gas phases) carbon dioxide (CO_2) within deep geologic formation(s). These sequestration wells are regulated under the Safe Drinking Water Act (SDWA). USEPA's Class VI Rule sets the federal minimum technical requirements for these Class VI wells to ensure the protection of underground sources of drinking water (USDWs).

The Class VI Rule requires the development of a Testing and Monitoring Plan for Class VI wells as part of carbon capture and storage (CCS) projects. Part of the Testing and Monitoring Plan deals with monitoring the natural environment, particularly USDWs, for any changes that may result from underground sequestration of supercritical CO_2. The regulatory goals for CCS sites are quite similar to those for Resource Conservation and Recovery Act (RCRA) groundwater monitoring at nonhazardous waste sites, particularly Municipal Solid Waste (MSW) and Coal Combustion Residual (CCR) disposal sites. SCS Engineers believes that the guidance and practices for MSW and CCR groundwater monitoring can fruitfully be adapted for CCS Testing and Monitoring Plans. However, some changes are required as the complexity and related cost implications of monitoring network errors for CCS are significantly higher. The purpose of this paper is to discuss key considerations for developing Testing and Monitoring Plans for CCS projects based on our understanding of MSW and CCR regulatory frameworks in the context of lessons learned from those developed monitoring programs. In particular, we put special focus on groundwater monitoring and the monitoring well network.

INTRODUCTION

Part of the permitting process for a CO_2 storage, or CCS project, includes the development of a Testing and Monitoring Plan. The USEPA published guidance for developing Testing and Monitoring Plans in 2013. However, this guidance provides generalized recommendations for monitoring geared towards meeting the basic requirements of the Class VI Rule. The guidance specific to geochemical monitoring of groundwater quality is particularly generalized. In addition, much research has been conducted over the past decade on CCS, which has initiated the development of new and innovative monitoring methods and technologies. Even with these advancements, challenges and complexities related to testing and monitoring still exist and must be considered during the Class VI permitting process.

With CCS being a newer permitting challenge for both permittees and regulators alike, it will be beneficial to draw on lessons learned from more familiar and well-developed regulatory frameworks, such as those for MSW and CCR. This paper will discuss the key considerations for developing an effective CCS Testing and Monitoring Plan based on lessons learned from developed MSW and CCR monitoring programs, as well as how early planning and good judgment can help navigate the complexities associated with CCS projects and ultimately reduce those complexities and associated project costs.

Basics of CCS Testing and Monitoring

Testing and monitoring is primarily required for detection of risks to USDWs imposed by injection practices. An ideal potential CO_2 storage site will have considerable vertical and stratigraphic separation between the target storage interval and USDWs. The site should also contain at least one ideal confining zone to keep CO_2 properly contained within the storage interval once injected. Great care also goes into the design of Class VI injection wells to ensure longevity and prevent integrity failures. Figure 1 shows a simplified cross-sectional diagram of a typical Class VI well (USEPA).

Monitoring at CCS sites functions as an additional safety net; by monitoring, we are ensuring that any risks posed to USDWs as a result of CO_2 injection are detected as soon as possible. Additionally, monitoring is required to verify that the injection well is operating in the manner that is permitted, and to aid in the periodic re-evaluation of the Area of Review (AOR), which is the delineated area of the subsurface determined by both multiphase modeling and monitoring and operational data where there is potential for injection practices to endanger USDWs through leakage of injectate and/or formation fluids (USEPA, 2013).

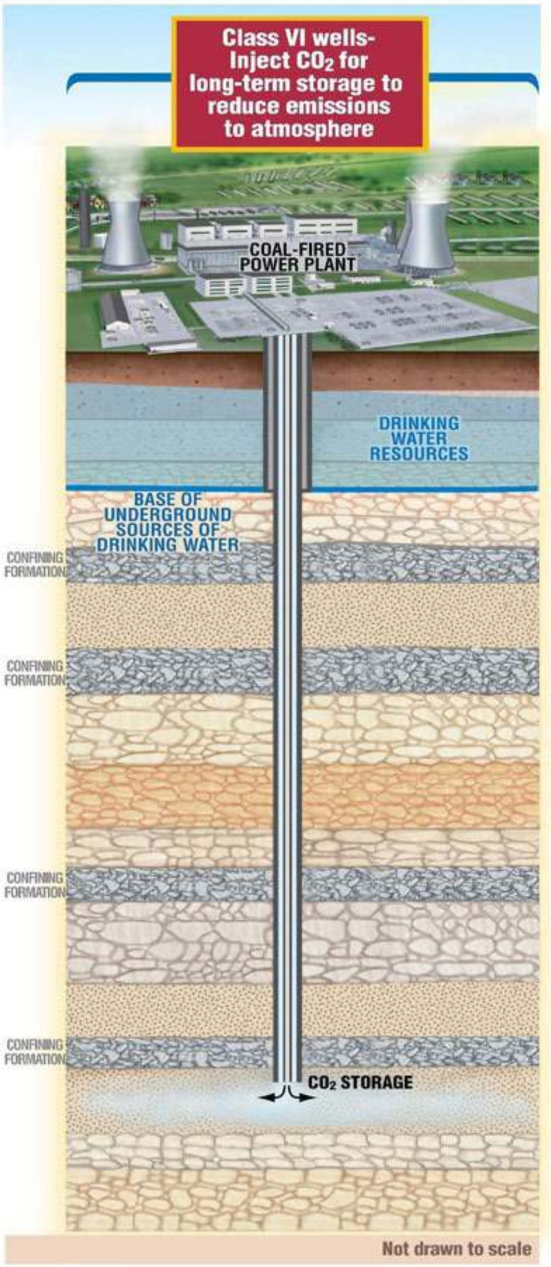

Figure 1

Testing and monitoring is also required to varying degrees during all phases of the CCS project once the Class VI permit is issued, including the pre-operational (pre-injection) phase, the operational (injection) phase, and the post-operational (post-injection/site-care) phase (Figure 2, below; adapted from USEPA's Class VI Well Testing and Monitoring Guidance [2013]).

Complexities of CCS Testing and Monitoring

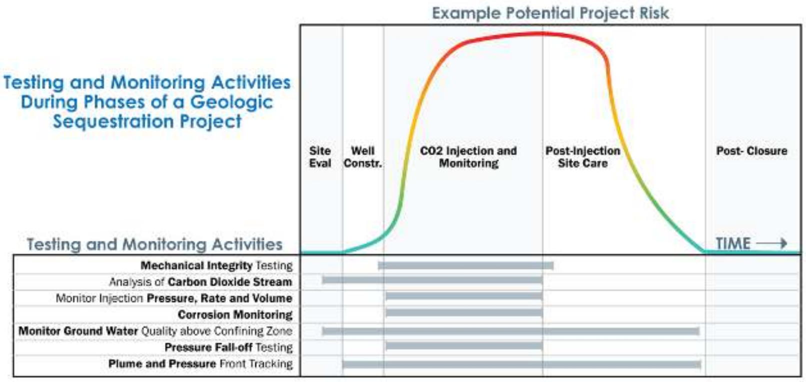

Figure 2

Figure 2 (above) graphically depicts how monitoring activities change over the various phases of a CCS project, as well as how this relationship corresponds to overall potential project risk. The left side of the diagram lists the required testing and monitoring activities for CCS projects. In general, we conduct the following testing and monitoring activities:

- Monitor operational parameters by
  - Analyzing the CO_2 stream
  - Monitoring injection pressure, rate, and volume
- Monitor Class VI injection well integrity by
  - Conducting mechanical integrity testing (external and internal)
  - Conducting corrosion monitoring of the well materials
- Monitor ambient conditions surrounding the Class VI injection well by
  - Monitoring groundwater quality above the confining zone
  - Tracking the migration of the CO_2 plume and associated pressure front
  - Conducting pressure fall-off testing

During the siting and evaluation phase, the operator will collect baseline data for the CO_2 stream and groundwater. Project risk is low at this stage because the injection well has not been permitted or constructed. Once the injection well is permitted and construction begins, other monitoring project risk begins to increase. An initial mechanical integrity test is completed on the injection well prior to the commencement of injection to verify mechanical integrity. The riskiest portion of the project is during the operational phase once injection begins. At that point, the operator must conduct all of the required Class VI testing and monitoring activities. Once injection ceases, project risk begins to decrease accordingly. Since no injection is occurring, monitoring of operational parameters may cease. A final set of integrity testing will be completed prior to plugging and abandonment of the injection well. Throughout the post-injection site care phase, project risk continues to decrease as the CO_2 plume migrates and dissolves within the reservoir and the pressure front dissipates. However, tracking of the plume and pressure front must continue throughout this phase, in conjunction with groundwater monitoring, to verify that the plume and pressure front are migrating as expected. Once the operator can demonstrate that the Class VI injection activities no longer endanger USDWs, all monitoring can cease and the project will enter the site closure phase.

When thinking of monitoring at a landfill or coal ash impoundment, what likely comes to mind is shallow groundwater monitoring, as well as leachate and landfill gas monitoring in the case of landfills. With CCS sites, as discussed above, more rigorous testing and monitoring methods are employed. The protection of groundwater is paramount at MSW, CCR, and CCS sites. Where these sites differ is in the level of complexity associated with their respective regulatory frameworks and the consequent requirements. What is it about CCS permitting that makes it more complex, and leads to more rigorous testing and monitoring requirements?

Scale of CCS Projects

One complexity to consider is the overall scale of these sequestration projects. CCS projects often encompass a large footprint of land. They can potentially have an expansive AOR that can range from 10s of square miles to 100s of square miles depending on various project-specific parameters. The shape and extent of the AOR will also vary throughout the lifetime of the project, as the delineation of the AOR is based on modeling that is continually refined with site-specific characterization and monitoring data.

CCS projects also involve large vertical scales, particularly compared to MSW and CCR projects (i.e., far below the lowermost USDW versus near the uppermost/shallow aquifers). Class VI wells for the sequestration of supercritical CO_2 typically range in depth from 3,500 feet (on the basis of meeting minimum pressure and temperature requirements to keep CO_2 in the supercritical phase) to 10,000 feet (on the basis of project economics). In addition to meeting this basic depth requirement, the injection zone cannot be a USDW (must be >10,000 parts per million [ppm] total dissolved solids), unless an aquifer exemption is obtained from USEPA. This leads to a more difficult permitting scenario where specific criteria must be met, and should be avoided when possible. The ideal site geology will involve as much vertical and stratigraphic separation as possible between the injection zone and any overlying USDWs, as well as numerous confining zones to prevent vertical fluid migration (Figure 3, right; from the Utah Geological Survey).

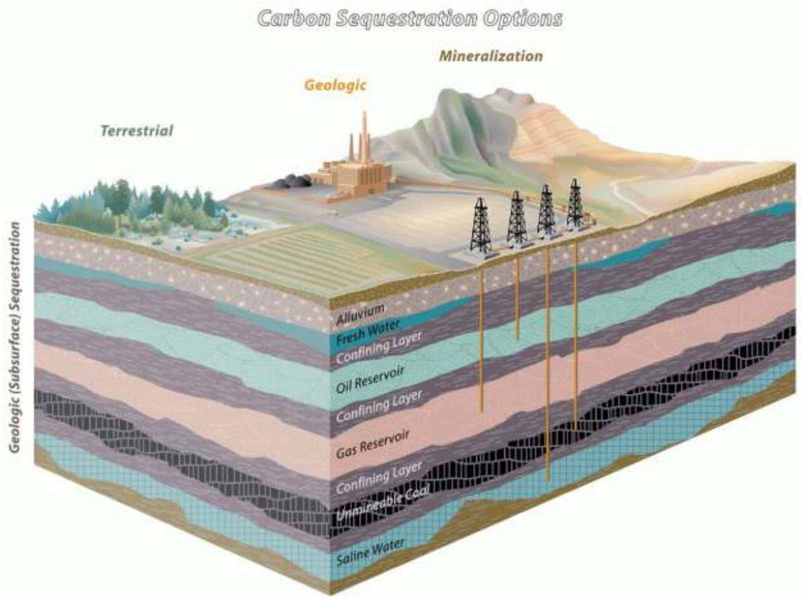

Figure 3

Capital and Operating Costs

Another complexity to consider is the overall capital and operating costs associated with CCS projects. Class VI permitting efforts are often extremely detailed and iterative. Due to the breadth of the requirements in a Class VI permit submittal, a large team of a variety of specialists is typically necessary. Costly pre-operational (background) data are also collected during the permitting process. This can include new data, such as data collected from a stratigraphic test well installation or geophysical survey, or existing data, such as data from nearby legacy wells and previous geophysical surveys (e.g., 3-D seismic surveys).

We must also consider the elevated costs for the Class VI well and monitoring network installations plus the associated monitoring, operation and maintenance costs. Class VI wells are deep (3,500 to 10,000 feet typically) and therefore require large volumes of heavy-duty well construction materials. Additionally, once the project is permitted and prior to beginning injection, baseline data collection should commence for refinement of the Testing and Monitoring Plan. The permit is refined with testing and monitoring data gathered during the injection and post-injection periods as well.

Enhanced Regulatory Risk

Finally, there is an inherent enhanced regulatory risk to consider. The Class VI Rule requires an AOR re-evaluation a minimum of every 5 years. This re-evaluation must additionally occur when certain conditions warrant. This can include when operations significantly change (e.g., change in CO^2 stream source or composition) or if new testing and monitoring data (e.g., CO^2 plume or pressure front tracking data, groundwater monitoring data) suggest that the AOR needs to be altered.

At MSW and CCR sites, we are working at comparatively shallow depths and relying on highly engineered systems such as liners and leachate collection systems. For CCS, we cannot simply rely on engineered systems to contain the disposed material; we are primarily relying on the natural, deep subsurface geology. When injecting CO_2, we are relying on the reservoir to store the CO_2 and confining system (cap rocks) and other trapping mechanisms to keep the CO_2 securely sequestered within the reservoir (Figure 3). While we can learn a great deal about the deep subsurface through cores and geophysical data, we must rely heavily on models and interpolated data to make decisions about which locations are suitable for CO_2 storage and which are not. Additionally, the great subsurface depths make our engineered monitoring systems relatively inaccessible, compared to the shallow groundwater monitoring wells, leachate collection systems, etc., that many of us are used to working with at MSW or CCR sites.

Many consultants and site owners/operators alike have experienced the slippery slope of permitting and additional monitoring that can result from groundwater exceedances in MSW and CCR monitoring programs. With all the other complexities highlighted above, this has the potential to be amplified for CCS monitoring. Fortunately, if these complexities are considered early in the process, the Testing and Monitoring Plan can be crafted accordingly to avoid regulatory issues.

Basics of Municipal Solid Waste and Coal Combustion Residuals

RCRA and USEPA's Unified Guidance

The USEPA's Resource Conservation and Recovery Act (RCRA) regulates the storage, transportation, and disposal of hazardous and non-hazardous waste. A well-developed part of RCRA deals with groundwater monitoring at disposal units. The fundamental goals of the RCRA groundwater monitoring regulations are to characterize groundwater quality at a regulated facility, and to assess whether a release of a constituent from the facility has occurred that impacts groundwater quality, and if so, determine whether groundwater quality meets compliance standards. USEPA released guidance for the statistical analysis of groundwater quality to support these fundamental goals starting in 1989, which have been refined into the current guidance issued in 2009. This guidance is widely used to evaluate groundwater quality at non-hazardous waste sites including MSW and CCR facilities. Class VI Testing and Monitoring Plans share a similar goal. Studying lessons learned from RCRA groundwater monitoring programs will benefit Class VI projects.

Municipal Solid Waste (MSW)

Historically, both hazardous and non-hazardous waste landfills have followed Title 40 Code of Federal Regulations (CFR) Part 258. Over time, most states have adopted their own regulatory frameworks for non-hazardous landfills. The general principle behind the monitoring program at both types of landfills is the need to monitor the uppermost aquifer around the landfill for contamination by screening groundwater data against established background levels for pre-determined parameters. This is the anti-degradation basis outlined in USEPA's Unified Guidance (2009). With this, the default monitoring regime is detection monitoring, where we are simply monitoring the aquifer for the presence (if any) of contamination. If we confirm exceedances of those established background levels, assessment monitoring is triggered and we must establish groundwater protection standards for additional geochemical parameters. If any groundwater protection standards are exceeded and the exceedance is attributed to the landfill, corrective action will be triggered. If it can be demonstrated that an alternate source caused the exceedance through permitting, the site can return to detection monitoring. Figure 4 (below) shows a simplified diagram of a municipal solid waste landfill and its groundwater monitoring network.

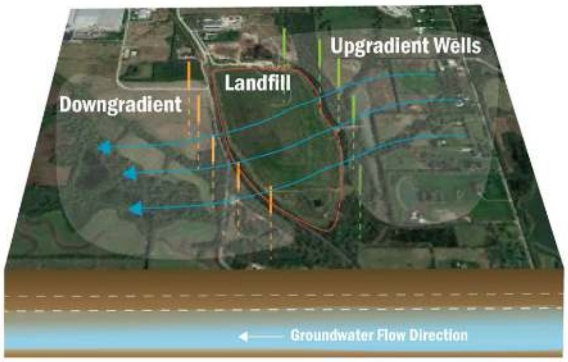

Figure 4

Coal Combustion Residuals (CCR)

Coal combustion residual or CCR sites adopt a similar regulatory framework to MSW sites. These sites must follow Title 40 CFR Part 257. CCR sites adopt the same anti-degradation basis outlined in USEPA's Unified Guidance (2009). The major difference from MSW is that since all CCR sites follow the federal regulations or state regulations that are required to be as or more protective, the chemicals of potential concern come from the same pre-determined lists (i.e., Appendix III and IV parameters), with additional parameters required by some states. The federal CCR regulations apply to any landfills, ponds, or other impoundments that contain CCR waste, including fly ash, bottom ash, and boiler slag, with the exception of landfills that ceased receiving CCR prior to the effective date of Title 40 CRF Part 257.

Lessons Learned From MSW and CCR

In previous sections, we highlighted some of the complexities that set CCS permitting projects at a higher bar. However, monitoring programs for CCS, MSW, and CCR projects all have the common goal of groundwater protection. With CCS being a newer permitting challenge for both permittees and regulators alike, it will be beneficial to draw on lessons learned from more familiar and well-developed MSW and CCR regulatory frameworks. Anyone who is experienced with MSW and CCR permitting and reporting can acknowledge that there is much to learn from these experiences.

It is important to note that even with these more well-developed frameworks, regulatory obstacles do still exist and can lead to errors in the monitoring network. One issue is the long, pre-determined monitoring parameter lists that are prescribed by the federal and state regulations. As mentioned previously, both MSW and CCR groundwater monitoring programs follow the anti-degradation basis outlined in USEPA's Unified Guidance (2009). According to the Unified Guidance, testing for too many analytes will weaken statistical power within a monitoring network and increase the chances of getting false positives, or exceedances, during a given monitoring event. In addition, the requirement that exists for having a minimum number of monitoring wells and minimum well spacing contributes to this problem. These regulations are designed to be stringent; however, they contradict USEPA's statistical guidance. This can and will paradoxically lead to artificially increased exceedances and, if not caught quickly and dispelled in an alternate source demonstration, unnecessary assessments and corrective actions.

We can make monitoring network errors as well. Often times, this points back to making mistakes and oversights during site characterization efforts as a result of tight project timelines or poor judgment. Keeping projects moving forward on clients' operational schedules or required regulatory/permit schedules can require making monitoring network decisions before we have as much information as we would ideally like to have. A mistake that occurs surprisingly and unfortunately often is simply designating the wrong unit as the uppermost aquifer, or attempting to monitor too many discrete units at a given site. Inadequately characterizing the uppermost aquifer will also lead to problems. Some common issues include not accounting for stratigraphic facies changes and spatial variability across borings, making false assumptions about groundwater flow patterns across the sites (such as ignoring vertical gradients), and last but not least, using insufficient data to establish site background levels. All of these examples of negligence in the early stages of a project can and will lead to potentially major errors in well construction and placement, which will ultimately lead to unnecessary and/or missed assessments and corrective actions.

Recommendations for CCS Testing and Monitoring Plans

With MSW and CCR stemming from developed regulatory frameworks, there are many fundamental lessons learned to consider when beginning a CCS project. Utilizing a combination of these lessons learned, early planning, and good judgment when developing CCS projects and their respective Testing and Monitoring Plans will help reduce regulatory complexities over the life of the project, and therefore overall project costs.

Recommendations for Site Characterization

Making mistakes and oversights during site characterization can lead to significant flaws in the monitoring network design. With CCS projects, we are working at great vertical depths and over large footprints of land. To minimize geologic uncertainty in the subsurface and ensure regulatory requirements for site characterization are met, it is essential to gather the most robust and representative data possible. Often this means collecting additional data during the site characterization phase, early in the permitting process. This can include drilling a stratigraphic test well near the location of the proposed Class VI injection well, purchasing seismic data, and conducting laboratory analyses on new or existing subsurface cores. This level of site characterization can appear costly at the front end of the project; however, collecting the data necessary to minimize geologic uncertainty in the area of review will 1) allow the development of a more refined Testing and Monitoring Plan, thus reducing associated costs over the lifetime of the project; 2) reduce the likelihood of having to make significant adjustments to the area of review or monitoring plan during the operational (injection) phase; and 3) greatly increase the likelihood of overall success with the regulatory agency and likelihood of receiving a permit for injection.

Being meticulous with site characterization efforts will ensure that all of the permitting requirements are met and that no major mistakes or oversights are made. As we've seen with MSW and CCR, the success of the monitoring network, and truly the project as a whole, depends on this.

Recommendations for Monitoring Networks

Like with MSW and CCR projects, the configuration of the monitoring network will be important to the success of a CCS project. The goal is to craft the CCS Testing and Monitoring Plan to be as robust and cost-effective as possible. To help meet this goal, we must consider monitoring well design and placement and how to effectively handle groundwater statistics.

Hydrogeology, Well Design, and Placement

At MSW and CCR sites, monitoring wells are typically placed around the perimeter of the landfill or impoundment at a pre-determined spacing and designated as either upgradient or downgradient of the facility. At CCS sites, this regulation-based methodology will not be effective because of the physical characteristics of the waste (injectate) we are monitoring. Unlike landfills or impoundments, the raw material we are sequestering is a buoyant, supercritical fluid, which can and will migrate in the subsurface. Due to the nature of the injectate, rather than migrating according to a gradient in an aquifer, the injectate will migrate according to structural dip. Once the buoyant fluid reaches the bottom of the overlying cap rock, it will spread laterally and migrate in the up-dip direction. As the injectate migrates, some may become trapped by structural and stratigraphic features in the reservoir, while the rest will become trapped via capillary trapping (i.e., by capillary forces between particles in the reservoir) and solution trapping (i.e., CO_2 dissolves in the formation fluids) (IPCC, 2005).

In addition, the injectate will displace formation fluids in the reservoir (i.e., brine), and lead to a buildup of pressure that must be monitored (pressure front). This is why multiphase modeling is one of the required components of a Class VI permitting effort. Details such as the number of monitoring wells and well placement must be carefully tailored based on these multiphase modeling results and where the CO_2 plume and associated pressure front are expected to migrate over time. One strategy is to use an iterative approach, where different clusters of monitoring wells will be appropriately phased into the plan over time as the plume and pressure front monitoring data reveal how CO_2 is migrating in the real world. This allows for more flexibility with planning, as the Testing and Monitoring Plan will be updated with any AOR re-evaluation and on an as-needed basis. The models allow for feedback in real-time to the monitoring network design.

In terms of vertical placement, the USEPA guidance for Class VI testing and monitoring (2013) recommends monitoring the first permeable unit above the confining zone (cap rock), where geochemical samples can feasibly be collected. The guidance also notes that the lowermost USDW or other USDWs may need to be monitored. It is wise to consider monitoring the lowermost USDW and the local USDW used for potable water regardless of the requirements, as protection of these USDWs is paramount. Great care should go into monitoring well construction design as well. Monitoring wells for CCS sites will often be monitoring deep units, and should be designed as such with the geochemistry of the monitored unit and potential for CO_2 interaction in mind (e.g., use of corrosion-resistant well construction materials to prevent degradation of wells through corrosion).

Groundwater Statistics

USEPA's Class VI testing and monitoring guidance (2013) provides basic recommendations on geochemical parameters to monitor and data trends that may be suggestive of fluid leakage and migration related to injection. However, the guidance is open-ended and leaves much of how to handle the data collection and interpretation process to the discretion of the operator, pending approval by the UIC program director. There are no specific suggestions for how to handle the statistical analysis.

In general, CCS should follow the anti-degradation basis recommended by USEPA's Unified Guidance (2009). It is essential to the project's success to carefully derive baseline/background data and conduct monitoring activities in terms of deviations from that baseline and plan ahead for how to handle when deviations do occur. Geochemical parameter monitoring lists should be optimized on a site-specific basis to maximize statistical power and minimize the site-wide false positive rate. In addition to collecting baseline data to characterize the geochemistry of monitored units, the geochemistry of the brine in the injection zone should be fully characterized. If fluid leakage and migration into a monitored unit occur, you would expect to see geochemical changes in the monitored unit suggestive of interactions with the reservoir's formation fluid and CO_2. To maximize statistical power and keep site-wide false positives low, it is important to only monitor parameters that will be strong geochemical indicators of formation fluid and CO_2 leakage and migration.

We must also consider the geochemical differences between various monitored units, such as other saline aquifers closer to the injection zone, versus the lowermost USDW, versus shallow aquifers (USDWs). Even in dilute, shallow aquifers, it may be hard to identify geochemical changes induced by fluid migration, and this only worsens in deeper units where the geochemistry will more closely mirror that of the reservoir formation. One strategy is to consider the concepts of geochemical correlation and demonstration of alternate sources. In a shallow, dilute aquifer utilized for drinking water, geochemical changes should be reviewed by comparing molar concentrations of parameters in the aquifer to those in the formation fluid (brine). If the changes are related to fluid leakage and migration, the geochemical changes should occur in equimolar ratios with the geochemistry of the injection zone brine. In essence, you would need to see an equimolar change in all expected parameters. If only one or two parameters are changing, it should be simple to attribute the change to an alternate source, as shallow aquifers are easily influenced by anthropogenic sources, and often have multiple recharge zones. In contrast, geochemical correlation may be more difficult in deeper, more saline aquifers with parameter concentrations closer to those of the injection zone brine. However, alternate sources cannot typically be demonstrated in deeper, more saline aquifers because they are not utilized, have no major recharge zones, and are not connected to anthropogenic sources.

Summary

With climate change becoming a center of attention globally, much focus has been pointed towards CCS in recent years. While USEPA has published general guidance for Class VI permitting, it is still a new permitting challenge for both scientists and regulators alike and it will be beneficial to draw on lessons learned from more familiar and well-developed regulatory frameworks. We focused on the testing and monitoring aspect of Class VI permitting and related complexities, which include the overall scale of the project, enhanced costs, and enhanced regulatory risk. We discussed the key considerations for developing an effective CCS Testing and Monitoring Plan based on lessons learned from developed MSW and CCR monitoring programs, as well as how early planning and good judgment can help navigate the complexities associated with CCS projects and ultimately reduce those complexities and associated project costs. Recommendations include meticulous site characterization efforts early in the project and tailoring the monitoring network. The latter includes placing monitoring wells based on multiphase modeling predictions, designing geochemically and geomechanically compatible monitoring wells, and using strategic statistical techniques to analyze and interpret monitoring data.

As a final takeaway, it is important to remember that groundwater monitoring is not intended to be the primary monitoring method for detecting fluid leakage and migration, and it is only one of many required testing and monitoring methods (Figure 2). Notwithstanding, it is critical that the monitoring network is appropriately planned and established and tightly coordinated with the other testing and monitoring methods to maximize protection of USDWs.

Acronym List

AOR	Area of Review
CCR	Coal Combustion Residuals
CCS	Carbon Capture and Storage
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
MSW	Municipal Solid Waste
RCRA	Resource Conservation and Recovery Act
SDWA	Safe Drinking Water Act
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USEPA	United States Environmental Protection Agency

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