Expert-Based Development of a Standard in CO_2 Sequestration Monitoring Technology

Project Summary
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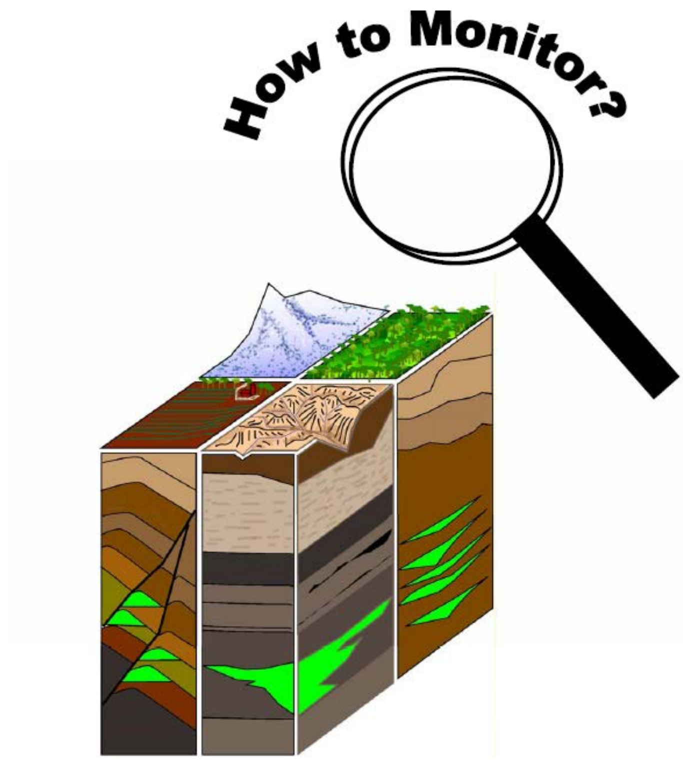

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I. Background

CO_2 produced from combustion of fossil fuels and emitted to the atmosphere is one of the major causes of increasing atmospheric concentrations of CO_2. CO_2 concentration impacts the thermal properties of the atmosphere, performing as a so called “greenhouse gas” to impact climate. Changes in atmospheric concentrations also equilibrate with and change ocean chemistry.

One mechanism proposed and being deployed in early projects to reduce atmospheric emission of CO_2 from large stationary sources such as power plants and carbon-intensive industries is known as carbon capture and storage (CCS). Facilities capture the CO_2 from stacks or vents prior to emission to the atmosphere and concentrate it by separation of the CO_2 from other gases and by compression. The resulting “dense phase” CO_2 is transported to be injected into selected and permitted porous rock units in the deep subsurface for storage. Storage units selected must be shown to be below and hydrologically separated from potable water and provide assurance that the storage is effective. Demonstration of effective storage requires collection of characterization data and construction of numerical models showing that the natural environment can accept the volume of fluid planned and effectively isolate (sequester”) it from returning to the atmosphere and from negatively impacting any other resource. This process changes the dynamic from a transfer of carbon geologically in the earth as fossil fuels, and released by combustion to the atmosphere and ocean, to a closed loop system where the carbon is returned to storage in the earth, stabilizing the atmosphere and ocean.

Sedimentary rocks commonly provide suitable environments for geologic storage. Porous and permeable rock layers allow fluids to move along them. In the near surface, porous and permeable rocks host groundwater resources. These are protected from injection in the US by underground injection control (UIC) programs. Similar rock systems in the deeper subsurface locally serve as reservoirs in which oil and gas has naturally accumulated, been stored over geologic time, and from which these fluids can be produced. In addition, injection of resources such as natural gas for storage or hazardous and non-hazardous liquid into porous and permeable sedimentary rocks is a common practice. Interbedded with permeable rocks are fine grained or tightly cemented rock types such as shale, mudrock, tight limestone, anhydrite, or salt. These units are laterally extensive and greatly retard vertical migration of fluids. Low permeability units above the injection zone are known as seals or caprocks, sequences of them are called confining systems.

II. Goals of this Project

EPA has developed rules and guidance for geologic storage of CO_2 captured as part of a carbon capture and storage program. A monitoring program provides assurance that the data on which the site was selected and the injection designed are correct and that the site is accepting and retaining CO_2 as planned. The monitoring program can allow midcourse correction should an unfavorable trend be discovered, such as the site cannot accept CO_2 at the planned rate or that retention is not adequate. It is widely agreed and required by the EPA program that the monitoring program should be “site-specific” and that a single standardized monitoring protocol will not be both effective and cost-effective. Application of an inadequate technique has two serious implications: (1) the operator increases costs without achieving desired benefit, and more importantly from a regulatory perspective, (2) the monitoring goal in terms of protection is not adequate to achieve this goal, and damage to protected resources or loss of CO_2 to the atmosphere could result without reporting or mitigation.

Although site-specific adaptation is important in correctly meeting regulatory expectations, the methods by which the monitoring program should be matched to the site are not provided in detail by most protocols. Site developers and regulators are, for the most part, “on their own” to make the selection of tools needed. The goal of this study is to provide some case studies, based on experience and modeling, that can provide a framework into which site developers and regulators can place their decision-making process.

This project resulted in preparation of a number of publications and reports, as well as workshops and stakeholder engagement activities.

III. Results of this study

During this study we evaluated many technologies and approaches used for monitoring. Our approach was to invest heavily in the growing body of expertise through dialog with global experts, formal and informal review of storage projects, and in-depth field experience designing and conducting field projects at the Gulf Coast Carbon Center. It became apparent that matching the monitoring to the site required consideration of a number of issues preceding monitoring design. Issues dealt with are (1) quantitative project goal setting (identification of material impacts); (2) characterization and uncertainties; and (3) assessment of low probability material impacts (ALPMI). Following this workflow allows a design for monitoring to be fit to purpose in that the monitoring can test for presence/absence of ALPMI. Two elements specific to sites are to be considered for all tool types: noise and strength of signal.

To meet the project goal of quantitative evaluation of potential monitoring strategies we reviewed inventories and experience with a large number of tools. For detailed study, we selected subsets of tools on which to conduct a detailed assessment of site-specific limitations.

We note that the performance of tools involves a complex interaction of many components. The design of the tool itself in terms of sensitivity to signal, the operation of the tool in terms of technical aspects such as calibration and optimized operation, the frequency, spacing, and duration of deployment of the tool, the precision and frequency of data recording, the analytical methods used to process the data, and the statistical approaches to filter noise, as well as the approach to interpretation can all have strong impacts on the suitability of the tool for the monitoring purposes. Project developers and regulators recognize the need to select a qualified vendor to operate a technology with best standards. For this reason, EPA requires development of a quality assurance project plan (QAPP) that provides assurance that data collected by monitoring projects are of known and suitable quality and quantity (U.S. Environmental Protection Agency, 2001). Experts in monitoring design that we interviewed concur that because of the complexity of interactions among these variables, the only way that an approach can be optimized for a specific site is to invest in a proper site-specific design program for the selected tools. This “leave it to the experts” approach, however, does not provide a process for determining if a monitoring program is adequate to achieve the project’s goals or to evaluate the value of investment in one type of tool over another.

The field of monitoring geologic storage sites is large and growing rapidly. Several previous reports have undertaken comprehensive inventories of types of tools (IPPC, 2005; British

Geological Survey, 2006; U.S. Department of Energy, National Energy Technology Laboratory, 2009). The viable approach to completing an optimized design is for the project developers to commission the needed study and design by a team of experts, who will prepare documentation of the plan for regulatory review, an approach demonstrated by commercial projects (for example, Shell for the QUEST project, 2010). However, to identify the correct types of expertise, substantive cross-discipline expertise is needed. The final product of this study is a workbook that project developers and regulators can use to build expertise to conduct the needed evaluation.

Because it is difficult for project developers to discuss “failure” in a situation where most of the effort is building confidence of the public, investors, and regulators, we use a more neutral term: “material impact.” Material impact is an event, or preferably a trend of measurements, that would cause the project not to meet its quantitative goals. The process of identifying material impact is the same as is known in many industries as risk assessment.

Geologic characterization provides the data to the predictive models on which the injection operation is designed and supports the prediction that the project goals can be met. Good characterization is therefore essential (for example US DOE, 2010, U.S. CFR, 2010b). A project will not be likely to be permitted to inject until the key uncertainties have been reduced such that successful performance is expected. Therefore, monitoring protocols that require that “possible leakage paths be monitored” are likely to receive the response from the project proponents that at an advanced stage of project development, all possible leakage paths have been evaluated and the risk has been essentially eliminated. For example, wells have been assessed and remediated as needed and no conductive fracture systems were found. This perspective can lead to a superficial evaluation and deployment of minimal monitoring to “check the boxes” in a plan. However, as discussed previously, a superficial approach is a risk to the project in terms of the possibility of collecting unexplained signal and lowering confidence or spending money and effort but missing important signal.

Some uncertainties remain in all model predictions, even those based on very good characterization (Cooper, 2009, p. 11), especially about events that are of larger magnitude or longer duration than were measured during characterization. The best practice from CO_2 EOR projects is to conduct a CO_2 injection pilot prior to committing to a full-scale injection (Teletzke and others, 2010). Other elements, such as the performance of the confining system including the adequacy of well penetrations in providing isolation, the nature of reservoir boundary conditions, and the geomechanical response of the reservoir to pressure increases, may also be critical needs prior to completing the risk assessment and designing a monitoring program (for example Birkholzer and others, 2013) . For large volumes and long durations, however, data from the full-scale injection may be the only way to reduce uncertainly far enough to meet project goals. In this case, monitoring is the approach needed.

The value of collection of data intermediate between characterization of ambient conditions and monitoring a large-scale injection for a long period should be further considered to make needed predictions without requiring large injection or long time frames. Such data include carefully designed laboratory-scale and small- to intermediate-scale field test programs. For example, the interaction of the rock system with CO_2 during stabilization can be tested at a small scale and for a short duration to provide data relevant to post-closure conditions to improve confidence in prediction (Daley and Hovorka, 2010).

The next step of an ALPMI process, following quantitative goal setting and characterization, is to identify the monitoring approach that can determine if the material impact is or is not occurring. Documenting the expected outcome, confirmation of a negative finding that the material impact is not occurring, requires thoughtful design but is of high value to the project.

The assessment proceeds with creation of the material impact in a model. Intersection of these ideas with a site characterization results in a series of scenarios to be tested to see if they are possible and, if so, if they lead to material impact. Material impact can be examined through very simple conceptual models, or more quantitatively as analytical or geocellular fluid flow models. Model uncertainty as two-phase fluids and buoyancy interact with porous media and reservoir structure has been explored at the basin-scale by Gibson-Poole and others (2008) in Gippsland Basin, southeast Australia, or through forward modeling and history matching example of Sleipner free-phase CO_2 (Cavanaugh 2013). In our experience, for some cases, attempting to model a material impact will show that the data already available eliminate the possibility that the material impact can occur. Other cases require additional data to confirm or refute the scenarios that lead to potential material impact. Acquisition of these data is then identified as the monitoring need. The workbook prepared for this study presents some examples of the ALPMI process (Hovorka and others, 2014a). In our experience, the monitoring needs tend to converge toward a relatively small number of types of measurements, as many material impacts are observed to have overlapping precursor signals.

Modeling ALPMI is essential to define the magnitude, timing, and evolution of the signal. Quantification of the signal is a critical step in designing a program to detect the signal, or importantly, to demonstrate that impact is not occurring. For example, if a time-lapse 3-D survey is the mechanism under consideration for detection of CO_2 that has migrated out of the planned project area, it is important to predict the plume thickness and parameters of the zone where it might migrate, such that a program for detection can be designed. If a program of surveillance of underground sources of drinking water (USDW) is proposed, it is important to conceptualize the various rates and mechanisms by which CO_2 could be introduced into different zones to design detection or to confirm that no impact to USDW has occurred.

It is important to note a major systematic difference in ALPMI arises when considering past site histories. As a project in part derived from this study and linked to a number of field tests we assessed the role of site history in geologic storage assurance (Wolaver and others, 2013). A site into which CO_2 will be injected for CO_2 enhanced oil recovery (EOR) has a well-known volume because of production history, well-known and actively managed areas of plume and pressure response, and a demonstrated confining system. For a similar site with no trapping or production history the monitoring plan may need to target these uncertainties. However, as discussed by Wolaver and others (2013), the EOR site may have other needs in terms of a fit-to-purpose monitoring plan, such as demonstration that well construction is adequate to provide the desired assurance of retention. This comparison is important in developing site-specific approaches to providing the same level of storage assurance for CO_2 injection at sites having different histories, for example, in design monitoring to meet the greenhouse gas reporting rules under Clean Air Act Subpart RR (U.S. CFR 2010a).

The limit on detectability created by irreducible variability in the parameter to be assessed is classified as noise and can vary strongly among sites. Each monitoring technology has a number of detection limits that are assessed during QAPP or other well-established methods. However, the ambient variability of the site with respect to signal is highlighted here. Noise is particularly important in geologic storage monitoring because of (1) heavy reliance on time-lapse detection of change and (2) sites that are vertically and aerially extensive, capturing diverse parts of the system.

Successful monitoring design depends on strength of the signal above noise. Within each technology, sophisticated techniques are available to assess the strength of the signal. In the context of this study, we illustrate some of the interactions of signal strength with site-specific parameters. Our goal is not to conduct a comprehensive assessment, but to demonstrate for stakeholders the importance of this assessment. Outcomes from this study are to illustrate quantitatively why a technique that was successful at one site may be of little value at another site and to inspire regulators, operators, financiers, and others stakeholders to invest in proper assessment of this element of site-specific design.

During the past several decades of geologic storage monitoring, seismic monitoring methods have gained a reputation as high-value performers. The value of seismic monitoring is that a 3-D survey volume is one of the few methods that can assess an entire rock volume, from the injection zone, including the interwell volumes, through the confining system, and up into the overburden or intermediate zone that isolates the deep subsurface from the USDW. Because seismic response is sensitive to fluid compressibility, repeating the same 3-D survey over time as the CO_2 is emplaced and stabilized provides a powerful tool in showing where CO_2 has replaced water. A 3-D time lapse (4-D) is created by differencing a preinjection survey from the survey collected after the CO_2 is injected. The areas of change can be interpreted as indicative of change in fluid properties including fluid composition and pressure, both of high value to geologic storage monitoring (Lumley, 2010).

However, it is clear from first principles of seismic measurements that detectability of fluid substitution is highly site specific. We conducted a series of simplified explorations to provide information to regulators and monitoring program designers about the intrinsic characteristics of the rock-fluid system (Hovorka and others, 2014a). It is clear that no simple screening tool can substitute for a site-specific evaluation by a qualified vendor. However, the purpose of our assessment is to identify site-specific parameters that lead to easier and more robust detection of CO_2 substitution for brine in either a within-zone or above-zone setting. Vendors may be able to use the large flexibility within 3-D seismic methods to optimize detection even in a difficult setting. However, the screening tools provided will give operators and regulators an alert that such optimization of techniques are called for.

Pressure is a basic history-matching parameter for reservoirs and is widely used for monitoring many subsurface projects. We have explored some novel approaches and limitations, for example, the use and limits of continuous pressure measurements from a dedicated observation well in a complex injection at Cranfield, Mississippi (Meckel and others, 2013).

We chose a method adapted from gas storage monitoring, which places a pressure gauge in a laterally continuous permeable formation above the injection zone, described as an above-zone monitoring interval (AZMI). To assess the sensitivity of the AZMI pressure monitoring technique to different geometries is essential to document that no leakage from the injection zone is occurring. If the distance between monitoring points is too large, leakage detection cannot be assured and a robust finding of retention cannot be made. The spacing between monitoring points is sensitive to the hydrologic properties of the system. We developed type curves to determine well leakage detectability through pressure monitoring. The type curves are based on a newly developed asymptotic solution (Zeidouni and others, 2011). The type curves are presented in dimensionless format to be applicable to any set of injection zone and AZMI. Zeidouni and others (2011) considered a single AZMI overlying the injection zone and the analytical solution was adapted to support evaluation of multiple AZMI (Porse, 2013).

The pressure signal is a function of the petrophysical properties of both the injection zone (from which fluid is leaking) and the AZMI (to which the leakage is occurring). Preliminary modeling and screening are required to determine which overlying zones provide the strongest pressure signals in response to a given leakage. One or more pressure gauges may then be deployed at favorable overlying permeable zones so that pressure measurements can be analyzed for leakage detection and characterization. For the design of early detection monitoring, the injection zone and potential AZMI were considered to be infinite acting. However, if leakage is sustained, pressure will eventually reach the boundaries of the injection zone and AZMI, causing larger pressure changes compared with those derived under infinite-acting conditions. The temporal impact is worth considering.To extend the analysis, we developed an analytical model for a vertical fluid flow planar feature described as a leaky fault (Zeidouni, 2012).

A pressure-based inversion technique has been developed to reconstruct leakage characteristics on the basis of inversion of pressure anomalies. The inversion algorithm solves a pressure anomaly deconvolution problem using a forward model that incorporates site geology and CO_2 injection history. Detailed description of the algorithm and numerical examples can be found in Sun and Nicot (2012). The technology developed here is practical (only requires a forward model) and can be readily embedded into an existing risk assessment framework. Reservoir models are always uncertain because of conceptualization assumptions and data limitations. Therefore, any prediction of the fate of CO_2 plume or leakage potential must be accompanied by uncertainty quantification (UQ). Detailed description of the algorithm and numerical examples can be found in Sun and others (2013b).

The ultimate goal of pressure-based monitoring is to institute an optimal monitoring network on the basis of site conditions. Given a monitoring budget and desired detection interval (defined as time elapsed from onset of leakage to detection by a pressure gauge), the Sun and others (2013a) provide a method for finding optimal monitoring well locations while satisfying the number of pressure monitoring locations an operator can afford.

Thermal methods are a way of detecting fluid flow from depth across the geothermal gradient. They can be used in the negative, to determine that local flow is not the cause of pressure change (Tao and others, 2013). Thermal methods are very attractive for monitoring because temperature can be measured simply and robustly across a wide variety of environments in real time and is highly quantitative. Equilibration of the CO_2 and reservoir brine away from the injection well with the ambient rock water temperature provides a potentially useful leakage signal. Fluids migrating upward through a focused path—for example, along a flawed well casing—are hotter than ambient fluids. We used numerical simulation tools to evaluate temperature changes associated with CO_2 leakage from the storage aquifer to an above-zone monitoring interval and to assess the feasibility of monitoring of CO_2 leakage on the basis of temperature data (Zeidouni and others, in press).

Leakage of CO_2 to groundwater is an important monitoring parameter for EPA because of the role of the UIC Program in protecting USDW. The key elements in this protecting role are the potential for negative impact of CO_2 leakage and water quality (for example, Carroll and others, 2009; Lu and others, 2009; Apps and others, 2010; Mickler and others, 2013). An additional element considered is the extent to which monitoring USDW can be used to document CO_2 retention, for example, under the Clean Air Act (CAA), part RR.

We classify the environmental factors that may affect sensitivity of detection into chemical factors and physical factors. The chemical factors are related to geochemical processes after CO_2 is leaked into the aquifer, such as mineralogy in aquifer sediments, and initial groundwater chemistry, which are the focus of the analyses (Yang and others, 2013d). Technical factors, including different sampling protocols, methods, and instruments, may also affect the measurements of the geochemical parameters. Impacts of the technical factors on measurements of geochemical parameters could be minimized, however, through careful selection of instruments and sampling methods and good sampling design.

We selected groundwater parameters pH, dissolved inorganic carbon (DIC), alkalinity, and HCO_3^- as primary indicators of leakage of CO_2 into groundwater and then further evaluated and ranked their sensitivity to CO_2 leakage. We also selected three sites with various characteristics located in Texas (Smyth and others, 2009; Romanak and others, 2012b), Mississippi (Yang and others, 2013b), and Montana (Wilkin and DiGiulio, 2010). The site-specific sensitivity of the response to leakage was tested considering reactive minerals in the aquifer sediments and initial aquifer chemistry. The detailed methodology and data are included in Yang and others (2013c).

The results of this study show that the presence of carbonate in the monitored aquifer has an important impact on groundwater monitoring for leakage. Models of aquifers with nonreactive mineralogy such as quartz exhibit a leakage response to CO_2 as negative shifts in pH, positive shifts in total inorganic carbon, and negligible changes in alkalinity (Yang and others, 2013c), results which are similar to the findings reported by Wilkin and DiGiulio (2010).

Groundwater pH calculated in the carbonate-bearing aquifer is buffered compared with groundwater pH in the carbonate-poor aquifer. Alkalinity is almost unchanged in response to leakage into the carbonate-poor aquifer, whereas alkalinity increases in the carbonate-rich aquifer as the CO_2 leakage rate increases. As expected, HCO_3^- shows very similar behavior as alkalinity after CO_2 is leaked.

Responses of DIC and dissolved CO_2 in groundwater to CO_2 leakage rate appear to be independent of aquifer mineralogy, although DIC and dissolved CO_2 could be slightly higher in the carbonate-rich aquifer than in the carbonate-poor aquifer. Among the four geochemical parameters, dissolved CO_2 and DIC are better indicators of CO_2 leakage in groundwater than pH and alkalinity.

We surveyed the substantive experience gained from monitoring injection for more than 50 years and 28 recent, relevant CO_2 storage monitoring programs and discussed successes, failures, uncertainties, and lessons learned with the members of the research teams. This analysis explores the reasons that different monitoring approaches are needed at different CO_2 geologic storage sites and makes recommendations of processes that could be used to fit a monitoring approach to a site. Three major sources of site-specific differences are recognized: (1) differences in project goals, (2) differences in mechanisms that might lead to failure of the project to reach the goals, and (3) differences in ability to detect a signal from a failure or incipient failure to reach the project goals. Differences in site-specific goals result from different concerns at each site from the geologic or cultural setting or from input from different stakeholders. It is important that these goals be stated quantitatively. We propose a new term—“assessment of low probability material impact" (ALPMI)—to facilitate the discussion of unexpected but possible outcomes that would fail to meet the project goals, and recommend that the ALPMI be modeled as a step in design of a robust monitoring program. Once the signal produced by an ALPMI or trend toward ALPMI is determined from the quantitative goals, a monitoring program can be designed to determine whether the signal is or is not found. We provide an analysis of tool-specific assessments that can be used to evaluate if the ALPMI signal is detectable at a site. Site-specific variables such as depth, thickness, and geochemistry can have an important impact on signal strength. Noise is also an important site-specific variable.

The recommendations from this study have been compiled in a workbook (Hovorka and others, 2014a) that will be submitted for publication.

IV. References

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