Injection of CO₂ into geological structures is a key technology for sequestering CO₂ emissions captured from the combustion of fossil fuels. Current projects inject volumes on the order of megatonnes per year. However, injection volumes must be increased by several orders of magnitude for material reductions in ambient concentrations. A number of questions surrounding safety and security of injection have been raised about the large scale deployment of geological CO₂ sequestration. They are site specific and require an effective monitoring strategy to mitigate risks of concern to stakeholders. This paper presents a model-based framework for monitoring design that can provide a quantitative understanding of the trade-offs between operational decisions of cost, footprint size, and uncertainty in monitoring strategies. Potential risks and challenges of monitoring large scale CO₂ injection are discussed, and research areas needed to address uncertainties are identified. Lack of clear guidance surrounding monitoring has contributed to hampering the development of policies to promote the deployment of large scale sequestration projects. Modeling provides an understanding of site specific processes and allows insights into the complexity of these systems, facilitating the calibration of an appropriate plan to manage risk. An integrated policy for risk-based monitoring design, prior to large scale deployment of sequestration will ensure safe and secure storage through an understanding of the real risks associated with large scale injection.

Introduction

Atmospheric concentrations of CO₂ have increased significantly from preindustrial levels of 280 ppm to current concentrations of 384 ppm (1), and global emissions are projected to continue to increase in the future. Rising concentrations are a concern because of their potential impact on global climate change. Reducing atmospheric CO₂ concentrations is an important objective in addressing climate change. Geological sequestration of CO₂ is a candidate technology for removing CO₂ emissions from fossil fuel combustion (2).

A clear challenge is how to stabilize atmospheric CO₂ concentrations without significant negative impact on the global economy. CO₂ sequestration is an attractive option for mitigating climate change because it can be deployed immediately and at scale, with minimal disruption to the existing energy production and distribution infrastructures. Two key questions of interest to scientists, policy makers, and the public are: is geological sequestration safe, and once it is injected, can we assume that the CO₂ remains sequestered? Monitoring and verification help address these concerns by providing a means to verify the location of the CO₂. If anomalies in operations are detected, they afford a mechanism to take appropriate action and remedy the situation.

This paper presents a model-based framework for integrated monitoring design. In order to design an appropriate monitoring system, a detection limit is required. The threshold of detection is intertwined with design variables of the network. These are constrained by operational concerns of cost, regulation and safety. A systems approach to monitoring design, integrating the responses of physical models encompassing all affected domains with the physical limits and uncertainties associated with the monitoring techniques, provides a tool for maximizing the available information. An integrated framework allows stakeholders to make sound decisions on the trade-offs between risks and costs. The challenges, risks and uncertainties of large scale injection are reviewed, and design considerations are discussed.

Sequestration Options for CO₂.

Geological formations identified for sequestration are depleted oil and gas reservoirs (3, 4), deep unminable coal seams (5, 6), deep saline aquifers (7, 8), deep ocean sediments (9–11), and basalts (12, 13). While depleted oil and gas reservoirs and unminable coal seams are attractive targets for injection because the additional recovery of oil and natural gas (which would otherwise remain trapped in the subsurface) can partially offset costs associated with capture, their capacities are small compared to those of saline aquifers (coal seams: 3–200 GtCO₂; oil and gas reservoirs: 675–900 GtCO₂ saline aquifers: 1000–10 000 Gt CO₂ (14)). Under most scenarios, saline aquifer storage will be the ultimate target because storage requirements necessary to manage the climate problem are expected to exceed the capacity of oil and gas reservoirs. Moreover, life cycle analyses of a number of CO₂-enhanced recovery scenarios that include the postcombustion emissions of the additional oil recovered suggest that these projects will increase the amount of CO₂ in the atmosphere, and are not viable solutions for long-term greenhouse gas mitigation (15). Aquifer storage is also attractive because their geographical distribution is more widespread than oil and gas reservoirs and they are often located in the vicinity of large point source emitters.

CO₂ emitted from one 500 MW coal-fired power plant is approximately 3 Mt/year (16). There are the equivalent of over 500 of such plants operating in the U.S. (17). Injection volumes of existing sequestration projects are on the order of Megatonnes per year, well below the scale of Gigatonnes per year required for meaningful impact. This upscaling of...
future operations far beyond the current knowledge base of injection operations and systems responses raises concerns of safety and security.

Monitoring and verification are essential components in managing risk in geological sequestration. Monitoring can confirm that a project is operating properly. If anomalies are detected, it serves as an early warning system to signal the need for intervention. In the event that a leak does occur, monitoring and verification facilitate remediation through the ability to locate the leak. Injection volumes can be reconciled with volumes detected in the subsurface, allowing proper assignment of carbon credits and project liability. Assimilating observations with output from dynamical models provides valuable data with which to calibrate models, allowing more accurate prediction of CO$_2$ behavior. The ability to obtain more accurate predictions by combining model predictions with observations has been demonstrated in many areas of the earth sciences (18–20) and can be extended to monitoring CO$_2$ sequestration. When model predictions are comparable to observations gathered from monitoring, the complexities of the physics and uncertainties in the system may be reasonably well understood, providing confidence that CO$_2$ can be securely stored in the subsurface.

Designing an effective scheme for monitoring and verification is not a trivial task. Technical issues such as determining whether a leak can be distinguished from background CO$_2$ levels and what type and magnitude of leak can be detected are intertwined with cost of deployment. Model-based design requires a solid understanding of systems interactions, uncertainties, and limitations.

### Framing the Monitoring Problem

Monitoring design is both an inverse problem and an optimization problem. An inverse problem arises because of the need to determine whether a leak has occurred, given the observed response of the monitoring network. If a leak has occurred, then the task is to locate the leak, based on the information supplied by the network. The design task is an optimization problem where network goals, such as detection threshold, are balanced with operational considerations, such as life cycle costs and network footprint. Effective monitoring network design is not a one-size-fits-all problem. Design choices include monitoring technique, type of instrument, density of the network, and frequency of acquisition. Constraints may also be imposed by various stakeholders.

Uncertainty enters the monitoring problem through measurement errors and modeling assumptions. Data are measured at discrete locations prescribed by the network. Measurements are subject to noise, and their precision and accuracy are dependent on the type of instrument. Therefore, the data used to estimate the presence and location of CO$_2$ are not perfect. The quantity of data from a network is limited, and the estimates of leakage and location of the leak are nonunique. The dimensionality of a basin scale sequestration project is large, and multiple surface and subsurface processes are coupled. Models representing physical process may be simplified to make solution of the system tractable. Limits on dimensionality may also be imposed by our own biases of what we believe the relevant physics governing the processes are, unintentionally excluding processes that may have material impact on system response.

If a leak has been detected and located, good decisions regarding intervention and remediation can be made only if the uncertainty in the system is adequately characterized. Monitoring and verification reduce uncertainty in the system by providing data to constrain our estimates of the location of CO$_2$. They also provide data to refine estimates of model parameters and reduce associated uncertainty, improving models used to predict CO$_2$ transport.

The objectives of a monitoring and verification program may be framed in terms of: maximizing the probability of detection, minimizing the size of the leak detected, or minimizing the cost of the system, given a required level of resolution. These may be correlated or they may be in conflict. For example, to maximize the likelihood of detecting a leak and minimize the threshold at which a leak is detected, a dense monitoring array is required, increasing the cost of the network and acquisition effort. The cost of detecting a leak could be minimized through fewer observations, but at the expense of increased uncertainty in detection. Because of the trade-offs involved, determining the “best” design for a cost-effective, reliable monitoring system is a complex task. An objective function provides a metric to compare network designs. Through the use of appropriate models, the physics of storage, transport, and monitoring are embedded in the objective function.

### Models for CO$_2$ Sequestration

Models are necessary tools for designing an effective monitoring scheme. Transport models provide a physical basis for answering questions such as the areal extent of the plume, the magnitude of the pressure disturbance and the expected leakage rate, to guide policies and decisions on the necessary footprint and sensitivity of the network. Inversion models relate observations to physical processes, converting indirect monitoring observations to meaningful information about CO$_2$ behavior in the system. They also guide decisions on the suitability of a monitoring technique for a particular site. Systems level models provide a platform for integrating multiple processes. They shed insight into the dynamics of CO$_2$ transport between affected systems and allow quantification of the impact of uncertainty on CO$_2$ behavior. Integrating these models with expert systems provides a framework to predict risk under uncertainty, and investigate how it can change with different monitoring designs.

#### Transport Models

Transport of CO$_2$ covers a wide range of scales, from pore scale processes at the fluid interface to basin scale dynamics of regional groundwater flows. A number of modeling approaches are available. These range from detailed coupled transport models incorporating multiphase, multicomponent effects to simplified analytical models to hybrid analytical-numerical approaches. The appropriate modeling approach is dependent on the questions to be answered. Celia and Nordbotten (21, 22) propose a framework for developing practical models. They start by focusing on the time and length scales of the questions of interest and use these to guide the formulation of the governing equations, resulting in a modeling framework that efficiently captures the appropriate level of physical detail.

Detailed numerical simulation models allow investigation of the nonlinear coupling among flow, geomechanics, geochemistry, and thermodynamics (23–27). Interaction of reservoir minerals with injected CO$_2$ can alter permeability pathways in contacted areas of the reservoir, affecting injectivity and distribution of CO$_2$ in the subsurface (28). These types of models provide more realistic estimates of critical information for effective monitoring design, such as plume extent, pressure build up and expected leakage rates (29). Detailed models also provide insights into flow behavior. Pruess used TOUGH2, a general purpose simulator for coupled multiphase fluid and heat flow in porous and fractured media, to assess the interplay between condensation and three-phase flow (30). This was used to investigate the likelihood of self-enhancing and self-limiting feedbacks during discharge from a secondary accumulation, providing better understanding of the behavior of a leak. Detailed simulations can also be used to obtain upscaled bulk properties that are required in simplified models.

A number of commercial and research simulators are available to model CO$_2$ sequestration. Many were originally
developed for oil field applications and have been modified to account for processes critical to modeling CO₂ sequestration, such as CO₂-brine solubility. Benchmarking studies (31, 32) have been conducted to validate the different modeling approaches. High spatial and temporal resolutions are required to resolve pore scale processes, such as convective dissolution, and the effects of small scale reservoir heterogeneity on the fate of CO₂. Iterative calculations, such as thermodynamic flash calculations to determine CO₂ partitioning between phases, add to the computational burden.

Analytical solutions of subsurface CO₂ transport (33–37) allow investigation of the dependence of plume evolution on a small number of key parameters, such as mobility ratio, or insights into the dominant physics affecting migration. Closed form expressions also allow for rapid estimation of site specific characteristics, such as area of review or storage capacity, facilitating fast screening of proposed monitoring designs. Analytical models make a number of assumptions to simplify the system. These include constant fluid properties and wind velocity profiles. They provide first order estimates of CO₂ behavior and cannot model effects of complex geology or diffuse leakage.

Hybrid models combining analytical and numerical approaches have been developed. This approach takes advantage of the computational efficiency of analytical solutions and the flexibility of numerical simulation. Streamline simulation coupled with analytical solutions for compositional flow decouples transport from the underlying heterogeneity of the reservoir. In this framework, the pressure field is solved numerically and components are advected along the pressure streamlines constrained by the permeability distribution in the reservoir (38). This allows fast and accurate calculation of compositional processes while retaining high spatial resolution in the permeability field. Rapid assessment of geological uncertainty can be performed, assisting in optimal placement of monitoring stations. Vertically integrated modeling frameworks combine sharp interface solutions for aquifer flow with subscale analytical models. Gasda et al. (39) coupled numerically calculated sharp interface solutions with subgrid block scale analytical models for wellbore flow. This framework was used to model CO₂ injection and migration in a geologically complex, heterogeneous formation under a variety of injection constraints (multiple wells, injection, and shut-off periods). Solutions obtained were comparable to those from more complex numerical simulators, at a fraction of the computational effort.

Inversion Models. Indirect monitoring methods require models to convert observations to information related to an attribute of CO₂, such as saturation or concentration. Regression based models relating shear wave (S-wave) velocity to compressional wave (P-wave) velocity can be constructed from well log data. However, representative log data to condition the velocity model may not be available in basin scale applications. These models are site specific and require calibration (40). Models calibrated to a specific data set may not be applicable to all areas of the basin. Inclusion models (41) are based on idealized pore geometries and rock type, enabling modeling beyond the range of physical conditions. They also allow exploration of the effect of uncertainty in rock parameters on seismic attributes, providing a bounds on the range of detectability for a particular site. When inversion models are integrated with transport models, the limits of a monitoring method in a proposed sequestration project can be explored and the monitoring network design can be optimized.

Systems Models. Transport processes in the subsurface directly impact leakage rates measured at the surface. Systems models capturing subsurface and surface interactions are necessary for designing a site specific monitoring strategy. They provide insights into behavior that cannot be revealed with simple stand alone process models. These types of models permit a systematic comparison of the impact of leakage detection in different domains of the sequestration system. Models representing the individual domains are usually simplified to reduce computational run times, allowing exploration of interactions between the large number of uncertain parameters. When sequestration process are combined with economic models, quantitative decisions regarding cost and deployment can be made.

CO₂-PENS (43, 44) integrates the main processes of carbon capture and storage, accounting for capture, surface transport, injection, leakage, and migration at the surface and subsurface. Each process is a module, which can be modified as the appropriate level of detail is revealed, incorporating evolution in the level understanding as more practice is gained from operating these systems. Process level lab experiments are integrated with field observations and numerical simulations to provide physically grounded estimates of the overall performance of the sequestration system.

Expert Models. The large number of uncertain parameters at the basin scale, imprecision in measurements and different types of observations require an automated tool for timely decision support. Systems level models can be combined with expert judgment on the likelihood of an event occurring. Bayesian methods provide a platform to integrate different types of data from multiple sources while accounting for uncertainty and missing data, identifying the optimal design for the available level of understanding. Construction of expert models provides insights into the complexities of entire system through the consideration of all possible interactions, failure modes, and their likelihood. Zhang et al. (45) constructed an expert system to estimate leakage through faults using fuzzy set theory. Percollation models were used to estimate the connectivity of a fault system. Numerical simulation was used to estimate the probability that a plume would encounter the system. Fuzzy rules were constructed to calculate the probability of leakage for a given set of input parameters.

The Need for Model-Based Monitoring Design

Effective monitoring design requires a clear understanding of the goal of the program and the consequences of design choices. Benson (46) discusses the monitoring needs required for inventory and carbon credit verification. Questions are addressed, such as the importance of establishing clear detection limits for monitoring and detecting whether a leak has occurred. Designing a monitoring program to manage risk can be framed in terms of a decision problem (illustrated in Figure 1). Concerns addressed at each stage of the process require a clear understanding of how the physical mechanisms governing transport and trapping combine with uncertainties in the system. Choices made in modeling and network design, based on a specified level of cost, uncertainty and risk, influence our ability to detect a CO₂ leak. Prior understanding of these risks and consequences will constrain the design space. As an injection project evolves, periodic re-evaluation of the efficacy of the program should be performed to ensure that the information gathered by the network are still relevant.
Concerns about an incident similar in scale to Lake Nyos (47) are commonly cited by opponents of geological sequestration. The Lake Nyos disaster occurred in a tectonically active volcanic crater where CO2 accumulated gradually at the lower depths of the lake. A natural event triggered the sudden release of approximately 1.6 million tonnes of CO2 to the atmosphere, causing harm to the health and welfare of surrounding villages. Model-based design provides a framework for understanding the complex dynamics of a system. Site specific systems-level modeling can quantify the real risks associated with large scale injection for a particular location. When combined with appropriate site monitoring, anomalies can be detected earlier so that an appropriate strategy can be devised to reduce the likelihood of catastrophic events occurring.

**Risks of Large Scale Injection**

CO2 injection in the subsurface may be accompanied by changes in compressibility and fluid pH, pressure elevation and displacement of fluids. Injection of fluids into the earth at the Gigatonne scale has not been performed. For perturbations of this magnitude, there are uncertainties in the response of geomechanical and geochemical processes in the target and overlying formations. These risks must be quantified for CO2 sequestration to be viable. Models that capture our understanding of processes governing flow and transport are required to quantify risks of large scale sequestration. Characterization of uncertainties in models and parameters is also necessary.

Risks may have environmental, economic and safety consequences. Table 1 summarizes some of these risks. The
TABLE 1. Potential Risks Associated with Large Scale CO₂ Injection

Environmental Risks

Induced by large pressure perturbations

- degradation of potable aquifer quality through mixing between lower quality water with potable water within an aquifer (91).
- if the aquifer is an open system, discharge of brine into surface water sources, such as lakes and streams, at rates which the ecosystem system cannot safely handle (32).
- alteration of flows in shallower, overlying aquifers, impacting regional water resources (93–95).

Direct interaction with CO₂

- acidification of freshwater and leaching of minerals and heavy metals bound in the rock formation (96, 97).
- mobilization of organic compounds initially present in the subsurface, contaminating potable aquifers.
- inhibition of root function and vegetative stress, leading to lower productivity or vegetation kills (98–101).
- alteration of microbial communities, favoring anaerobic and acidophilic species that can thrive in environments of elevated CO₂ concentrations (102).

Economic Risks

- financial liability for mitigation of leak and remediation of site.
- loss of carbon credit offsets or payment of carbon tax for release of CO₂.
- property damage associated with induced seismicity or changes in land surface elevation (103).
- loss of investment, if a project is unable to meet the designed injection capacity once the project has commenced.
- inability to conduct future business in the region and loss of company goodwill (104, 105).

Safety Risks

- physiological effects, such as disorientation, headaches and blurred vision, due to prolonged exposure (106).
- asphyxiation, if concentrations build up to sufficiently high levels in depressions or poorly ventilated areas.
- workplace operator safety.

Footprint estimates for basin scale injection projects are expected to be on the order of tens to hundreds of square kilometers (62, 63). Subseismic features such as fractures and discontinuous thin shale barriers have length scales on the order of centimeters, while the resolution of many geophysical monitoring techniques is much larger (on the order of tens of meters). These features may not be resolved during the characterization process and pose a risk. Thin shale features will have a strong influence on the migration of CO₂ in the subsurface (64). Because the areas over which the plume is expected to migrate are much larger than current operations, the probability of encountering a leakage pathway is greater, making likelihood of leakage in basin scale saline aquifer injection greater than in existing projects.

Various stakeholders will value risk differently and their appetite for risk will differ depending on the location of the project. The requirements for monitoring will vary depending on the stakeholders, maturity of the industry and the location of the site. A sequestration project in a highly populated area may have less tolerance for leakage events and require more stringent regulations. Protection of fresh water resources may be the prime concern in these types of areas, focusing monitoring efforts on that aspect of the system. Risk tolerance will also vary depending on the maturity of the industry. Due to the small number of projects in operation, it is difficult to accurately quantify the risks associated with sequestration (65). As noted by a number of groups (16, 66), there is a critical need for more, at scale, demonstration projects. Conservative monitoring programs will be necessary to demonstrate safe operations at early stages of sequestration deployment. As more experience is gained in operating geological storage projects and a better understanding of the likelihood of risks is achieved, stakeholders will become more confident in the ability to safely sequester CO₂ and manage risks appropriately. Monitoring efforts can be directed to target those events. A model-based framework will assist in determining the appropriate level of monitoring for an acceptable level of risk and a given experience base. Benson and Cole (67) suggest that support for sequestration will be gained once all the interests of the wide variety of stakeholders, each with a different set of perspectives and goals, are addressed. A framework grounded in sound, scientific theory provides a platform for addressing concerns of the multiple interests involved.

Challenges in Monitoring at the Basin Scale

Designing a monitoring campaign at the basin scale presents a number of challenges not encountered in existing injection operations. Reservoirs used in enhanced oil recovery projects are well characterized due the presence of production wells. As a result, the spatial variability of reservoir properties is well understood. Well data also provides direct observations to calibrate rock physics models used in geophysical monitoring applications. Years of production from oil and gas reservoirs provide insights into dominant flow pathways in the subsurface. In most practical situations, saline aquifers are not as well characterized as oil reservoirs. Compared to
enhanced oil recovery projects, a much smaller fraction of data sampling the aquifer is available. Additionally, we have much less experience injecting into saline aquifers. Significantly more uncertainty exists in the fluid and reservoir properties controlling CO2 migration in aquifers, affecting our confidence in predictions of plume migration in basin scale sequestration.

The large footprints of Gigatonne scale injection projects are expected to cover a variety of surface and subsurface environments (Figure 2). Because CO2 has the potential to migrate from the reservoir to the atmosphere and impact multiple domains along the way, an effective monitoring program must have the ability to detect the response to CO2 in each of these domains.

Trapping mechanisms have different length and time scales. Table 2 lists the mechanisms contributing to long-term storage. Over the course of an injection project, the dominant physics of trapping will change. Dynamic trapping mechanisms, such as structural trapping and capillary trapping, occur on the injection time scale of years or less, and dominate the injection period. Geochemical trapping time scales are much longer, occurring on the scales of tens to thousands of years. The ability to monitor changes caused by trapping demonstrates that geological sequestration is safe. Designing a monitoring program that can capture these changes at the appropriate length and time scales is a challenge.

Chalaturnyk and Gunter (68) propose three monitoring periods and levels: operation, verification and environmental. The first two periods cover monitoring during the injection phase and confirm expected operations (tens of years). The last period covers potential seepage (50—100 years). For each period and level, monitoring methods according to need and time frame are identified. At early times, monitoring is required to ensure that CO2 is being injected into the target formation and that the project is operating in a safe and effective manner. At this stage, uncertainty about the subsurface and how CO2 migrates is highest. Leakage risk is also higher during injection because the volume of mobile CO2 is at its largest. Early stage trapping processes such as residual trapping and dissolution have not reduced the volume of mobile CO2 compared to later stages, resulting in a larger driving force for upward migration of the plume. Appropriate monitoring data would focus on measurements that yield the greatest information about the state of operations, such as injection pressures and rates, and well logs confirming which formation CO2 is injected into. At later times, monitoring is necessary to ensure long-term storage occurs. At this stage of the project, uncertainty about the subsurface and the behavior of CO2 in the reservoir is the lowest. Driving forces on plume movement are small and risk of leakage is low. Appropriate monitoring data at this

### TABLE 2. Trapping Mechanisms Available to Contribute to Long Term Storage of CO2 in the Subsurface

<table>
<thead>
<tr>
<th>mechanism</th>
<th>time scale for onset</th>
<th>description</th>
</tr>
</thead>
</table>
| structural trapping (107) | < year               | • upward migration of buoyant CO2 is prevented by an impermeable seal  
|                           |                      | • if the system is open, structural trapping is important in situations where CO2 migrates slowly  
|                           |                      | • time scales for structural trapping are governed by the dynamics of CO2-brine flow                                                       |
| capillary trapping (108, 109) | < year        | • CO2 phase is disconnected into an immobile saturation  
|                           |                      | • upward migration forces on the total mass injected decrease as more CO2 is immobilized through the dynamic interaction between plume migration and capillary trapping  
|                           |                      | • because capillary trapping is a dynamic, multiphase flow process, its time scale is similar to that of structural trapping |
| solubility trapping (110, 111) | years to hundreds of years | • CO2 is dissolved in the brine  
|                           |                      | • at injection conditions, brine with dissolved CO2 is slightly more dense than brine without dissolved CO2, reducing tendency for upward migration and enhancing gravitational instabilities, promoting further solubility trapping  
|                           |                      | • time scales for dissolution are limited by contact area between the CO2 phase and undersaturated brine |
| mineral trapping (112)    | tens to thousands of years | • CO2 reacts with minerals in the geological formation to precipitate into the solid phase  
|                           |                      | • considerable uncertainty exists in the values for rate constants of these reactions |
stage would yield information about the spatial distribution of CO₂ in the subsurface, such as seismic.

Cortis et al. (69) propose a three phase approach to monitor surface leakage. Resolution at each stage is progressively increased. The first stage involves a static network to characterize background processes and estimate admissible seepage rates. The second stage involves the collection of finer scale data which can be used to train an expert model. The final stage involves deployment of a dynamic monitoring network to pinpoint the precise location of the leak and quantify its magnitude. Four critical length scales affecting cost and sensitivity (size of the region to be monitored, footprint of the monitoring technique, footprint of the leak and region influenced by the leak) are identified in their proposed approach.

**Monitoring Techniques.** A number of technologies are available to monitor and detect CO₂ in the surface and subsurface. Many of these techniques have been used in resource optimization and natural hazards monitoring. Their ability to monitor CO₂ has been demonstrated through a variety of means: theoretical studies (70, 71), pilot tests (72), and field scale implementation (73–75). Monitoring technologies employed in existing sequestration projects are summarized in Table 3.

**TABLE 3. Monitoring Programs in Existing Sequestration Projects**

<table>
<thead>
<tr>
<th>project</th>
<th>monitoring objective</th>
<th>methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleipner, offshore Norway (113)</td>
<td>• demonstrate safe storage in primary reservoir</td>
<td>• fluid movement: 4D seismic, 4D gravity, electromagnetic</td>
</tr>
<tr>
<td>• saline aquifer</td>
<td>• observe distribution of CO₂ in reservoir</td>
<td></td>
</tr>
<tr>
<td>• 1 million tonnes CO₂/year, since 1996</td>
<td>• provide early warning against CO₂ migration toward sea floor</td>
<td></td>
</tr>
<tr>
<td>Weyburn, Saskatchewan (114)</td>
<td>• monitor CO₂ migration</td>
<td>• fluid movement: 4D seismic, tracers</td>
</tr>
<tr>
<td>• EOR-CO₂ project in a mature oilfield, with many preexisting wellbores</td>
<td>• assess interaction of injection CO₂ with other reservoir fluids</td>
<td>• geochemical interaction: produced fluid analysis</td>
</tr>
<tr>
<td>• 1 million tonnes CO₂/year, since 2000</td>
<td>• optimize enhanced recovery through identification of anomalous flow behavior</td>
<td>• geomechanics: microseismic, downhole pressure</td>
</tr>
<tr>
<td>In Salah, central Algeria (75)</td>
<td>• optimize simultaneous gas production and CO₂ sequestration operations within the same formation</td>
<td>• leakage: soil gas samples</td>
</tr>
<tr>
<td>• injection into downdip water leg of a producing gas field</td>
<td>• monitor stress changes to prevent reactivation of fractures and faults in overlying formations</td>
<td></td>
</tr>
<tr>
<td>• 1.2 million tonnes CO₂/year, since 2004</td>
<td>• extensive characterization of preinjection reservoir state</td>
<td></td>
</tr>
<tr>
<td>Frio, Gulf Coast Texas (115)</td>
<td>• demonstrate safe injection of CO₂ in a brine aquifer, without adverse health or environmental effects</td>
<td>• fluid movement: crosswell seismic, vertical seismic profile, crosswell electromagnetic, trace rs, well logs, downhole multiphase fluid samples</td>
</tr>
<tr>
<td>• saline aquifer</td>
<td>• observe the movement of CO₂ in the aquifer</td>
<td>• geochemical interaction: produced fluid chemistry</td>
</tr>
<tr>
<td>• small volume injection test (1600 tonnes), 2004</td>
<td>• monitor changes in brine chemistry due to CO₂ injection</td>
<td>• geomechanics: downhole temperature and pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• leakage: soil gas samples, aquifer chemistry, tracers</td>
</tr>
<tr>
<td>Otway, Australia (116, 117)</td>
<td>• demonstrate ability of subsurface, near-surface, surface and atmospheric technologies to monitor CO₂</td>
<td>• fluid movement: seismic, vertical seismic profiles, tracers</td>
</tr>
<tr>
<td>• depleted gas reservoir</td>
<td></td>
<td>• geochemistry: produced fluid pH</td>
</tr>
<tr>
<td>• small volume injection test (100 000 tonnes), 2008</td>
<td></td>
<td>• geomechanics: microseismic, downhole pressure and temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• leakage: chemistry of shallow and deep aquifers, water level changes, soil gas samples, atmospheric flux measurements</td>
</tr>
</tbody>
</table>
in high porosity, high permeability reservoirs. Microseismic monitoring analyzes low level seismic activity triggered by naturally occurring events or induced by injection operations. This technique is effective in assessing induced seismicity hazards and mapping the migration of CO₂ resulting from induced fracturing or fracture reactivation. Gravimetry is used to detect variations in gravitational acceleration due to mass distributions in the subsurface. These can be used to detect variations in fluid density, indicating the location of the injected plume. Electromagnetic techniques detect variations in electrical conductivity of a medium. CO₂ is more resistive than brine. Areas where CO₂ has displaced brine correspond to areas of low conductivity. Geodetic methods, such as GPS and tiltmeters, measure changes in the elevation Earth’s surface to indicate where the CO₂ has migrated. Pressure changes associated with CO₂ cause changes in stress and strain in the reservoir, resulting in deformation at the surface. Geochemical monitoring analyzes the concentration of CO₂ and other chemical species in fluids and gases to identify concentrations above background levels.

Surface monitoring methods detect leakage and quantify the amount of CO₂ that has migrated into the vadose zone and atmosphere (Table 4). Soil gas samples measure the atmosphere present in the soil pore spaces. A probe is inserted into the ground and chemical species can be collected actively (pumped into a container) or passively (via a sorbent). Infrared gas analyzers rely on the absorption of infrared radiation by CO₂ to detect a leak. Closed path configurations pass an infrared source through a closed chamber containing the sample. In open path measurements, the sample is part of the free atmosphere. In this configuration, CO₂ concentrations are averaged over the path length, linking network sensitivity to path length.

Monitoring methods can be divided into two categories: direct and indirect. Direct measurements have high resolution, but low spatial coverage. In order to capture the spatial variability of CO₂ distribution and reduce the uncertainty associated with interpolation between measurements, a dense sampling array is required. High accuracy methods, such as mass spectrometry, may also be limited by portability of equipment. Observation wells allow direct monitoring of CO₂ movement in the subsurface, but they could serve as a leakage pathway. Fluid samples provide an integrated response of subsurface flow from injection to collection point. Prior knowledge of flow pathways are required to extract additional information about CO₂ migration. The trade-off in an observation well lies in balancing the cost of drilling the wells and the increased risks of leakage with the reduction in uncertainty resulting from high quality information provided by directly probing the aquifer.

Indirect methods, such as seismic or electromagnetic, have the ability to monitor large areas, but at low resolution. In the subsurface, indirect methods may be the only practical option. A rock physics model is required to relate the measurements of seismic velocity or electrical resistivity to CO₂ in the subsurface (76–78). The Gassmann equations...
are frequently used to identify and quantify fluids in seismic reservoir analysis. These equations relate rock properties to pore, solid and fluid properties, and allow one to relate changes in seismic velocity to changes in fluid saturation due to CO₂ migration.

Uncertainties in model parameters (such as the mineral composition of the rock), simplifications made to represent the system (such as choice of averaging (80)) and assumptions (such as constant rock and fluid properties) may lead to a confounded response (pressure changes due to injection, and saturation changes due to fluid migration can produce the same seismic velocity response). A nonunique combination of parameters will lead to multiple equally valid solutions of system response. Integration of complementary monitoring methods can constrain the solution space, and thereby reduce the uncertainty in the interpretation of the observed response. Figure 3 shows a schematic of an integrated monitoring program. Data can be static (measured once during the life of the project and assumed constant) such as geochemical reaction rate constants, or dynamic (measured through the life of the project) such as surface gas samples. Data may be quantitative, such as injection pressure, or qualitative, such as rock lithofacies type, requiring expert judgment, and subject to interpretation. Each type of data yields information about the system at specific spatial and temporal scales (Figure 4).

Hoversten et al. (81) combined coincident high resolution crosswell seismic, electromagnetic surveys and well logs to monitor a CO₂ flood in Lost Hills, California. The presence of three distinct reservoir fluids made interpretation of individual surveys challenging. The well logs provided strong correlations between conductivity, saturation, and porosity. Seismic and electromagnetic data were used to generate velocity and conductivity tomograms. Saturation estimates were combined with the S-wave velocity tomogram to calculate the change in pressure, allowing calculation of changes in P-wave velocity. This was compared to the measured changes in P-wave velocity. From the difference between the calculated and observed changes in P-wave velocity, the change in the CO₂ gas-oil ratio was calculated, allowing estimation of CO₂ plume migration in the reservoir. By combining seismic, electromagnetic and well logs, pressure and saturation changes were decoupled from resistivity effects, resulting in an improved constraint on the subsurface pathways controlling flow.

The choice of technology is dependent on the goals of the monitoring program. In the case of the Sleipner and Frio, both seismic and electromagnetic methods were used to demonstrate the ability to track the plume in the subsurface. While both methods allow visualization of plume migration in the subsurface, the information revealed about the plume is complementary. Seismic is sensitive to small amounts of CO₂ (82), making it an effective technique for detecting the presence of CO₂ in the subsurface. However, there is little difference in seismic response between high CO₂ saturations and low CO₂ saturations, making it a poor technique for estimating the distribution of saturation in the subsurface. Electromagnetic response is sensitive to the saturation of brine.
in the pore space, making it an effective tool for quantifying the amount of CO$_2$ trapped (83). Although multiple techniques are employed to track plume migration, the different types of information extracted from these methods complement each other, permitting both monitoring plume migration and verifying the amount of CO$_2$ injected.

Implicit in the choice of monitoring technique is the decision of the property to be measured. A challenge in surface detection of a leak is distinguishing between CO$_2$ due to a leak and CO$_2$ due to background sources. Natural sources, such as vegetative respiration and natural seeps, and anthropogenic sources, such as industrial activity and transportation emissions, operate over a number of temporal and spatial scales. These fluctuations may mask the presence of a low concentration leak. If background concentrations are well characterized, the contribution of CO$_2$ from a leak can potentially be identified. Tracers coinjected with the CO$_2$ remove ambiguity about the source of CO$_2$ (84), provided they propagate through the system at the same or greater velocity of the injected CO$_2$. Naturally occurring isotopes ($^{14}$C and $^{222}$Rn) and concentrations of associated species (CO) can be used to discriminate between CO$_2$ due to fossil fuels and CO$_2$ due to the natural biogenic signal in the atmosphere. Levin et al. (85) and Levin and Karstens (86) used changes in $^{14}$C/$^{12}$C and CO/$^{14}$CO$_2$ ratios to calculate the CO$_2$ attributed to combustion of fossil fuels.

**Cost.** The cost of a monitoring network is strongly dependent on the expected footprint of the CO$_2$ plume, extent of elevated pressure and the required resolution. Table 5 lists per survey costs for a number of methods. The small estimate represents the survey cost for monitoring a Sleipner sized area. The large estimate represents the survey cost for monitoring a basin scale injection project. In existing sequestration projects, the goal of monitoring is to answer basic scientific questions regarding CO$_2$ storage and ensure successful demonstration of geological sequestration, requiring high resolution monitoring. Under current valuation regimes for carbon and incentives for saline aquifer storage, scale up of similar high resolution monitoring programs in existing projects to basin scale projects may not be economically feasible. Basin scale monitoring will require implicit decisions on the acceptable level of risk for a given cost. A model-based approach to monitoring design allows one to assess these trade-offs and allow efficient allocation of resources appropriate to the level of risk.

At the basin scale, life cycle deployment costs are also an important consideration. In Sleipner, seismic surveys are performed once every two years (on average). If an injection project lasts 50 years, the monitoring cost for seismic alone would be 25 times the listed cost. Currently, there are no clear regulatory guidelines for the required resolution, how frequently sequestration projects must be monitored during injection and how long monitoring must continue after injection ceases. A model-based framework for monitoring will assist in providing guidance in developing these policies.

High cost, high resolution methods, such as seismic, are effective at tracking the movement of CO$_2$ in the subsurface with a relatively high degree of certainty. However, frequency of acquisition is lower. Low cost, low resolution methods, such as surface deformation, permit more frequent measurements. The interval between surveys represents the minimum time required for an anomaly in operations to be detected. There is a lower degree of certainty in the exact location of the CO$_2$ or that the event is real with less expensive techniques. However, an anomaly in operation may be detected earlier, with potentially smaller remediation costs. Moreover, earlier detection of anomalies offers a wider range of options to mitigate a leak. The public perception associated with earlier action compared to that of later action, with fewer options, may also have value in monitoring design.

**Network Configuration.** Decisions on sensor configuration include location and density of the array. These are guided by the objectives of the program and the resolution of the monitoring technique. Additional operational considerations, such as fail-safe mechanisms, redundancy and ability to transmit information will also play a role in determining the location and number of observation stations. Seismic instrumentation can be deployed in a variety of configurations. Surface surveys monitor large scale fluid movements away from injection wells. Crosswell seismic can yield high resolution fluid distributions between wells (87, 88). Shot-receivers can be placed in wellbore-surface configurations, providing information about vertical fluid movement, useful for visualizing leaks out of the aquifer.

Prior information will also guide the location of observations and the frequency of data acquisition. Information about likely migration pathways, such as the location of faults or prevailing wind patterns, provides valuable information on the expected location of CO$_2$. In mature sedimentary basins, the large number of existing wellbores of various vintages pose a challenge in developing a cost-effective monitoring program to reduce the risk of leakage from wells. An analysis of the spatial distribution of wells penetrating the Viking aquifer in the Western Canadian Sedimentary Basin found that oil and gas exploration activity

### Table 5. Costs for a Selection of Monitoring Techniques

<table>
<thead>
<tr>
<th>Technology</th>
<th>Unit Cost</th>
<th>20 km$^2$ ($\text{MM}^a$)</th>
<th>1000 km$^2$ ($\text{MM}^b$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>high resolution 3D seismic</td>
<td>$38,610/km$^2</td>
<td>0.8</td>
<td>38.6</td>
<td>McCoy and Rubin (129)</td>
</tr>
<tr>
<td>observation well*</td>
<td>$3,000,000/well (including logs)</td>
<td>3</td>
<td>120</td>
<td>McCoy (130)</td>
</tr>
<tr>
<td>InSAR</td>
<td>$2,000–3,000/km$^2</td>
<td>0.04</td>
<td>2</td>
<td>U.S. Department of Transportation (131)</td>
</tr>
<tr>
<td>gravity</td>
<td>$14,000/km$^2</td>
<td>0.3</td>
<td>14</td>
<td>U.S. Department of Energy (132)</td>
</tr>
<tr>
<td>fluid sample and analysis*</td>
<td>$200/sample</td>
<td>0.0008</td>
<td>0.03</td>
<td>EPA (133)</td>
</tr>
<tr>
<td>eddy covariance tower</td>
<td>$25,000/tower (basic instrumentation)</td>
<td><strong>3.9</strong> (2 m tower height, 0.1 km$^2$ flux footprint)</td>
<td><strong>198.9</strong> (2 m placement)</td>
<td>Baker (134)</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>0.03</strong> (30 m tower height, 38 km$^2$ flux footprint)</td>
<td><strong>0.8</strong> (30 m placement)</td>
<td></td>
</tr>
</tbody>
</table>

* Estimated costs for a Sleipner sized survey area. b Estimated costs for a basin scale survey area. c One well/25 km$^2$, minimum one well/site. d Four repeat samples/observation well.
TABLE 6. Research Areas to Improve Integrated Monitoring of CO₂ Sequestration

<table>
<thead>
<tr>
<th>area</th>
<th>research need</th>
</tr>
</thead>
<tbody>
<tr>
<td>integrated modeling tools</td>
<td>• development of modeling tools capable of incorporating systems level interactions (e.g., subsurface and boundary layer communication) to assess realistic magnitudes of risk for a given injection volume.</td>
</tr>
<tr>
<td></td>
<td>• coupled interactions between physical processes of CO₂ transport, geochemical reactions and geomechanical changes for more accurate estimation of the magnitude of risks.</td>
</tr>
<tr>
<td></td>
<td>• development of computationally efficient analytical models capturing key physical processes to facilitate probabilistic risk assessment (135, 136).</td>
</tr>
<tr>
<td>uncertainty quantification</td>
<td>• quantitative comparison of impact of modeling choices, such as the choice of dispersion model, and model representation on uncertainty (31, 32).</td>
</tr>
<tr>
<td></td>
<td>• development of a stochastic framework to allow an integrated exploration of correlations between the large number of uncertain variables associated with the overall sequestration system (42, 44).</td>
</tr>
<tr>
<td></td>
<td>• efficient tools for uncertainty propagation through the entire system, allowing integration of the effect of uncertainty in parameters, models and measurements.</td>
</tr>
<tr>
<td>efficient data assimilation</td>
<td>• algorithms to efficiently integrate different types of monitoring data, consistent with the different length and time scales of the technique and their associated uncertainties (137, 138).</td>
</tr>
<tr>
<td></td>
<td>• efficient algorithms to handle large amounts of high frequency data, to utilize advancements in low cost, permanent sensors.</td>
</tr>
<tr>
<td></td>
<td>• tools, such as geographical information systems for land use optimization (139), to efficiently incorporate spatial variability data attributes, such as risk or data uncertainty.</td>
</tr>
<tr>
<td></td>
<td>• tractable assimilation techniques to integrate categorical spatial information (140, 141).</td>
</tr>
</tbody>
</table>

led to a spatial clustering of wells (at the end of 2001, there were 189,520 wells penetrating an aquifer of a spatial extent of 468 000 km²) (89). This analysis suggested that the number of wells that could be impacted by CO₂ injection ranged from about twenty, in a low density area, to several hundred, in a high density area. Further analysis of the type of wells in these areas indicated a higher fraction of abandoned wells in low density areas than in high density areas, suggesting a different likelihood of leakage from these areas. Leakage risk from wellbores has a spatial component and will influence the placement and type of monitoring techniques deployed. Geographical information systems can capture spatial information. This can be combined with mixed integer linear programing or heuristic methods, such as genetic algorithms or simulated annealing, to optimize spatial configuration and incorporate spatial variability of risk into the design framework (90).

Road Map for Research Needs. Models provide the framework to integrate uncertainty, assess risks and compare monitoring designs for large scale injection. Research is needed in the development of integrated, systems level tools to improve our predictive capability of coupled responses associated with a given injection volume of CO₂ in these complex systems. Three key areas of focus are: development of tools for efficient, integrated simulation of CO₂ transport and trapping; development of tools for accurate quantification of risk; and efficient methods for data integration, honoring the multiple scales of the many processes involved in sequestration and the spatial variability the data.

Table 6 identifies components that would assist in meeting these needs. A number of these research areas are actively being pursued in areas of atmospheric modeling, hydrology, and petroleum engineering communities. The risks of CO₂ sequestration intersect many disciplines in the earth sciences. Integration of research activities among these areas will provide a more complete view of the risks associated with basin scale sequestration.

Conclusions

An integrated, model-based framework for monitoring network design provides a platform for addressing the concerns of safe and secure storage of large scale geological CO₂ sequestration operations. Construction of site specific models facilitates an understanding of the interactions between CO₂ storage and transport in these complex systems. This allows a physically grounded quantification of the likely risks associated with injection and permits development of appropriate strategies to mitigate them. Understanding the risks and uncertainties guides the type of monitoring techniques employed and informs the suitability of design choices.

Large scale injection has the potential to create perturbations in multiple interconnected systems, between the reservoir and the atmosphere, and laterally away from the injection site. A comprehensive monitoring program integrates technologies with the ability to detect injection response in each of these systems at multiple temporal and spatial scales. A framework for monitoring design which integrates observations, process models, systems-level interactions, and uncertainty provides a platform for exploring the trade-offs between cost, safety, and risk. Through careful consideration and weighting of these objectives, informed decisions on policy development and practical implementation of large scale deployment of geological CO₂ sequestration can be made.

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Note Added after ASAP Publication

This review posted ASAP on January 10, 2011. Due to a production error, an incomplete version was posted. The correct version posted on January 12, 2011.

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