Expert-based development of a standard in CO2 sequestration monitoring technology

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S. D. Hovorka
J.-P. Nicot
M. Zeidouni
A. Y. Sun
C. Yang
D. Sava
P. J. Mickler
R. L. Remington

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

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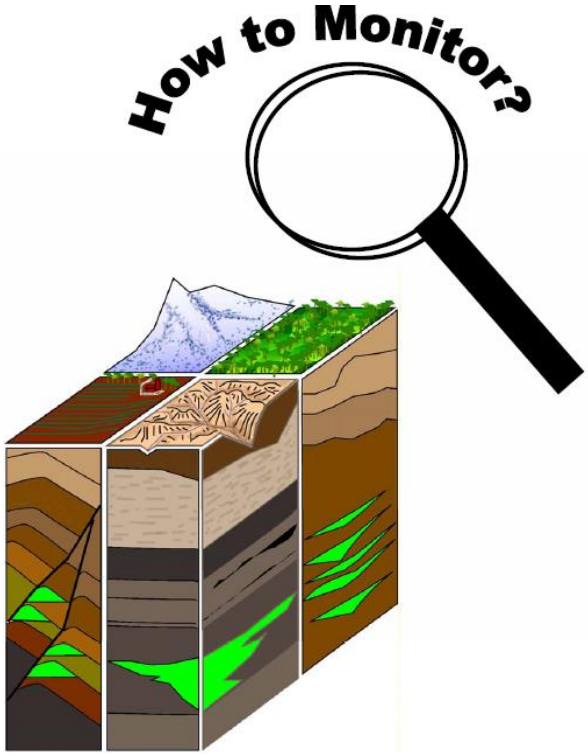

Susan Hovorka, Jean-Philippe Nicot, Mehdi Zeidouni, Alex Sun, Changbing Yang, Diana Sava, Pat Mickler, Randy L. Remington

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin
Austin, Texas

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Acronyms

ALPMI	Assessment of low probability material impacts
AZMI	Above zone monitoring interval
DIC	Dissolved inorganic carbon
EOR	Enhanced oil recovery
GCCC	Gulf Coast Carbon Center
InSAR	Interferometric synthetic aperture radar
MCL	Maximum contamination level
QAPP	Quality assurance project plan
RCSP	Regional carbon sequestration partnership
SDWA	Safe drinking water act
SECARB	Southeast regional carbon sequestration partnership
UIC	Underground injection control
UQ	Uncertainty quantification
USDW	Underground sources of drinking water

Abstract

This study provides a methodology to optimize the match between the characteristics of a geologic storage site and the monitoring technologies selected for it. Components of this study include

(1) Modeling the sensitivity of selected representative monitoring strategies to the expected variability of sites;
(2) Testing the evaluation against the growing array of field measurements, gathered from field test sites;
(3) Building consensus that the proposed improvements in mechanisms for matching monitoring methods to sites are properly applied and adequate;
(4) Compiling a workbook of test cases for training practitioners in applying the strategies to an array of sites.

Three types of site-specific parameters must be considered to develop a monitoring program: project/site-specific goals, site-specific risks of not accomplishing those goals, and site-specific tool sensitivity. Each of these elements is explored.

Goals vary among projects because of different regulatory drivers, different industry drivers, and different issues of public concern. As an example, we highlight the difference between a research- or demonstration-oriented project, as most current storage projects would be classified, and a fully commercial project in a mature storage industry, which is the ultimate goal for the carbon capture and storage. An optimized monitoring program for a research program will be quite different from that for a commercial program. Goals must be stated quantitatively so that a plan can be developed to document that the goals are reached. The term “material impact” is proposed for scenarios where project goals might not be achieved.

Site-specific risks of not meeting the project goals are widely recognized, because of geologic differences between sites. In this study, we propose a workflow to select elements of the project where confidence from characterization is insufficient to provide adequate assurance that the project will reach its goals. This process is described as an Assessment of Low Probability Material Impacts (ALPMI) and is a simple test design method. For each goal, thresholds that would constitute material impacts are set. Monitoring is then designed to detect the signal above the material impact threshold; only by this method can the expected finding of project success be documented.

Site-specific sensitivity of methods is broken down into noise and signal. Noise is irreducible fluctuations that obscure the signal, and it can be highly variable among sites. The strength of the signal also varies among sites. Case studies to illustrate site-specific signal strength for specific elements of 4-D seismic, pressure, thermal methods, and geochemical techniques were completed.

I. Motivation of this study and scope of final report

This study was conducted under funding from the U.S. Environmental Protection Agency (EPA) and from the CO_2 Capture Project Joint Industry Project (http://www.co2captureproject.org/). The study was proposed and initiated prior to EPA's release of two major rules related to carbon dioxide (CO_2) geologic storage: the Mandatory Reporting of Greenhouse Gases added to the Clean Air Act (U.S. CFR 2010a) and the Class VI rule added to the Underground Injection Control Program (U.S. CFR, 2010b). The perspectives provided by these rules were incorporated into the study; however, the scope remains high level, in terms of accepting and generating information relevant to geologic storage projects in many contexts, including those seeking to meet the site-specific requirements of the EPA's greenhouse gas and Class VI rules but also to conduct CO_2 accounting for federal or state credit (for example, U.S. Code, 2011; Texas House Bill 469, 2009), or to follow the guidelines of an exchange (for example, prototype of McCormick, 2012), or to contribute to improving the quality of storage monitoring in an international arena (for example, Official Journal of the European Union, 2009).

Essentially all the rules, guidance documents, and frameworks promulgated or being developed for the regulation and accounting of geologic storage of CO_2 in the United States or internationally require a monitoring program (Table 1). In many cases, a recommendation or requirement is given that the monitoring program be "site-specific." Few details are provided, however, on how to comply with this expectation.

The overarching goals of monitoring are relatively consistent in reviewed documents. Overarching goals are to provide assurances to regulators and stakeholders that the retention of CO_2 implicit in the term "storage" will occur. In particular, goals must be designed to ensure (1) that the site characterization based on which permits were granted is correct and (2) that injection operations are being conducted as planned to assure retention. Site characterization shows that the injection zone has sufficient capacity to store the CO_2, and injectivity shows that the zone can accept the CO_2 at the planned rate. Characterization also shows that the confining system overlying the injection zone has characteristics that will sufficiently retard vertical migration of CO_2 and that the retention is effective to benefit the atmosphere and prevent damage. Operations include remediation of existing man-made structures such as wells, installation of new wells, injection operations, and any other relevant operations such as production.

Frameworks for monitoring are in agreement that the monitoring program should be adapted to the specific site at which it is deployed. The methods by which the monitoring program should be matched to the site, however, are not provided in detail. This site-specific adaptation is very important in correctly meeting regulatory expectations. For example, a technique that works well at one site to detect leakage could be inadequate at another site. 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.

Despite the importance of site-specific adaptation to project success, site developers and regulators are, for the most part, "on their own" to make the selection of tools needed. In the end, a collaborative negotiation will always be needed. The goal of this study is to provide some case

studies based on experience and models that can provide a framework into which site developers and regulators can place their decision-making process.

Table 1. Seventeen representative best-practice manuals, suggested protocols, regulatory guidance, and regulations with relevance to monitoring design and site-specific adaptation.

Source	**Scope**	**Citation**
IEAGHG study	Inventory	Benson and others, 2004
US NETL/DOE	Suggested best practices, monitoring	U.S. Department of Energy, National Energy Technology Laboratory, 2009
US NETL/DOE	Suggested best practices, risk assessment	U.S. Department of Energy, National Energy Technology Laboratory, 2009
US EPA	Rule – UIC program	U.S. CFR, 2010b
US EPA	Rule – CAA program	U.S. CFR, 2010a
US Internal Revenue Service	Tax credit for CCS	U.S. Code, 2011
US EPA	Class VI Well Testing and Monitoring Guidance	U.S. Environmental Protection Agency, 2013
International Energy Agency	Model regulatory guidance	International Energy Agency, 2010
US EPA	Guidance Subparts RR and UU greenhouse gas reporting program	U.S. Environmental Protection Agency, Office of Air and Radiation, 2010
Pew Center / C2ES	Suggested protocol: Accounting framework	McCormick, 2012
Interstate Oil and Gas Compact Commission	Suggested protocol	Interstate Oil and Gas Compact Commission, 2007
Texas Railroad Commission	Rule for credit	Texas Administrative Code, 2010
Det Norske Veritas	CO_2QUALSTORE guidelines	Det Norske Veritas, 2009
European Union	Directive of the European Parliament	Journal of the European Union, 2009
Shell	Commercial MMV plan for Quest Project	Shell, 2010
Canadian Standards Association	Recommended standards	CSA Group, 2012
World Resources Institute	Recommended standards	World Resources Institute, 2008

A review of previous injection projects (Figure 1) shows an advancement in technology, leading from skills in handling and permitting injection as part of other subsurface activities, to storage in isolation from atmosphere and ecosystem as a goal, and to the introduction of an expectation of monitoring for storage assurance. The present study is part of a progression moving toward fully commercial projects.

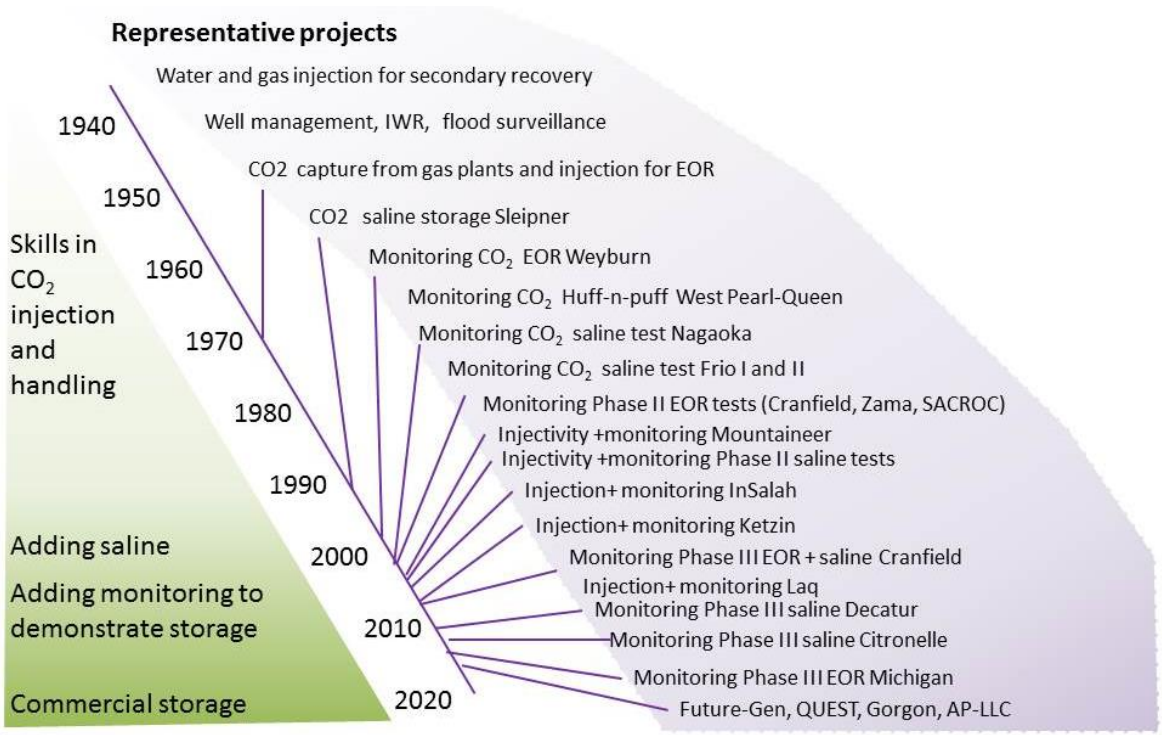

Figure 1. Representative injection projects showing project evolution. Storage in isolation from atmosphere and ecosystem and introduction of an expectation of monitoring for storage assurance are recent developments now maturing.

Figure 2 illustrates part of the motivation of the present study by showing that the amount of monitoring for geologic storage has been highly variable. Early and feasibility tests check injectivity and injection equipment using only a few monitoring techniques. Monitoring tests and model validations are designed to test the maximum number of technologies and to probe uncertainties. Research and development approaches require duplication of results and experimental tests that may not succeed in the early stage, or may be found to be unsuitable for the case. More commercial projects show maturation, in that technologies have been reduced to those that have been shown to be effective, to be viable in commercial settings, and to fit the focused purposes of the commercial projects. This inventory is somewhat subjective in that the count of number of technologies is sensitive to “lumping and splitting.” For example, if a number of variants in soil gas methods were used, how many should be counted? The inventory was arbitrarily baselined against the approaches used at the SECARB Early test and Frio test because the authors are familiar with those results. In addition, commercial project reporting probably has some undercounting biases, in that the projects are newer and coordinators may have less motivation to publish results. In a number of cases we obtained confidential access to plans to improve data.

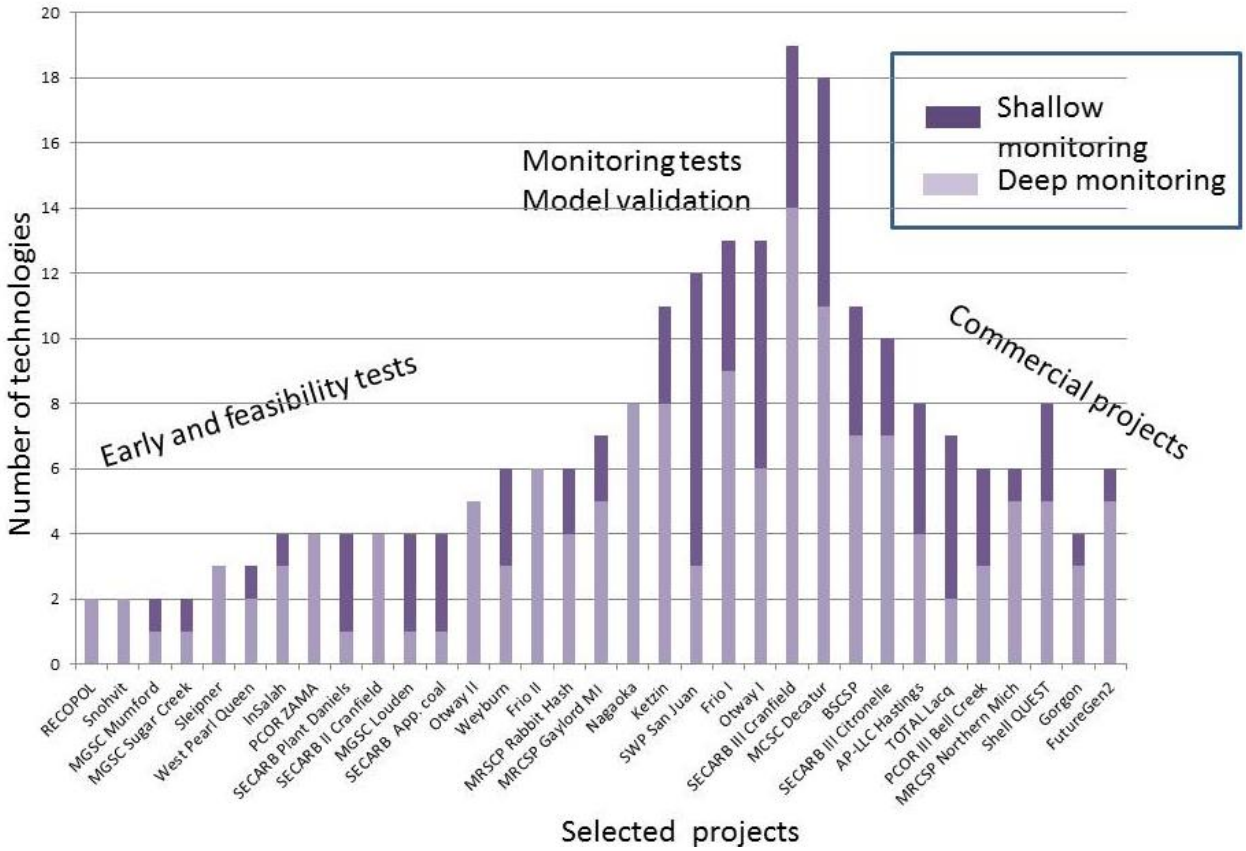

Figure 2. Count of shallow and deep focused monitoring technologies for selected projects of different maturities horizontal axis is project maturity.

The results of the research conducted for this study are organized into the following sections:

(II) Select strategies for application of monitoring to specific sites
(III) Field test sites
(IV) Develop consensus
(V) Workbook preparation

This final report provides an overview of the steps by which the project objectives were completed, which includes a number of publications and reports, as well as workshops and stakeholder engagement activities. Results that are published or in publication are cited and reviewed briefly but not quoted in entirety.

II. Select strategies for application of monitoring to specific sites

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. These activities are discussed in detail in section IV. It became apparent that matching the monitoring to the site required consideration of a number of issues preceding monitoring design. Issues dealt with and discussed

in detail in this section 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, both of which are further discussed in this section.

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 wells 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.

Few published works related to geologic storage provide simple and accessible assessments of the limitations of tools. We note that projects in which a limitation of a tool was encountered tend not to fully assess this limitation. Data on limitations are most accessible through informal conversations and at technical working group reviews. It is common for limitations to be expressed in publication in terms of future work or lessons learned, and full quantitative details may not be available. To fill this gap, we conducted an analysis focused on the interaction of selected site-specific parameters on the use of four tools: time-lapse 3-D seismic monitoring, pressure monitoring, temperature monitoring, and geochemical monitoring for leakage detection. Each of the tools was assessed in one or more technical papers, and a synopsis was used in compilation of a workbook (Hovorka and others, 2014a).

II-1. Limits of this study

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). Review of these inventories shows that a comprehensive overview of the site-specific limitations on the large array of tools is a very large undertaking. Further, technical trends observed show that rapid technology advancement is occurring as a result of global efforts on geologic storage testing and demonstration; soon after a tool limitation is identified, techniques to reduce the limitation follow. Many of the tools considered constitute large subdisciplines of

geoscience with their own focused expertise, for example, seismic 3-D collection and interpretation of groundwater geochemistry; it is not pragmatic to collect all of this expertise into a geologic storage-specific reference work.

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.

This study is focused on illustrative cases selected because (1) they are widely considered as basic approaches for monitoring and (2) they are illustrative of some of the different disciplines and technologies in the monitoring portfolio. We emphasize that the goal of this project is far short of providing all the information needed to develop a site-specific monitoring plan; however, we intend that it will be of value to project developers and regulators who are working with a team of technology experts as they evaluate and select monitoring options suitable to the project and site.

II-2. Activities precedent to monitoring design

During our work with experts, we learned how much impact the context in which the monitoring is conducted has on the development of monitoring. Many intense debates arise because of unstated differences in assumptions of the project goals. Most projects have broad programmatic objectives; however, different backgrounds, experiences, and contexts cause different stakeholders to interpret these objectives differently. One finding from this project is the need for explicit and quantitative metrics for project success with a strong and clearly expressed linkage to a site-specific monitoring program. A second issue observed is a mismatch of perception of uncertainty and risk between the site proponents and those who are reviewing and providing assurance that the site will operate as planned. As a resolution to these needs, we propose a process of assessment of low probability material impacts (ALPMI) described in Hovorka and others (2014a) and reviewed in this section. These precedent activities are essential to development of a successful site-specific monitoring plan.

II-2-1 Quantitative project goal setting

A monitoring program that is not based on a series of well-defined project goals is a high risk to the project. A monitoring design that is not carefully fit to purpose is at risk of (1) detecting changes that are unimportant to the project intent but confusing to the stakeholders or (2) failing to detect events that are indicative of current or future problems leading to failure to achieve the project objectives.

As an example, consider a high-level project goal of causing no unacceptable impact. Injection is likely to cause some level of microseismicity (IEAGHG, 2013), which in case (1) might be perceived by stakeholders as something not tolerable, and might cause the project to be shut down. In case (2), a trend of increasing seismicity in part of the site might be ignored until a felt event was triggered, which might cause the project to be shut down. The process of quantitative goal setting would define a distribution of acceptable microseismicity in terms of magnitude and probability and collect appropriate data to confirm that the range of events detected matches the

projected performance. Stakeholders would be reassured that the project is well managed. If an unexpected trend is detected prior to any events that harm public confidence, the operation can modify the injection to decrease risk.

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 used in many industries under the classification of risk assessment. For an example of an industrial approach applied to a geologic storage project, see Shell's (2010) plan for measurement, monitoring, and verification at the QUEST project.

For design of a monitoring strategy, a complete risk assessment in the sense of U.S. Environmental Protection Agency, Office of Science Policy (2000), or U.S. Department of Energy, National Energy Technology Laboratory (2011), or Det Norske Veritas (2013) is not needed. Quantitative data on the magnitude of loss or the probability of loss are difficult to develop for low-probability events and for sites where historical data on frequency are lacking. Such data are not needed for the design illustrated here; however, if such quantification is available, it can be used to develop a formal value-of-information approach to optimize the monitoring costs. In addition, because of the nature of CO_2, a detailed study of risk to human health or to the ecosystem is not needed. An example of a material impact might be that the reservoir cannot accept the planned volume of CO_2 at the planned rate because bottom-hole pressure in the injection zone was observed to be increasing more quickly than modeled. Proper measurement can identify such a trend and modify the plan needed to avoid the impact of injecting less CO_2 than originally planned or exceeding the acceptable bottom-hole pressure. An example of such a successful detection of unexpected limits in capacity and mitigation is provided by Statoil's injection at Snøhvit field in the North Sea (Hansen and others, 2013).

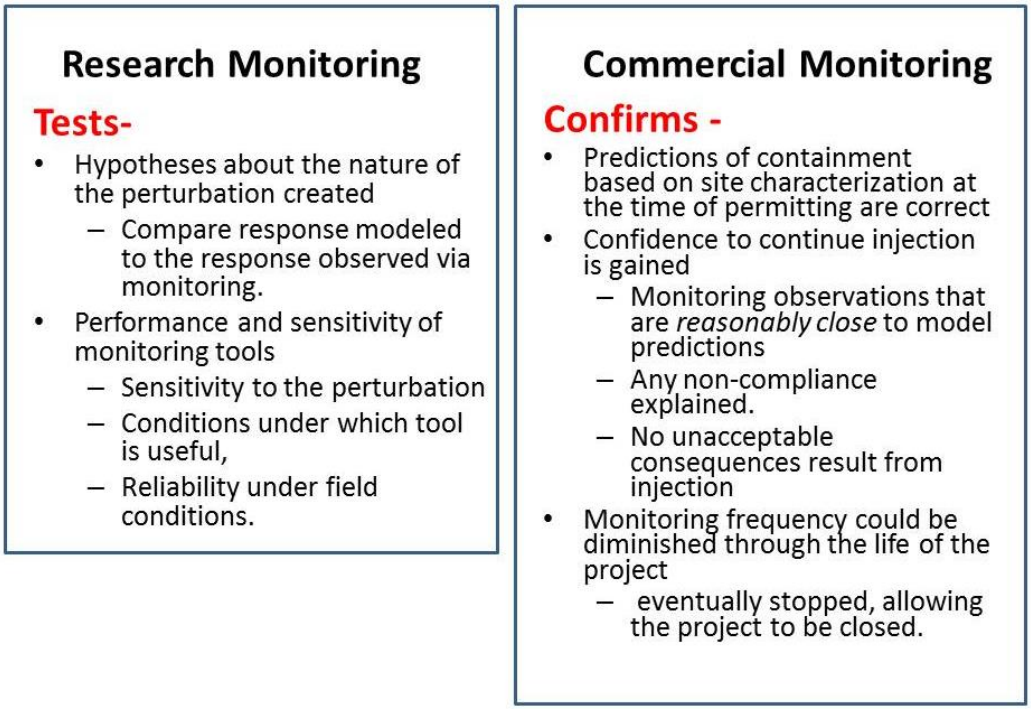

Figure 3. Comparing the goals and motivations of research and commercial monitoring.

From our experience, the transition from research-oriented projects to commercial projects is an important change that needs to be understood in the context of selection of monitoring technologies (Hovorka, 2012). Figure 3 diagrams some typical differences in motivation we have observed between demonstration projects having a research focus and those having a commercial focus. It is important that monitoring program designers not confuse an excellent monitoring plan having a research goal with an equally excellent but much more focused monitoring plan having a commercial goal.

II-2-2 Characterization and uncertainties

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). 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. Such unprecedented perturbations can be referred to as "in the white space" (Figure 4). Prediction of the reservoir response to sustained large-volume injection of an allochthonous fluid as occurs during CO_2 storage falls in this category. To complete a quantitative characterization of the system response, it is usually necessary to energize the reservoir system by injecting or withdrawing fluids to obtain reliable data on the hydrological properties of the reservoir (Cooper and others, 2009, p. 53). 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.

A formal, iterative process is recommended to evaluate the uncertainty in characterization data. Early in project development, modeling is conducted to define the most likely outcome of injection, and perhaps a probability envelope around the most likely outcome as shown in Figure 5. However, as part of the monitoring design in a mature part of the project development, we recommend focusing instead on modeling conditions that would lead to material impact with respect to the project goals, the outer box in Figure 5. The boundary between an acceptable outcome and an unacceptable outcome can be considered for many reservoir responses. It might

be lateral or vertical CO_2 migration or pressure increase in a larger area than permitted or leased; it might be pressure elevation above a geomechanically defined threshold, or microseismic response over a threshold defined as not acceptable.

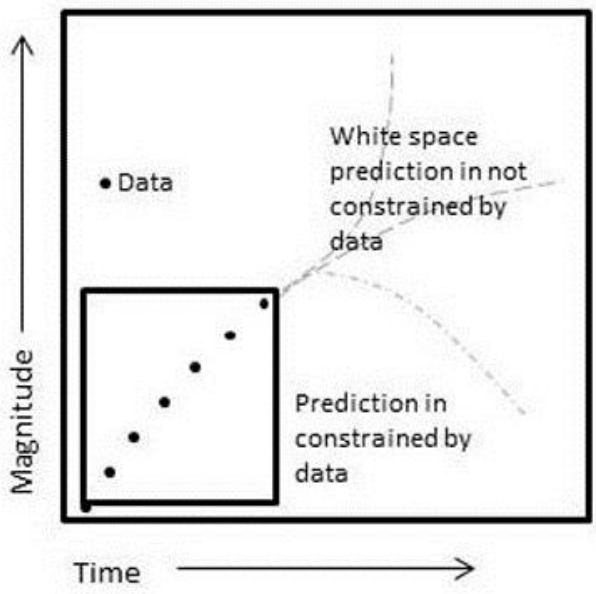

Figure 4. Prediction of system response is well defined where it is constrained by data (solid dots); however, modeling high magnitudes and longer time frames is more conjectural (dotted lines). Monitoring is one method of filling in the "white space" with data.

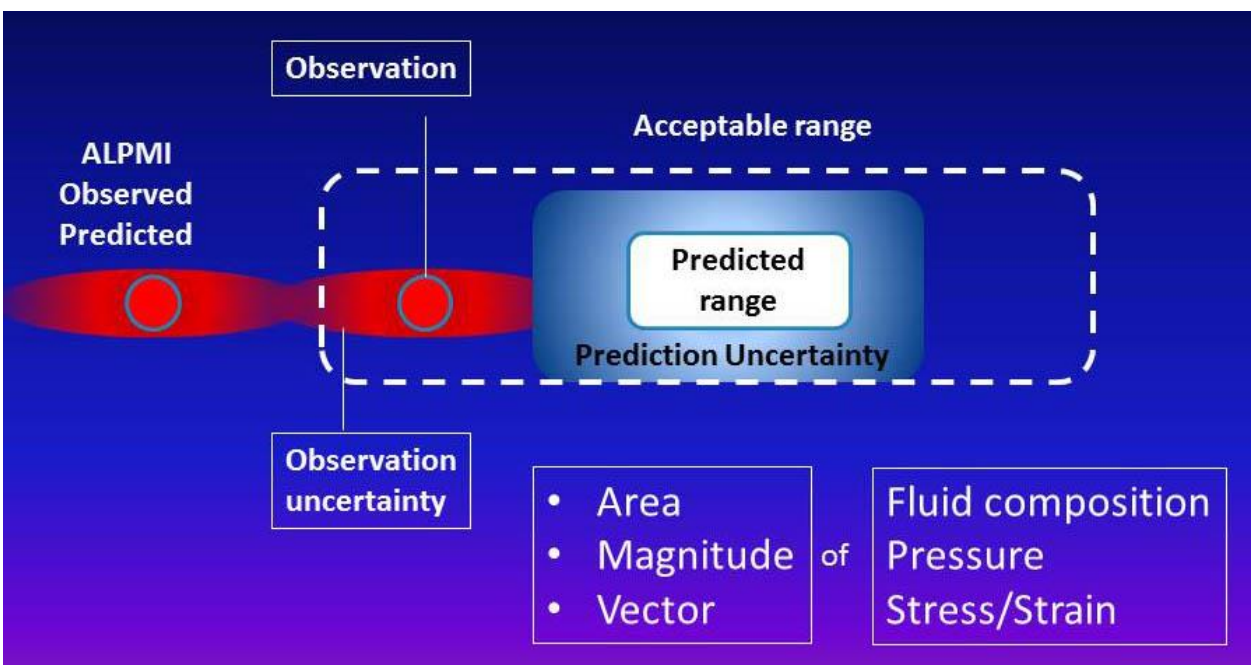

Figure 5. The predicted range of reservoir responses and the prediction uncertainty are the focus of early stages of developing a project. At the stage of developing a monitoring plant, the limits of the acceptable range of responses become important. In addition, for this study we consider the observation uncertainty, and whether the selected monitoring technology is sufficient to determine if the reservoir response is inside of the acceptable range.

Not all characterization data are equally important to the goals set by the project. In an assessment workflow, we suggest that early and approximate characterization data be taken through a preliminary modeling-driven risk assessment, to determine the precision with which reservoir properties need to be characterized to meet project goals. For example, the rate at which rock-water-CO_2 reaction stabilizes the plume may slow, and therefore not be defined as important criteria defining project success. We note that surveying the low-probability but possible situations, which may lie at the ends of distributions of characterization parameters, may be important in elimination of potential material impacts. For example, a few well-connected preferential flow "thief" zones could cause the plume to increase in size beyond what is acceptable. Assessment of scenarios for such zones requires consideration of the end of the permeability distribution, not of the average. Risk assessment and modeling can then be used interactively with characterization to optimize monitoring design, as described in the next section.

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 fill in the "white space" 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 postclosure conditions to improve confidence in prediction (Daley and Hovorka, 2010).

II-2-3 Assessment of low probability material impacts (ALPMI)

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. An example of a series of conceptual models of nonconformant migration for a highly generalized site is shown in Figure 6. 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.

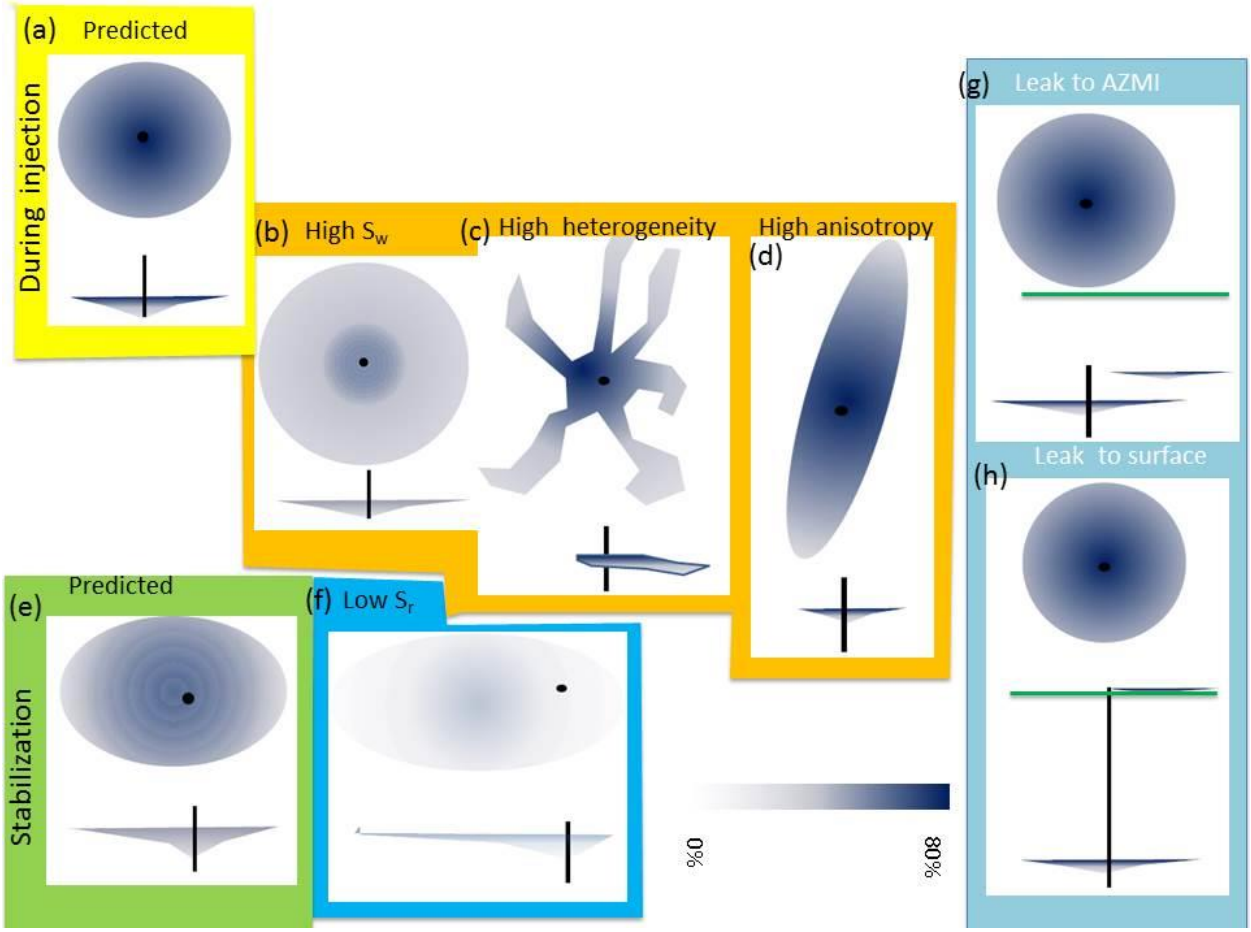

Figure 6. Simple conceptual models exploring the possible uncertainties in free-phase CO_2 distribution in map view and cross section. (a) the modeled more likely plume geometry at the end of injection, (b) a larger but less highly saturated plume form high residual water saturation (S_w), (c) high heterogeneity, (d) high anisotropy, (e) the predicted distribution of free-phase CO_2 at stabilization, with local dip to the right, (f) the free-phase CO_2 at stabilization of the residual CO_2 saturation (S_r) is lower than expected, (g) flaws in confinement that allow the CO_2 to migrate to a shallower zone, the above zone monitoring interval (AZMI), and (h) the CO_2 migrated to the surface.

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). Figure 7 reviews some of the significant differences between a site that has a long geologic history as a hydrocarbon trap and operational of production, termed a "*brownfield*," and a site that is developed for storage in an unused saline aquifer, termed a "*greenfield*." 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).

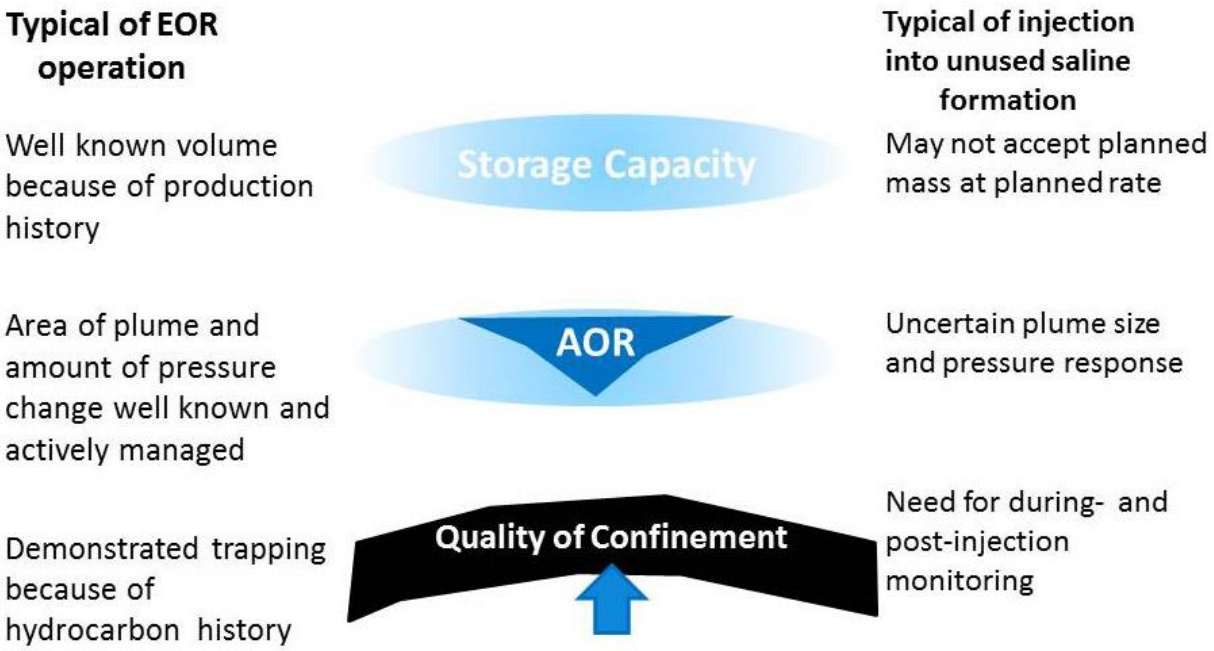

Figure 7. The history of site has a major impact on ALPMI.

The next two sections discuss additional site-specific elements of noise and signal. Following this workflow allows a design for monitoring to be fit to purpose in that the monitoring program can test for the presence/absence of ALPMI.

II-3. Noise: a critical site-specific parameter for monitoring

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 areally extensive, capturing diverse parts of the system.

An important example of noise for geologic storage is ambient variability in CO_2 at the surface, in groundwater, and to a lesser extent, at depth. CO_2 is generated by biologic processes and reduced by uptake during photosynthesis, by dilution by addition of other fluids, and by reactions that consume CO_2. The amount of CO_2 changes with temperature, light, and moisture in diurnal and seasonal trends. It may also change over time, for example, in response to climate or land use change. In some cases, much of this variability can be reduced numerically or by picking more stable sampling points. However, in so far as it cannot be reduced, this variability limits the ability to isolate and identify CO_2 input from leakage. For soil gas, an alternative process-based detection method has been proposed, in which processes such as respiration can be separated from leakage (Romanak and others, 2012a). Similar approaches are needed for groundwater systems, which can be complex in terms of groundwater variability, mixing, and impact on carbonate ions (Romanak and others, 2012b). Site-specific acoustic noise is important to measure as part of planning a seismic survey (Pevzner and others, 2011). Noise in other signals is less commonly considered; however, it can be critical for success. For example, pressure signal from injection can be complicated by other activities, such as distant or future injection or extraction, or recovery from such activities.

Many monitoring techniques rely on collection of a suite of static measurements prior to perturbation of the system by injection. Such measurements are typically described as *baseline*. Baseline plays several important roles: it is important to correctly define the purpose of the survey for assessment of trends and noise, to assess signal strength, to determine repeatability, or to collect a preinjection stable baseline from which later changes can be subtracted. The last goal, having a stable baseline against which to detect change, is a derivative of assessment of trends, noise, and repeatability.

II-3-1 Site-specific strength of signal for monitoring technologies

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.

As is illustrated by this study, forward modeling is the workhorse of estimating signal strength. However, because of the value of a negative finding (no detection) of ALPMI, a best practice is to make measurements at the site to determine experimentally the strength of the signal. For a 3-D seismic survey, this assessment can be made by testing the response of an array of geophones placed in a well to various types of seismic sources at the surface. Such a test can be part of a vertical seismic profile (VSP) and is a well-known important part of designing a 3-D survey. Similar tests of sensitivity are recommended for pressure and temperature. For example fall-off testing, a standard tool of underground injection control, can play this role (Johnson and Lopez, 2003). Sensitivity tests for pressure might be an injection fall-off test to calibrate pressure response to a rate of injection and recovery. A sensitivity test for detection of CO_2 in

groundwater might be a push-pull test, in which a small, controlled release of CO_2 is tested to determine the signal produced by rock-water-CO_2 interaction (Trautz and others, 2012; Yang and others, 2013b, 2013c).

An element related to signal strength is repeatability, which can usually be collected at the same time as signal strength. It is important to repeat the test response of the instrument to the system enough times under the same conditions to determine how accurately the test can be duplicated, especially if time-lapse measurements are to be made. In a seismic survey, repeatability can be formally determined by collecting statistics (Al-Jabri and Urosevic, 2010; Kinkela and others, 2011). Similar tests of repeatability are recommended for hydraulic pressure and thermal perturbation tests. Tests of repeatability are classically conducted for geochemical analysis programs using duplicates and blanks; it is important for gas-liquid systems such as CO_2 in water to test the repeatability of the field sampling protocols as well as the laboratory analysis.

In the following review, we considered time-lapse 3-D seismic versus depth, bed thickness, and porosity; pressure change in an above-zone monitoring interval in terms of interval thickness and monitoring well spacing; thermal sensitivity in relationship to depth and distance from signal source; and sensitivity of chemical detection of CO_2 with respect to ambient aquifer and water composition. Each of these findings was subject to in-depth study, many of which have been published separately. In addition, we review some other aspects of site-specific monitoring explored to less detail during the study.

II-3-2 Site-specific sensitivity of time-lapse 3-D seismic methods

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).

Monitoring the area of change in successive 3-D surveys has been demonstrated with high success as part of the Sleipner project, offshore beneath the North Sea (for example, Arts and others, 2004; Chadwick and Noy, 2010; Williams and Chadwick, 2012). At this setting the area of change contributed mostly the replacement of brine by CO_2, as little change in pressure has been observed within the injection zone. The vertical migration of CO_2 through a number of locally permeable within-reservoir barriers can be obtained by observation of the lateral spread of CO_2 in the permeable zones. In addition, the effectiveness of the confining system is shown by no change above the top of the injection zone.

A second project in which the area of change was highly successfully monitored was through a number of repeat 3-D surveys as CO_2 injections for EOR began at Weyburn field, Saskatchewan (White, 2013). At this field, the change in seismic response includes both compositional change as CO_2 replaces oil water and a pressure effect. In addition, assessment of change in seismic

properties of the zones immediately above the reservoir have been identified as potential subtle indicators of vertical migration out of the injection zone in localized areas of the field.

Experience shows, however, that not all seismic data are of equal value in monitoring geologic storage. A number of studies have collected 4-D seismic data over geologic storage projects and failed to definitively and uniquely map the extent of the CO_2 plume. Among the 4-D seismic surveys presented that had less than complete confidence in the output of the survey being equivalent to the area occupied by changes in CO_2 saturation and pressure increase are West Pearl Queen, New Mexico (Pawar and others, 2006); Nagaoka, Japan; Otway, Victoria, Australia (Urosevic and others, 2011); Pembina Cardium, Alberta Canada (Lawton and Alshuhail, 2007); and Cranfield, Mississippi (Zhang and others, 2013).

Potential reasons for decreased confidence in the survey after the data were collected are diverse and difficult to uniquely diagnose. Potential reasons are (1) low sensitivity of the seismic response substitution of one fluid by another, (2) noise and static errors in the system above the magnitude of the seismic response, (3) nonoptimal data collection conditions, and (4) nonoptimal processing. Because of the large number of options available in the system, it is difficult to diagnose the reason why the survey performed poorly. In our experience in this project, experts have recommended that collection of additional surveys and more data processing have the potential to improve the quality the survey such that it would provide the desired value.

Methods of 3-D seismic data collection and data processing have been heavily invested in for resource exploration and management, and a large number of possible combinations of approaches are available. It is well known that selection of the correct data collection and processing methods is critical to obtaining high-quality data. For example, a number of types of seismic sources having different frequency content, surface distribution, repeatability, and optimal climate conditions are available such as dynamite in boreholes, weight drop methods, and seismic “thumper” trucks capable of creating different types of signals. Recording locations can be distributed over the area in different patterns. Distribution of sources and receivers provides different types of coverage of the subsurface volume, known as fold. A number of different types of recording options are also very important to data quality, for example, the possibility of collecting multiple components of ground motion; so-called multicomponent data provide potential for breakthrough imaging. Seismic data processing is mature and flexible technology, and processing options can be used to optimize many aspects of the rich data content.

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.

II-3-3 Sensitivity of above-zone pressure methods for leakage detection

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).

For the selected case study, 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). Figure 8 shows an idealized deployment of AZMI monitoring. The concept underlying this method is that if the confining interval isolates the AZMI from the injection zone, a change in pressure from injection in the injection zone will not cause a pressure change in the AZMI. Analytical models can be used to estimate cross-formational flow should a hydrologically connected pathway connect the injection zone with the AZMI (Nordbotten and others, 2004). In this study we considered the characteristics of the AZMI that allowed a detectable signal should the zones be hydrologically connected. In a separate study we assessed the geomechanical signal that would be transmitted from injection zone to an AZMI, using field data from one site (Kim and others, 2013). In another study we compared the sensitivity of using pressure versus geochemical signal for leakage into an AZMI (Porse, 2013). Above-zone chemistry was used at Ketzin, Brandenburg, Germany (Nowak and others, 2013).

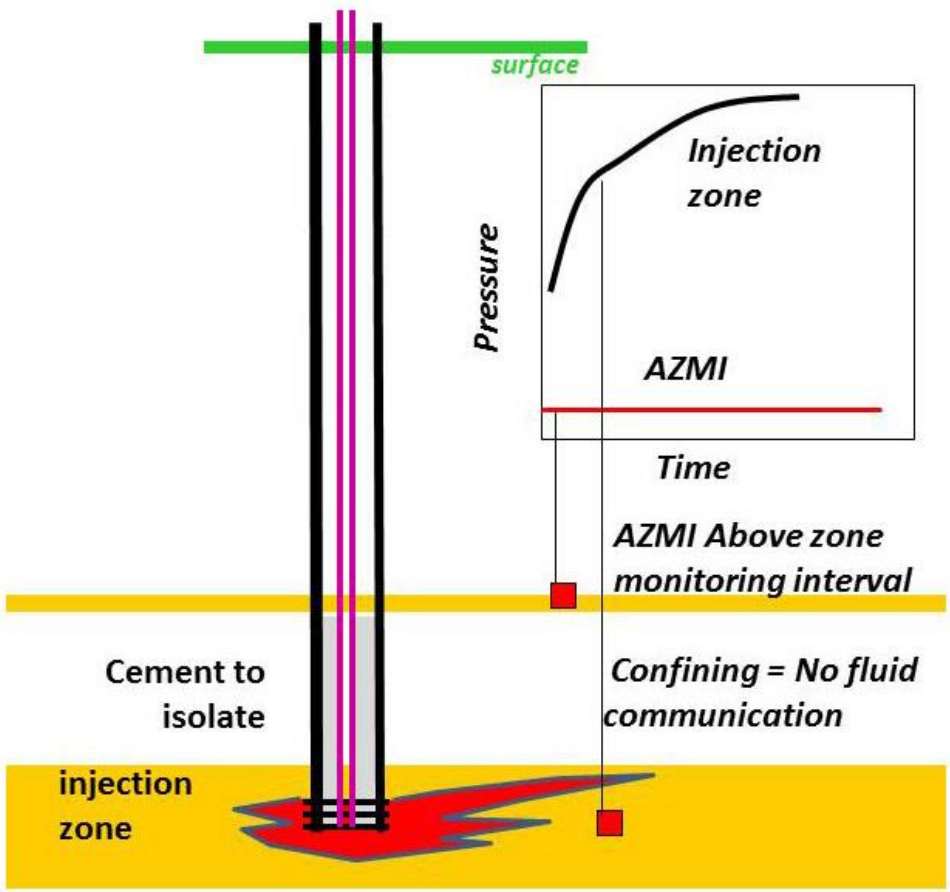

Figure 8. Idealized AZMI monitoring design.

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, the simplification used in this study. 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.

Most analytical work considers the leakage risk through a vertical feature with the geometry of a flawed well. To extend the analysis, we developed an analytical model for a vertical fluid flow planar feature described as a leaky fault (Zeidouni, 2012). The analytical model can be used to evaluate the leakage rate and pressure perturbations related to fault leakage both in the injection zone and in an overlying formation separated by an impermeable confining layer. The solution is extended to evaluate the vertical leakage attenuation considering multiple overlying formations with alternating aquitards. Such calculations can be done quickly without the need for spatial and time discretization, which can ease uncertainty quantification, and Monte Carlo–type analysis. The pressure signature of a leaky fault has been distinguished from that of leaky wells and/or a leaky aquitard using analytical solutions.

Work performed under pressure-based leakage detection in AZMI is organized around three coherent subthemes:

- Inversion of pressure anomaly signals
- Risk-based detectability analysis
- Optimization of monitoring network design

1. Inversion of pressure anomaly signals

The capability to accurately identify or eliminate concerns about pathways by which stored CO_2 could leak, has leaked, or is leaking from the targeted storage zone is important to operators, investors, and regulators. In the current context, a *leak event is characterized by its three attributes: start time, location, and magnitude*. Although many monitoring techniques have been improvised over the past decade, pressure-based monitoring technology provides high benefit/cost ratio and has the high potential of offering early detection over a large area.

Under this subtheme, 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. Figure 9 illustrates the results for a synthetic problem in 2D. In that case, the goal was to identify leakage history by deconvoluting pressure signals. In addition, by coupling pressure deconvolution with an optimization routine, the challenging problem of leakage location detection is solved. 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.

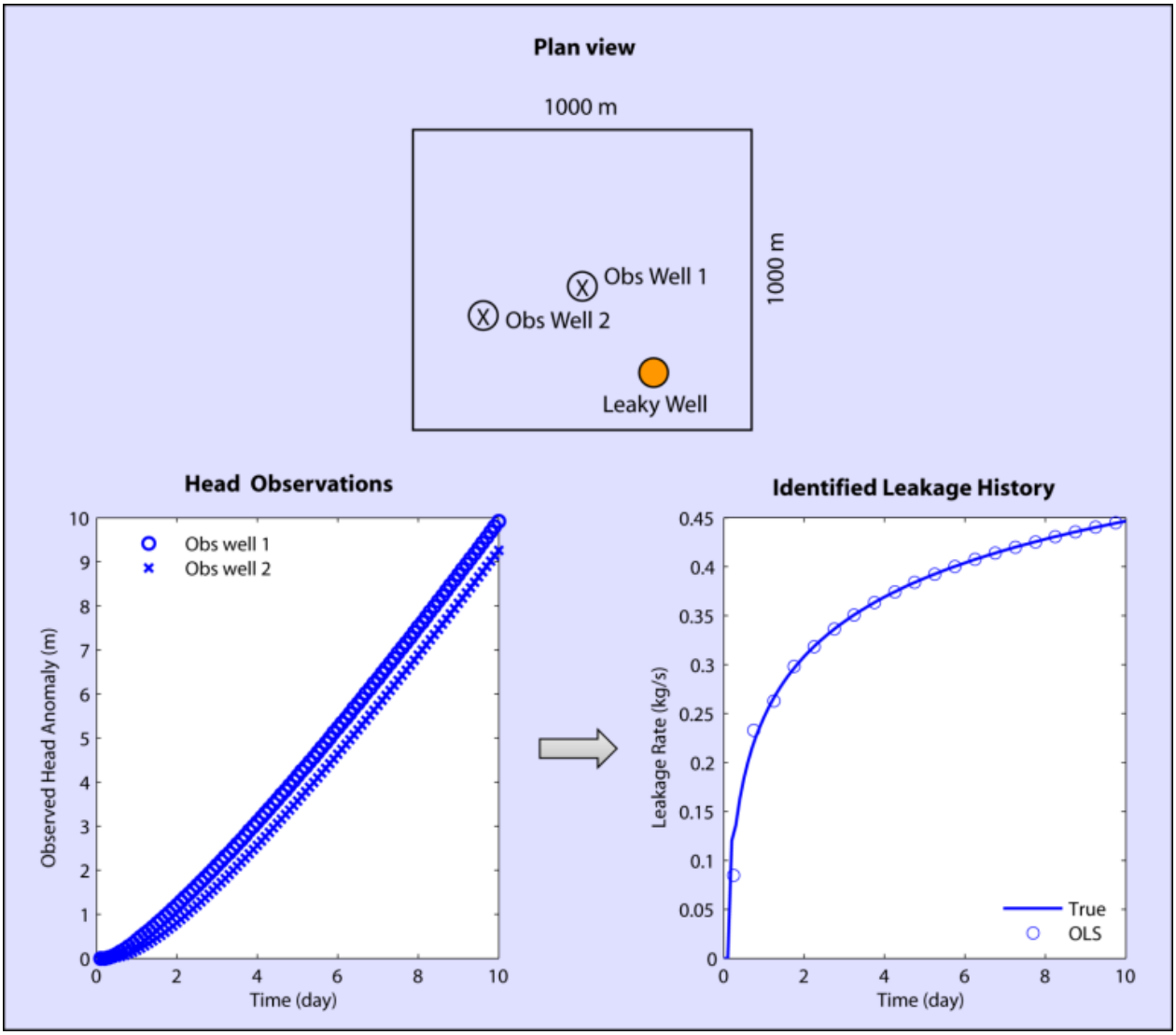

Figure 9. Deconvolution pressure anomalies. Top: plan view of problem set-up; bottom left: observed pressure signals (in hydraulic head); and bottom right: comparison between identified leakage history and synthetic truth. (Adapted from Sun and Nicot, 2012).

2. Risk-based detectability analysis

A main purpose of this EPA project is to make predictions of the system performance to accept and retain the planned volume of CO_2 at the planned rate for the planned duration. 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).

Driven by the need for UQ, this subtheme is concerned with assessing leakage detectability when information (for example, forward model) on hand is uncertain. A tool has been developed that allows fast assessment of leakage detectability for a given monitoring location and under model uncertainty. An example is shown in Figure 10, where dark lines show the detection threshold (related to pressure gauge resolution and site noise level). The horizontal axes give the probability of pressure exceeding a certain threshold at a given time. The diagnostic tool is site specific and incorporates parametric uncertainty such as permeability and compressibility. The tool can be used for (a) assessing the suitability of a monitoring location for intercepting leakage signals and (b) performing hypothesis tests on observed leakage signals. Forward reservoir models are commonly time consuming to run. A reduced-order modeling technique was used to perform Monte Carlo simulation required for generating a probability map like the one shown in Figure 10. Detailed description of the algorithm and numerical examples can be found in Sun and others (2013b).

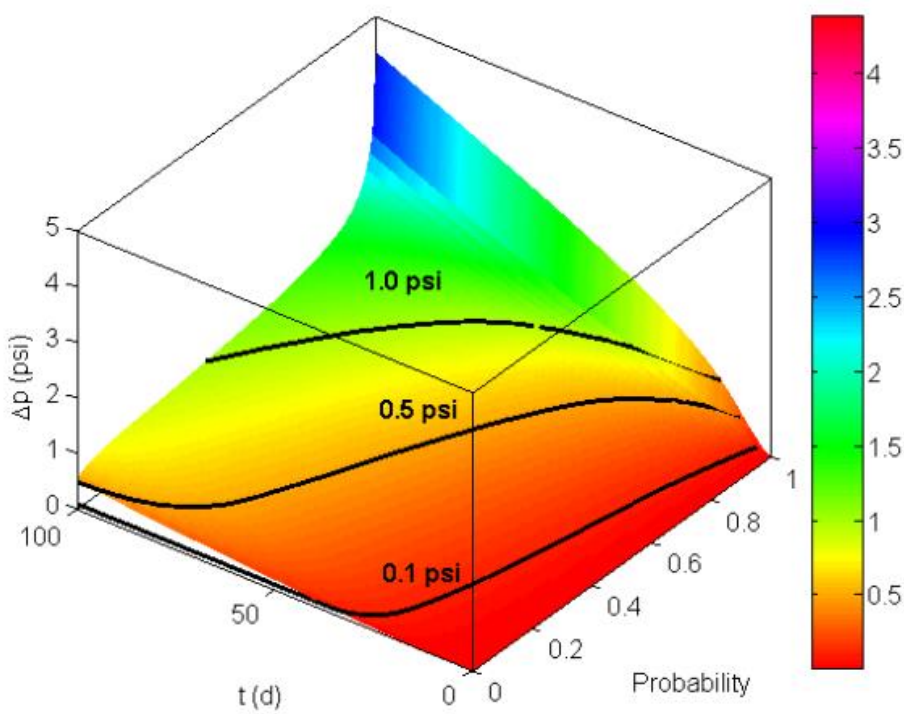

Figure 10. Diagnostic tool for detectability analysis. Color bar is pressure anomaly in psi; dark solid lines are different pressure detection thresholds.

3. Optimization of monitoring network design

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 third subtheme is concerned with finding optimal monitoring well locations while satisfying the number of pressure monitoring locations an operator can afford. Two major design objectives are (a) maximization of network coverage and (b) minimization of expected total leakage (in volume or mass). The number of monitoring wells that can be deployed is used as a cost constraint. In the current context, expected total leakage is defined as the cumulative amount of leakage fluid migrated into a monitoring layer before leakage signal is detected by any of the monitoring wells. An integer programming problem is formulated and solved. A scenario-based approach is used to incorporate model uncertainty and to calculate the optimal solution among all scenarios. Detailed description of the algorithm and numerical examples can be found in Sun and others (2013a). The optimization algorithm has been applied to aid monitoring network design at a proposed storage site in Texas.

II-3-4 Sensitivity of thermal methods for leakage detection

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. For CO_2 storage temperature monitoring has a number of attractive characteristics. CO_2 can be transported to a site through a surface infrastructure of pipelines and delivered into a well at surface temperatures, which are quite cold compared with subsurface temperatures. The CO_2 plume, therefore, creates a thermal pulse in the reservoir zone. In diagnosing performance of the injection well, thermal properties of the cold CO_2 can be of high utility..

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. Running a temperature log is the classic method of diagnosing leakage along the rock casing annulus where it is incompletely plugged by cement. This is a very useful tool for geologic storage monitoring because at many sites retention risks are associated with flawed well completions.

Away from the flowpath, the thermal mass of the surrounding rocks and water attenuates the thermal pulse over short distances, limiting its utility of thermal monitoring techniques through the reservoir. Temperature data is useful if collected along potentially leaky wells and/or wells intersecting potentially leaky faults.

CO_2 injection in saline aquifers induces temperature changes owing to processes such as Joule-Thompson cooling, endothermic water vaporization, and exothermic CO_2 dissolution, besides the temperature discrepancy between injected and native fluids. CO_2 leaking from the injection zone, in addition to initial temperature contrast due to the geothermal gradient, undergoes similar processes, causing temperature changes in the above-zone interval. 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). We considered the impact of both CO_2 and brine leakage on temperature response for three cases: (1) a leaky well co-located with the injection well, (2) a leaky well distant from the injector, and (3) a leaky fault. We performed a sensitivity analysis to determine key operational and reservoir parameters that control the temperature signal in the above-zone interval.

Several secondary thermal properties may be of use in diagnosing the reservoir response. Unlike pressure, which increases in response to both CO_2 and brine leakage, temperature signal may differentiate between the leaking fluids. In addition, the strength of the temperature signal correlates with leakage velocity, unlike pressure signal, whose strength depends on leakage rate. Increasing leakage conduit cross-sectional area increases leakage rate and thus increases pressure change in the above-zone interval. Thermal signal decreases with decreasing leakage velocity, thereby reducing temperature cooling and signal. As CO_2 saturated fluid moves from zones of high pressure toward low pressure, Joule-Thompson cooling is expected to occur, causing minor drops in temperature. CO_2 dissolution into the water is exothermic, resulting in a slight increase in temperature where this reaction occurs.

Sensitivity of groundwater leakage detection

Leakage of CO_2 to groundwater is an important monitoring parameter for EPA because of the role of the Underground Injection Control Program (UIC) 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). The physical factors are related to CO_2 migration or transport processes, and variations include confined or unconfined aquifers, variable groundwater velocity, groundwater recharge, extraction, aquifer heterogeneity, and monitoring location and depth. Evaluating physical factors on geochemical sensitivity to CO_2 leakage in USDW is one of our ongoing studies. In addition, 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).

Various minerals could be present in aquifer sediments. Three of the most common minerals were selected (quartz, albite, and calcite) and simulated in the generic model as carbonate-poor aquifer (quartz + 5% albite) and carbonate-bearing aquifer (quartz + 1% calcite). For the first set of models, aquifer chemistry is held constant, with a composition of the fresh water aquifer (Dockum and Ogallala formations) above the SACROC aquifer in Scurry County, Texas (Romanak and others, 2012b). As a follow-on, the influence of aquifer water composition was compared with that of the Cranfield shallow aquifer in Natchez, Mississippi (Yang and others, 2013e), and a shallow aquifer in Montana (Wilkin and DiGiulio, 2010).

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.

It is very interesting to note that 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 are now collaborating with Intellectual Optical Systems, a high-tech company, to develop real-time in situ dissolved CO_2 sensors that can be used for CO_2 leakage detection. Preliminary field tests have shown that dissolved CO_2 is a good indicator for CO_2 leakage detection (Yang, 2013; Yang and others, 2014b).

For a specific site, a general step-wise procedure for CO_2 leakage detection in USDW above geological carbon sequestration sites can be followed (Yang and others, 2013e): Step 1, baseline characterization of groundwater chemistry and aquifer mineralogy at the sensitive area in USDW; Step 2, selection of a set of geochemical parameters (such as pH, DIC, alkalinity, trace metals) on the basis of results of characterization in Step 1; Step 3, validation and test of the set of geochemical parameters with laboratory experiments, numerical modeling approaches, and controlled-release field tests; and Step 4, determination of whether these parameters are sensitive to CO_2 leakage. If so, they may be used for CO_2 leakage detection; if not, this set of geochemical parameters may not be reliable for CO_2 leakage detection.

The EPA UIC program addresses potential impacts on USDW from CO_2 injection activities using the Safe Drinking Water Act (SDWA). Because little information on field tests is available, impacts of CO_2 leakage on USDW discussed in the EPA UIC program rely mostly on the modeling analyses. Understanding of sources and mobilization mechanisms of trace metals and the ways CO_2 may impact these processes is important.

In the last three years, we conducted integrated studies by combining laboratory experiments, field push-pull tests, and reactive transport modeling to assess potential impacts of CO_2 leakage on groundwater quality (Mickler and others, 2013; Yang and others, 2013a, 2013b, 2014a). Laboratory batch experiments of water-rock-CO^2 interactions were conducted to identify

geochemical processes affecting aquifer mineralogy and aqueous geochemistry and provided preliminary information on designing single-well push-pull tests. During single-well push-pull tests, groundwater equilibrated with CO_2 was injected into an aquifer, and after a specified time, groundwater was extracted for analyses of major and trace elements, providing direct information on water-rock-CO_2 interactions. A preliminary reactive transport model with general information on the target aquifer and geochemical information from the laboratory batch experiments were used to design the push-pull tests. Then the reactive transport model was further refined to analyze the results of the field push-pull tests and identify geochemical processes that dominate changes in groundwater quality caused by CO_2 leakage. These results, funded by several research programs, were synthesized for this project and simplified for the workbook (Hovorka and others, 2014a).

Four sets of water-rock-CO_2 batch experiments were run for about one-half year and were incrementally sampled over the course of the experiments to quantify changes in aqueous geochemistry caused by CO_2 introduction. Sedimentary samples and groundwater used in the batch experiments were collected from different aquifers. Carbonate content varies in the sedimentary samples (carbonate-poor sediments collected from Helena and Cranfield sites and carbonate-rich sediments collected from the Edwards and Brackenridge sites). Experimental results show that introducing CO_2 into the batches led to a sharp drop in pH. This pH reduction led to dissolution of minerals (carbonates and silicates). For the batch experiments with carbonate-rich sediments, carbonate dissolution proceeded until calcite saturation was reached and pH was buffered. For the batch experiments with carbonate-poor sediments, carbonate dissolution proceeded until carbonates were exhausted.

It appears that dissolution of carbonates and silicates proceeds kinetically; however, carbonate dissolution was much faster than silicate dissolution. Mobilization of trace metals was also observed after CO_2 gas was introduced into the batches. Although trace metals can be categorized into several groups on the basis of their observed behavior after CO_2 introduction, mobilization of trace metals may be dominated by two geochemical processes: dissolution of carbonates and silicates, such as Mn, Sr, and Cd, and desorption from clay mineral surfaces, such as As and Pb. Note that some trace metals, such as As, Mo, and Se, were initially mobilized from clay mineral surfaces owing to the sharp increase in pH associated with an Ar flush at the beginning of the experiment and then sequestered, most likely as a result of a drop of pH with the introduction of CO_2 and precipitation of clay minerals resulting in increased clay mineral surfaces. Maximum concentrations of trace metals observed in the batch experiments are less than their maximum contamination levels (MCLs).

Single-well push-pull tests were conducted at the Cranfield site where aquifer sediments contain little carbonate and the Brackenridge site where aquifer sediments contain as much as 20% carbonates. The Cranfield shallow aquifer is confined, about 70 m below land surface, whereas the Brackenridge shallow aquifer is unconfined, about 3.5 m below land surface. Results of the two field tests show that mobilization of major cations and trace metals was dominated by geochemical processes similar to those observed in the batch experiments. Whereas trace metal concentrations increased, maximum trace metal concentrations remained below EPA MCLs; for instance, in the Cranfield push-pull test, the maximum As level was ~3% of its EPA MCL, and the maximum Pb level was only ~1% of its EPA action level. Overall reaction rates of major cations calculated from the push-pull test are generally lower than those estimated from batch experiments. However, overall estimated reaction rates depend on case-specific parameters and

may not be directly applicable to other sites, even similar ones, because varying dilution factors (water:rock ratio in the batch experiment and mixing between background water and injected water in field test) were not considered in the comparison of overall rates estimated from the push-pull tests.

A reactive transport model was used to interpret results of the push-pull test conducted in the Cranfield aquifer. The model simulates groundwater flow and solute transport in the aquifer, coupled with various geochemical reactions, such as aqueous complex, mineral dissolution/precipitation, and adsorption/desorption from clay mineral surfaces. Hydraulic parameters used in the model were calibrated to fit measurements of a conservative tracer (Br), which was added to the injected water. The geochemical model was tested with the results of the batch experiment. The reactive transport model reproduces the overall trends of groundwater pH, alkalinity, and major ions (Ca, Mg, Si, Na, and K) and also concentrations of some trace metals in the Cranfield push-pull test. A review of this literature is reported in the recent paper by Yang and others (2014a).

II-4. Other tools considered

During the development of the project, many tools were considered, and although they did not continue to full development in the context of the workbook, the following notes are presented to record progress. Discussion starts with tools that are used in the reservoir and moves to tools that are used at shallower depths.

Pressure within the reservoir is the most fundamental tool for matching observed to modeling response. A field analysis of injected data collected as part of the Southeast Regional Carbon Sequestration Partnership project at Cranfield shows the strength of this method for assessing the connectivity of the reservoir, as well as significant uncertainty created by heterogeneity of the reservoir and uncertain boundary conditions (Meckel and others, 2013). This study observed that at this site, the pressure signal at a dedicated observation well created by beginning production was smaller than the variability of the pressure resulting from other factors—presumably pressure was responding complexly to multiphase flow and boundary conditions in a heterogeneous reservoir. If the well production is considered as a proxy for out-of-zone leakage, in-zone pressure would not be able to detect the change. Other experiments showed that mass-balance methods were ineffective in detecting the start of producing wells, showing that in-zone pressure has limitations as a method of assuring conformance of the injection (using production as a proxy for unintended leakage). Additional experiments with other reservoirs would be valuable to determine the site-specific limits of pressure and mass-balance methods for monitoring conformance.

Direct fluid sampling has been widely considered as a monitoring technique for geologic storage. Research-oriented projects have used sampling methods such as the U-tube that can extract high-frequency samples with reduced fluid mixing (Freifeld and others, 2005). High-frequency sampling yields important data to assess processes such as multiphase fluid interactions with natural and introduced tracers (for example, Kharaka and others, 2006; Boreham and others, 2011; Lu and other, 2013). In addition, data about dissolution of CO_2 into water (Mito and Xue, 2011, Lu and other, 2012) are useful to calibrate conceptual models of dissolution. However, experience shows that sampling a two-phase fluid system with a well provides only a limited interrogation of what happens in the pore system. In particular, after CO_2 arrival at any perforated part of the well, CO_2 will preferentially migrate into the well. Unless the

well is strongly produced, water will be displaced from the well back into the formation and will not be possible to sample, except in the inactive stagnant lower parts of the well. Direct sampling cannot provide high-quality information about the distribution of fluids in the porosity outside the well because the well itself strongly fractionates multiphase fluids. In addition, specialized sampling and laboratory technologies are needed to conserve dissolved phases that are sensitive to pressure and temperature (for example CO_2) when a sample is brought to the surface. Fluid reconstruction via modeling is needed.

In addition to the issue of if geochemical sampling in the reservoir produces data relevant to the project goals, sampling can be of high cost and risk. Preserving well conditions such that sampling can occur is difficult and can limit other types of monitoring. We note that an idle well is subject to more rapid corrosion than an injector or a producer and that techniques for managing corrosion in idle wells can damage the geochemical sampling. High-frequency sampling has a high cost in terms of installation, operation, and analysis, and would only be needed at times and places where it could answer a specific question.

For commercial projects, we think it likely that the need for geochemical data from the reservoir will be reduced or absent. Issues of rock-water reactivity could be addressed at modest cost in the laboratory. Only where a material uncertainty arises (thus far not identified in studies) would field sampling be needed.

If information about arrival of CO_2 at a well is needed, a number of other technologies may be preferable. A perforated well will rapidly fill with CO_2, displacing brine, and result in a strong and diagnostic change in the trend of pressure at the surface that is conventionally used by operators to identify CO_2 "breakthrough" to the well. Combined with bottom-hole instrumentation and logging, additional information about the nature of breakthrough can be extracted (Verma and others, 2011). Other methods that do not require perforation may have advantages in commercial settings, such as (1) better detection of change above the reservoir, (2) longer well life, and (3) simplified well handling.

Wireline logging is another high-value technique for making measurements to confirm the performance of the reservoir in accepting CO_2. Pulsed neutron methods and sonic logging time-lapse cased-hole tools have been tested for CO_2 detection (for example, Sakurai and others, 2005; Butsch and others, 2013). If boreholes are constructed of nonconductive materials, resistivity can be added to the tool set (Mito and Xue, 2011). Wireline logs provide high-resolution sampling of fluid changes very near the borehole. However, because of this high resolution, borehole construction and management can be significant in creating noise. Fluids in perforated sections of the borehole, both those placed in the borehole such as workover and "kill" fluids and those that enter the borehole from the formation such as CO_2, can invade the formation and create a false appearance of change. We detected interference with sonic and resistivity logs from a complex observation well construction that required a larger than conventional borehole with an array of tubing-encapsulated cables and other instruments installed on the outside of the casing and cemented in place (Butsch and others, 2013).

Site-specific parameters that impact wireline log tool detection of CO_2 in the reservoir and in the overburden include fluid and rock properties (Ellis and Singer, 2007). For example, pulsed neutron tools are highly sensitive to Cl^-. In water low in total dissolved solids, detection of CO_2 substituted for water may be low resolution, and other tool responses may be needed. Because of the flexibility with which modern tools can be operated, proprietary software available through

logging service companies was recommended as the best method of assessing if an expected fluid substitution is detectable at a site. If logs are collected in a perforated well, when the CO_2 arrives at the well it will displace water. This displacement creates issues for logging programs for several reasons. Well control is needed to insert tools into wells that are filled with CO_2, which can involve adding dense brine known as "kill fluid." This allochthonous brine disturbs near-well conditions. In addition, change in fluids within the well requires correction for wireline measurements.

Gravity measurements are of interest for monitoring CO_2 storage because they respond to replacement of high-density water by low-density CO_2 (Krahenbuhl and Li, 2012). However, the maturity of the tool for CO_2 monitoring use is low. One application of gravitometers on the sea floor application at Sleipner field in the North Sea has had positive results (Alnes and others, 2011), and one application of gravitometers within the well was also encouraging at Cranfield, Mississippi (Dodds and others, 2013). Several other deployments are being tested. The geometry of the injected CO_2, the ambient variability of the density of the host rocks, and the amount of porosity into which CO_2 can be substituted are site-specific aspects that could impact success; additional modeling is needed.

Geophysics in optimized geometries has been successfully deployed in many geologic storage research projects. Most tests have used acoustic (seismic) tools in downhole vertical seismic profile and cross-well geometries (Daley and others, 2007; Fabriol and others, 2011). Several tests have used electrical methods with success (Kiessling and others, 2010; Carrigan and others, 2013). Placement of receivers or both sources and receivers at depth increases signal strength and resolution and decreases noise. Other technology improvements such as other types of geophysics, permanent installation of sources, and continuous data collection are in consideration. The value of these technologies is high in research because they probe the value of the technology and provide high-resolution observational data for evaluation of conceptual and numerical models of two-phase flow. However, the value of these geometries will require screening against purpose for commercial operations. High success in research should not, by itself, provide motivation for deployment in settings where the purpose is very different. In particular, the high resolution of cross-well and downhole deployment geometries can result in limited volumetric coverage. Methods for assessment of site-specific limitations of geophysics are mature and follow a pattern similar to the 3-D case presented.

Advanced seismic data collection and processing that can reduce noise, enhance signal, and push the site-specific limitations of the technology should be considered, and new breakthroughs are emerging. Technologies such as collection of multicomponent data and Amplitude versus Offset (AVO) are research topics that have become mainstream (Pérez and others, 1999; Young and LoPiccolo, 2005; Sodagar and Lawton, 2011). The importance of accessing the deep expertise available, developing diverse advanced techniques, and critically evaluating the value of technology against site-specific goals, signal, noise, and repeatability is noted.

Tilt and surface deformation have become high interest for monitoring geologic storage sites because they are surface- or shallow-borehole-based measurements that have potential to provide information over a wide area about pressure increase at depth, which is likely to be important to ALPMI in geologic storage. A number of technologies can be used in time lapse. To measure elevation change, one can used repeated elevation surveys, for example using GPS technologies or Interferometric Synthetic Aperture Radar (InSAR) based on differencing radar images produced by satellites to create interferograms. Tilt meters can be deployed at the surface or in

boreholes to measure very small changes in geometry of these features, and these methods can be combined. Mature applications are conducted in areas where land surface change is linked to risk, for example at volcanoes (USGS, 2009).

Researchers assessing the InSalah geologic storage project, near the Krechba gas field, Algeria, were successful in using InSAR to detect surface elevation change in response to elevated pressure at depth (Vasco and others, 2010). Signal was used to diagnose nonconformant pressure response, where a fracture system in the lower part of the confining system had allowed pressure to increase over a thicker interval and closer to the surface than predicted (Rutqvist and others, 2008).

On the basis of our efforts to apply these technologies to storage sites in the Gulf Coast (Swart, 2010), we have found the applicability of these methods to be strongly site specific. The viability of the approach being fit to purpose can be analyzed in terms of signal strength and noise. Signal is modeled using the geometry of layered rocks with various properties. Rock geomechanical properties for sites we have studied are underconstrained to make robust predictions of geomechanical signal, although progress is being made (Kim and Hosseini, 2013). In addition, we note that noise is strongly site specific. Groundwater can have a strong signal on land surface elevation both from withdrawal and from recovery (Leake, 2013) and be dynamic at the scale relevant to storage. In addition, noise from vegetation and other land use and moisture in the atmosphere must be assessed to make sure that extraction of signal is viable, and these factors are highly site specific (Foster and others, 2006).

Soil gas geochemistry is another technology that has been widely tested at geologic storage sites. Soil gases have been widely used to locate hydrocarbon resources (Jones and Drozd, 1983) and assess other connectivity between the surface and subsurface (Ma and others, 2012). The success of this technology is encouraging to researchers seeking a tool that allows fairly direct measurement of any leakage from depth to be measured at the most relevant earth/atmosphere interface and reported in accounting frameworks. However, since the first geologic storage experiment at Weyburn issues of noise and sensitivity have been noted (Wilson and Monea, 2004, Riding and Rochelle, 2009). The process-based method (Romanak and others, 2012a) developed at the GCCC as part of the SECARB project is one step toward isolation of signal from noise.

Site-specific parameters that need to be assessed are the strength of any leakage signal and the noise and trend in the environment. Leakage signal is related to the mass balance of the migrating CO_2 compared with processes such as microbial and root respiration, barometric pumping and soil gas dissolution that attenuate signal. Noise is related to temporal variability in process, including change over time. We note at some field sites that past uses have strong impact on stability of soil gas compositions; in particular, naturally high methane and hydrocarbon degradation resulting from past uses are problematic (Wolaver and others, 2013).

III. Field test sites

One goal of the project was to test the results of evaluation against the growing array of CO_2 -specific field measurements gathered from field test sites. The portfolio of field measurements available to the project has grown substantively, with monitoring from 28 projects surveyed (Table 2). In addition, a wide variety of experience outside of the geologic storage test literature

such as contaminant clean-up sites, gas storage, oil production, other types of deep well injection, and ecosystem studies was used as industrial analogs for monitoring technologies.

Table 2. Examples of storage tests with outcomes considered in this study.

Site name	Location	Major monitoring case(s) examined	Overview citations	Project stage
SACS/CO_2STORE monitoring projects at Sleipner	Near Sleipner gas field, Norwegian North Sea	4-D seismic, gravity	Arts and others, 2004; Chadwick and others 2008; Chadwick and Noy, 2010; Eiken and others, 2011, many others	R&D program completed, commercial injection continues
IEAGHG Weyburn Monitoring program	Weyburn oil field, Saskatchewan	4-D seismic, soil gas, in-zone geochemistry, microseismic	Wilson and Monea, 2004; Riding and Rochelle, 2009; Verdon and others, 2011; White, 2013	R&D program completed, commercial EOR continues
West Pearl Queen	West Pearl oil field, New Mexico	4-D seismic, soil gas PFT tracers	Pawar, and others, 2006; Wells and others, 2007	Completed
Nagaoka	Near Nagaoka oil field, Japan	4-D wireline logging, in-zone fluid sampling, cross-well seismic, surface seismic	Saito and others, 2006; Mito and Xue, 2011	Post-closure monitoring
Frio test	South Liberty oil field, Texas	Cross-well seismic and VSP, wireline logging, tracers, and in-zone and above-zone fluid sampling, groundwater and soil gas post injection	Hovorka and others, 2006; Daley and others, 2007; Daley and Hovorka, 2010	Completed
Zama	Zama oil field, Alberta	Reservoir geochemistry and PFT	Smith and others, 2011	R&D program completed, commercial EOR continues
Snøhvit	Near Snøhvit oil field, Barents Sea, offshore Norway	In-zone pressure measurements, 4-D seismic	Hansen and others, 2013	Continues
In Salah	Near Krechba gas field, Algeria	InSAR, 4-D seismic	Cooper and Members of the CO_2 Capture Project 2009, overview	R&D program completed
SECARB Early Test	Cranfield field, Mississippi	In-zone and above-zone pressure, wireline logging, 4-D seismic, in-zone natural and introduced tracers, ERT, cross-well seismic, groundwater geochemistry, soil gas, microseismic	Hovorka and others, 2013; Ajo-Franklin and Daley, 2013; Zhang and others, 2013; Yang and others, 2013e	Nearing completion

Site name	Location	Major monitoring case(s) examined	Overview citations	Project stage
AEP Mountaineer	American Electric Power, Mountaineer Station, New Haven, West Virginia	Reservoir pressure response		Pilot completed, commercial scale canceled
SWP –SACROC	SACROC oil field, Scurry County, TX	Groundwater chemistry	Romanak and others, 2008, 2012b	R&D program completed, commercial EOR continues
ZERT experiment	Montana State University, Bozeman, MT	Controlled release, soil gas, ecosystem response, atmospheric measurements	Lewicki and others, 2009; Fessenden and others, 2009; Spangler and others, 2009; Oldenburg and others, 2010	Several stages complete
CO_2 field lab	Svelvik Ridge, Norway	Controlled release, vadose and saturated zone complexity	Barrio and others, 2013	Completed
Otway	Near Naylor gas field, Victoria, Australia	Seismic methods, VSP, reservoir, tracer and ambient geochemistry, soil gas, groundwater	Jenkins and others, 2011	Stage 1 and 2 completed
CO_2SINK Ketzin	Near Ketzin gas field, Brandenburg, Germany	4-D seismic, ERT, in-zone sampling, introduced tracers, thermal survey	Giese and others, 2009; Boreham and others, 2011	Completed, post-closure monitoring
SWP-Aneth	Aneth oil field, Utah	Microseismic survey	Zhou and others, 2010	Completed
SWP Pump Canyon	Pump Canyon coalbed methane, New Mexico	Introduced tracers	Wilson and others, 2012	R&D completed
MRCSP Michigan test	Gaylord, Michigan	Cross-well seismic, wireline logging	Battelle, 2011	R&D completed
Pembina Cardium	Alberta, Canada	Reservoir chemistry, seismic	Johnson and others, 2011; Lawton and Alshuhail, 2007	R&D completed
SECARB Citronelle	Citronelle oil field, Alabama	In-zone and above-zone fluid pressure and sampling, cross-well seismic, soil gas survey	South East Regional Carbon Sequestration Partnership, 2013	Nearing completion
Illinois Decatur Project	Decatur, Illinois	In-zone and above-zone fluid pressure and sampling, cross-well seismic microseismic, soil gas and groundwater survey	Finley, 2013	Continuing
Bell Creek field	Bell Creek field,	In-zone and above-zone pressure, pulsed	Plains CO2 Reduction	Continuing

Site name	Location	Major monitoring case(s) examined	Overview citations	Project stage
	Montana	neutron logging	Partnership, 2013	
Shell Quest	Alberta, Canada	Commercial monitoring plan and risk assessment	Shell, 2010	Planned
Aquistore	Near Estevan, Saskatchewan	Commercial monitoring plan and risk assessment	Whittaker and others, 2009	Drilling underway
Gorgon	Barrow Island, Northwest Australia	Commercial monitoring plan and risk assessment	Flett and others, 2009	Drilling underway
FutureGen 2.0	Morgan County, Illinois	Commercial monitoring plan and risk assessment	Permit documents	Planned
NRG Parish plant capture	West Ranch field, Texas	Commercial monitoring plan and risk assessment	Confidential	Planned
Air Products/Lake Charles/Hastings	Hastings field, near Alvin, Texas	Commercial/research monitoring plan and risk assessment	Confidential	Continuing

IV. Develop consensus

The consensus development activities conducted for this study have two interlocking goals. First, to access information about limitations of technologies in most cases requires in-person discussion. Only a few studies in the literature formally report the limitations of technologies (Urosevic and others, 2011). However, researchers have often delved deeply during pilot studies for technologies that were not deployed at full scale into reasons for poor or uninterpretable signal. Interaction with researchers was needed to understand distinctions between poor signal because of the specific technology and the way it was deployed and the characteristics of the site such as high noise or poor signal. The second reason for consensus building is to obtain peer review through talks and workshops, as well as through peer-reviewed papers as the project progressed.

During the planning for the project we designed an expert project panel. At project start, we held the expert panel meeting with the Monitoring Network hosted by the International Energy Agency Greenhouse Gas Research and Development Programme (IEAGHG R&D Programme) annual meeting. This meeting worked so well we used this group as the expert panel, presenting updates and getting feedback each year (Table 3). In addition a number of opportunities arose to work in detail with committees reviewing monitoring plans. Although these interactions cannot be reported in detail here because of confidentially, learnings from these activities have been taken up and used to guide the assessments and the workbook. Exchange of concrete information with other review panelists was especially important, as well as consideration in detail of the practical aspects of deployment of a monitoring program. It has been important to work with

stakeholders from diverse perspectives such as researchers funded by the DOE's Regional Carbon Sequestration Partnership (RCSP) program, EPA staff and contractors, EOR operators and project developers, and representatives of source industries. Table 3 highlights 86 examples of consensus-building activities of highest value to the site-specific study both in terms of collecting information and in terms of having information reviewed and receiving feedback. Many of these activities were funded and leveraged by other GCCC projects. A more complete inventory of activities is presented in the "News and Events" section of the GCCC webpage (www.gulfcoastcarbon.org).

Table 3. Consensus-building activities conducted that supported this project.

Activity	Meeting	Place	Date
Kick-off meeting	IEAGHG R&D Program	Natchez, MS	May 5, 2010
Technical meeting	UK-Texas CCS Technology and Legislation Seminar	Pittsburgh, PA	May 9, 2010
Industry dialog	Review of GCCC groundwater studies	Houston, TX, and UK via web	May 19, 2010
Public workshop	Environmental Defense Fund and the National Resources Defense Council	Sacramento, CA	June 9, 2010
International review	UK, BGS, and DECC	Edinburgh, Scotland	July 7, 2010
Symposium on role of EOR in CCS	Massachusetts Institute of Technology	Boston, MA	July 23, 2010
Technical conference	International Conference on Greenhouse Gas Technologies (GHGT10)	Amsterdam	September 19-23, 2010
Technical conference	Southwest Regional Partnership Phase II SACROC groundwater study	Albuquerque, NM	September 21-22, 2010
Technical meeting	DOE/NETL Regional Carbon Sequestration Partnership Review Meeting	Pittsburgh, PA	October 5-7, 2010
Technical meeting	Carbon Sequestration Leadership Forum (CSLF) Annual Meeting	Warsaw, Poland	October 6-8, 2010
Technical meeting	60th Annual Gulf Coast Association of Geological Societies Convention	San Antonio, TX	October10-12, 2010
Technical meeting	IEAGHG workshop: Natural Releases of CO2: Building Knowledge for CO2 Storage Environmental Impact Assessments	Maria Laach, Germany	November 2-4, 2010
Technical meeting	Society of Petroleum Engineers International Conference on CO2 Capture, Storage and Utilization	New Orleans, LA	November 10-12, 2010
Technical meeting	8th Annual EOR Carbon Management Workshop	Houston, TX	December 6-7, 2010
Technical meeting	Japanese Research Institute of Innovative	Japan	December 9,

Activity	Meeting	Place	Date
	Technology for the Earth (RITE)		2010
Technical meeting	3rd U.S.-China CO2 Emissions Control Science & Technology Symposium	Hangzhou, China	December 10-12, 2010
Technical meeting	American Geophysical Union Fall Meeting	San Francisco, CA	December 13-17, 2010
Technical meeting	4 Kingdoms CCS Initiative: First Technical Workshop	Al Khobar, Saudi Arabia	February 28, 2010
Data contribution	RCSP Risk Assessment and Simulation Questionnaire	via e-mail	June 2011
Review	Confidential monitoring review, ARAMO	Houston, TX	June 2011
Field collaboration planning	Weyburn-Midale CO2 Project	Saskatchewan, Canada	March 1-4, 2011
Technical meeting	SECARB Sixth Annual Stakeholder's Meeting	Atlanta, GA	March 9-10, 2011
Technical meeting	10th Annual Conference on Carbon Capture and Sequestration	Pittsburgh, PA	May 2-5, 2011
Technical meeting	Texas Commission on Environmental Quality Trade Fair	Austin, TX	May 3-4, 2011
Technical meeting, project review	International Energy Agency Greenhouse Gas Monitoring Network Meeting	Potsdam, Germany	June 7-9, 2011
Research meeting	CO2CARE Workshop	Potsdam, Germany	June 9, 2011
Technical meeting	Trondheim CCS Conference	Trondheim, Norway	June 14-16, 2011
Review meeting	BIGCCS, Norwegian Research Council	Jaegtvolden, Norway	June 17-18, 2011
Review	Consulting to Stratus, Assessment of CCS monitoring technologies	via e-mail	June 2011
Data contribution	RCSP Risk Assessment and Simulation Questionnaire	via e-mail review	
Review	Pew Center on Global Climate Change Accounting Framework report	digitally	June 2011
Technical review	Electric Power Research Institute (EPRI) Capture and Storage Technical Meeting	Palo Alto, CA	July 26, 2011
Knowledge sharing	C12 Energy	Austin, TX	July 27, 2011
Technical meeting	KEPS-KORDI CCS Workshop	Houston, TX	July 28, 2011
Technical meeting	United Nations Framework Convention on	Abu Dhabi	September 11,

Activity	Meeting	Place	Date
	Climate Change Technical Workshop		2011
Technical meeting	The Midwestern Governors Association (MGA), in partnership with the Great Plains Institute	Houston, TX	September 27-30, 2011
Technical meeting	NSF Science, Engineering and Education for Sustainability Workshop	Minneapolis, MN	October 8, 2011
Technical meeting	Society of Petroleum Engineers Forum	The Algarve, Portugal	October 9-14, 2011
Workshop	Next Generation Project: Texas Assembly	Fort Worth, TX	October 21, 2011
Technical meeting	The National Academies Division on Earth & Life Studies	San Diego, CA	October 28, 2011
Technical meeting	2011 International Forum on CCS and Energy Storage Technologies	Taipei, Taiwan	November 1-2, 2011
Technical meeting	Global CCS Institute Austin Regional Meeting	Austin, TX	November 8, 2011
Technical meeting	NETL Carbon Storage Program Infrastructure Annual Review Meeting	Pittsburgh, PA	November 15-17, 2011
Technical meeting	GCCC/Houston British Consulate Collaborative Technical Workshop	Austin, TX	December 2-3, 2011
Technical meeting	American Geophysical Union Fall Meeting	San Francisco, CA	December 5-9, 2011
Field collaboration	Kerr-Weyburn Investigation	Regina, Saskatchewan, Canada	December 12, 2011
Technical meeting	University of Texas Carbon Capture and Storage Conference (UTCCS-1)	Austin, TX	January 25-27, 2012
Technical meeting	Carbon Management Technology Conference	Orlando, FL	February 7-9, 2012
Technical meeting	7th Annual Southeast Regional Carbon Sequestration Partnership Stakeholders' Briefing	Mobile, AL	March 7-8, 2012
Technical meeting	Permian CCUS Center, Colorado School of Mines	Golden, CO	April 5, 2012
Review	Confidential monitoring plan related to HECA	California	2012
Technical meeting	China-Australia Geologic Storage Technical Symposium	Beijing, China	April 17, 2012
Technical meeting	Annual Carbon Capture, Utilization, and Sequestration Conference	Pittsburgh, PA	April 30-May 3, 2012

Activity	Meeting	Place	Date
Technical meeting	International Knowledge Sharing in MVA/MMV	Mobile, AL	May 15-17, 2012
Short course	2012 AAPG Southwest Section Convention	Fort Worth, TX	May 19-22, 2012
Technical meeting	DOE-FE-China Exchange Project Meeting	Houston, TX	May 30, 2012
Technical meeting	IEA GHG Joint Network Meeting	Santa Fe, NM	June 19, 2012
Technical meeting	International Workshop on Geological CO2 Sequestration	Jilin University, Changchun, China	July 4-5, 2012
Technical meeting	Water and Biodiversity Impacts of Energy Change, The Nature Conservancy	Denver, CO	July 12-13, 2012
Technical meeting	34th International Geological Conference	Brisbane, Australia	August 5-10, 2012
Course	The Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC) and the Carbon Sequestration Leadership Forum (CSLF)	Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil	July 30 - August 3, 2012
Research collaboration	Center for Frontiers of Subsurface Energy Security Meeting	Austin, TX	August 20, 2012
Technical meeting	NETL Carbon Storage R&D Project Review Meeting	Pittsburgh, PA	August 21-23, 2012
Technical meeting	International Conference on Greenhouse Gas Technologies (GHGT-11)	Kyoto, Japan	November 18-22, 2012
Technical meeting	United Nations Framework Convention for Climate Change/COP-18	Durban, South Africa	November 27, 2012
Technical meeting	American Geophysical Union Meeting	San Francisco, CA	December 3-7, 2012
Project review	Progress Review of STAR Grant Research on Carbon Sequestration	EPA, Washington DC	January 7, 2013
Technical meeting	RITE CCS Technical Workshop	Tokyo, Japan	January 20, 2013
Technical meeting	8th Annual SECARB Stakeholders Briefing	Atlanta, GA	March 4, 2013
Technical meeting	3rd Annual Korean CCS conference	Jeju Island, Jeju City, South Korea	March 15-16, 2013
Course	1st Course Advanced Topics in Carbon Capture and Storage	Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil	April 1-4, 2013
Technical meeting	Carbon Sequestration Leadership Forum CO2	Rome, Italy	April 18, 2013

Activity	Meeting	Place	Date
	Monitoring Interactive Workshop		
Technical meeting	14th Annual MIT Carbon Sequestration Forum	Cambridge, MA	April 24-25, 2013
Technical meeting	12th Annual Conference on Carbon Capture Utilization & Sequestration	Pittsburgh, PA	May 13-16, 2013
Technical meeting	7th Trondheim CCS Conference	Trondheim, Norway	June 4-6, 2013
Technical meeting	Workshop, Center for Climate and Energy Solutions, Permian CCUS Center, and the Railroad Commission of Texas	Houston, TX	June 11-12, 2013
Technical meeting	American Geophysical Union's Science Policy Conference	Washington, DC	June 24-26, 2013
Technical meeting	Carbon Storage R&D Project Review Meeting	Pittsburgh, PA	August 20-22, 2013
Technical meeting and project review	IEAGHG Monitoring Network and Environmental Research Network	Canberra, Australia	August 26-30, 2013
Short course	Global CCS Institute's Capacity Development Program for Mexico	On-line	August 28-November 6, 2013
Review	Confidential Review Futuregen2	Richland, WA	2013
Technical meeting	IEAGHG-OPEC Workshop on CCS in the UNFCCC Clean Development Mechanism	Vienna, Austria	October 29-30, 2013
Technical meeting	CSLF Side Meeting	Washington, DC	November 4-6, 2013
Technical meeting	Norway's Ministry of Petroleum and Energy, the International Energy Agency, the US DOE, and the Norwegian Research Council	Houston, TX	November 19-21, 2013
Technical meeting	CO2 Conference Week	Midland, TX	December 9, 2013

V. Workbook preparation

The results of a decade of intense research and development of geologic storage as an essential component of carbon capture and storage has created a large inventory of practical experience, which has been compiled into “best practice” manuals, protocols, regulatory guidance, and regulations with relevance to monitoring design (Table 1). Many of these documents recommend or require site-specific adaptation of the planning and execution of monitoring at the site; however, details about how to adapt the monitoring plan to the site are limited. The recommendations provided in this study complement the literature reviewed.

In addition, the outcomes of dozens of storage tests conducted globally provide a rich literature that gives examples of how projects pragmatically adapted the knowledge at the start of the project to conditions at the site, and in many cases documents the outcome of the design (Table 2). However, this wealth of information shows that the types of adaptations are very diverse and nonsystematic. It is difficult to pick out which adaptations are to the characteristics of the site, and which adaptations are from other variables such as the expertise and interests of the research team or different authors of the of the funding opportunities for the research. The findings from field tests are discussed, but only in selected cases can the data be used in a fully quantitative way to match the monitoring design and consideration of site characteristics to the success of the measurement.

The recommendations from this study have been compiled in a workbook (Hovorka and others, 2014a) that will be submitted for publication. Reviewers recommended a format that could accompany a part-day short course looking specifically at the site-specific aspects of monitoring would be of highest value. Figure 11 shows a flowchart of the methods illustrated in the workbook.

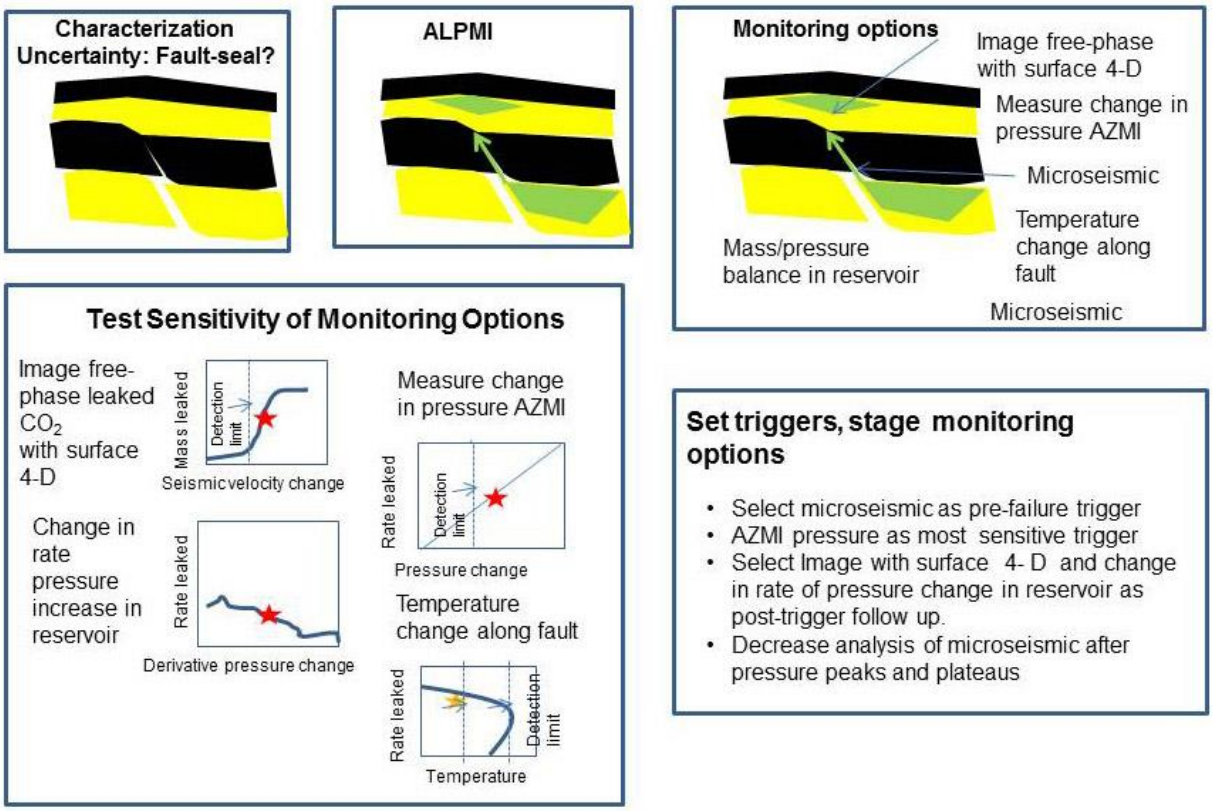

Figure 11. Flowchart of AZMI-based tool selection.

To support the workbook format, we developed case studies. After several drafts, we rejected "real world" cases for two reasons. Experiments with students showed that real cases are too complex to examine in a short-course format, as time is wasted on details that are not important for the issues to be illustrated. A greater barrier is that few real cases of problematic migration or leakage from geologic storage were identified. A case of unexpected CO_2 lateral migration

resulting in leakage to surface at Salt Creek field, Wyoming, is too sparsely documented to be a useful case (U.S. Department of Interior, 2006). Most reported other problems are related to well maintenance, which is a universal problem for many types of wells, and fall outside of the site-specific scope of this study. Initially we considered adapting data from a site to add a site failure; however, the possibility that an artificial case would be confused with a successful storage project seemed too high. Therefore the failure cases used in the workbook are excerpted from real cases but highly idealized and simplified.

We emphasize that the purpose of the workbook is to support the need for investment in proper detailed design by a team of monitoring technology experts by letting prospective site developers and regulators experiment with the basics of designing an appropriate site and a specific monitoring plan. The main message of the guidebook is to show that such investment is essential to a successful monitoring design. In particular, extrapolating a successful design from one site to another site without a detailed evaluation is not recommended.

VI. Conclusions

Guidance and rules for geologic storage generally agree that site-specific approaches are needed, but they provide few specifics to match the monitoring plan to the site. The absence of a method for accomplishing this matching is a substantive risk to successful development of plans. Concurrence of diverse stakeholders in CO_2 storage projects such as operators, and finance, legal, and regulatory teams is needed. Without a method for making choices, risk (1) missing a signal that the system was not responding as expected or (2) measuring an unexpected signal that was not actually important to the project success but was misinterpreted by stakeholders. Either of these outcomes could damage the reputation of the project and imperil its completion.

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 information collected was used to publish a sequence of papers and a workbook that synthesizes the outcomes in a format prepared for knowledge-sharing.

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