Title
A Strategy for Monitoring of Geologic Sequestration of CO2

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Abstract:

Monitoring of geologic sequestration projects will require the measurement of many different parameters and processes at many different locations at the surface and in the subsurface. The greatest need for technology development is for monitoring of processes in the subsurface in the region between wells. The approach to fitting this need is to build upon decades of experience in use of geophysics in the oil and gas industry. These methods can be optimized for CO_2 monitoring, and customized and extended in order to meet the need for cost-effective methods applicable to saline disposal sites, coal bed methane sites, as well as oil and gas reservoir sequestration sites. The strategy for development of cost-effective methods follows a three step iterative process of sensitivity analysis using numerical and experimental techniques, field testing at a range of scale in different formations, and analysis and integration of complimentary types of data.

Keywords: Geologic Sequestration, Monitoring, Carbon Dioxide, Geophysics

Background and Technology Needs:

In several industry, academic and government sponsored workshops in the past two years, monitoring has been identified as one of the highest priority needs for geologic sequestration (1, 2). First, it will be necessary to verify the net quantity of CO_2 that has been sequestered in the subsurface. Second, it is necessary for determining the efficiency with which the available subsurface sequestration capacity has been utilized. Third, it is needed for optimizing collateral economically beneficial processes such as EOR and enhanced coalbed methane recovery. Finally, monitoring will be necessary to ensure the safety of sequestration projects by demonstrating that the CO_2 is retained in the formation into which it is injected.

Accommodating these diverse needs will require the measurement of many different parameters and processes at many different locations and scales at the surface and in the subsurface. The state-of-the-art of measurement techniques is highly variable. For example, technology needed to monitor net sequestration is generally available. Monitoring of net sequestration depends primarily upon direct measurement of parameters such as volume, temperature, pressure and composition in surface facilities (e.g., wellheads, pipelines, and separation facilities.) There is general agreement that surface facility monitoring technology is sufficiently well developed for industry to implement immediately. In contrast, significantly more development is needed for monitoring in the subsurface, particularly in the region away from, and between, injection and production wells. In this region measurements must be made remotely, raising issues of sensitivity and scale. In addition the measurements are indirect, requiring interpretation to arrive at the parameters of interest.

Though further development of subsurface monitoring techniques is needed, firm basis for development is provided by decades of experience in use of geophysics in the oil and gas industry. Surface seismic technology, for example, is highly sophisticated. In recent years, oil and gas applications have also prompted development of higher resolution subsurface geophysical methods such as crosswell, single-well, and surface-to-borehole seismic, electromagnetic and electrical techniques. Areas in which further development is needed include greater detection sensitivity, higher spatial resolution, better measurement quantification, and lower costs. It is also noted that experience in the oil and gas industry is most applicable to monitoring hydrodynamic trapping processes. Significantly more R&D will be required to develop reliable methods for monitoring solubility and mineral trapping.

An Approach for Technology Development:

Methodologies and technologies must be developed which will permit selection of the most cost-effective monitoring strategy for any given site. This is also one of the goals of GEO-SEQ (3), a public-private R&D partnership that will deliver technology and information needed to enable application of safe and cost-effective methods for geologic sequestration of CO_2. A starting point are geophysical methods developed in the oil and gas industry. These can be optimized for CO_2 monitoring, and customized and extended in order to meet the need for cost-effective methods applicable to saline disposal sites, and coalbed methane sites, as well as oil and gas reservoir sequestration sites. The approach is to carryout an iterative process of (1) numerical simulation and laboratory experiments to assess the sensitivity of a technique for CO_2 monitoring, (2) field testing at a range of scales in different formations and (3) analysis and integration of multiple, complementary types of data and measurements.

Sensitivity Assessment:

Numerical simulation can be used to evaluate the sensitivity of candidate techniques and design optimum sensor configurations for a given site of interest. An iterative, three-step process is proposed. The first step is reservoir simulation. This is performed using the best available geologic model for the candidate site, incorporating the intended CO_2 injection strategy. Results of simulating the proposed CO_2 injection scenario provide fluid pressures, relative saturation, and distribution of the fluids in the reservoir. If the candidate site is an oil or gas reservoir, reservoir simulation may also be required to obtain an estimate of these quantities prior to CO_2 injection.

The second step is to perform forward geophysical modelling on the same geologic model, integrating in the results of the reservoir simulation. This integration is carried out by converting reservoir parameters such as porosity and saturation to geophysical properties such as seismic velocity or electrical conductivity. These conversions are based on laboratory measurements, of which only limited numbers have been made. Much more work needs to be done to determine the electrical and seismic properties of candidate formation rocks containing brine and CO_2 at different levels of saturation. Separate simulations are carried out for each candidate technique, such as seismic or electromagnetic.

The result of the geophysical modeling is the response of the candidate geophysical method to the fluid distribution predicted by the reservoir simulation. The geophysical response also depends on source location and its characteristics. Multiple realizations are performed to evaluate the optimum source/receiver configuration for a given technique.

The third step involves application of geophysical processing, analysis and inversion techniques to the results of the geophysical modeling. These are the same techniques that would be applied to geophysical data acquired in the field. Results provide an estimate of the response of particular candidate sensor configurations. Application of inversion algorithms result in images of fluid distribution which can be directly compared to results of reservoir simulation. At the conclusion of the third step decisions can be made about the geophysical method or combination of methods, and the optimum configuration of sources and receivers for a given monitoring application.

Field Testing and Evaluation:

Field testing is an essential step in the development of cost effective monitoring technologies. First of all, field testing is necessary to confirm and validate numerically based sensitivity assessments (as described above). Simplifying assumptions about geologic heterogeneity, physical properties, and processes are always made in the numerical simulations. Field testing establishes whether or not these assumptions are appropriate. There is considerable variability in geophysical response between formation types. Hence, field tests need to be performed in each type of formation being considered for sequestration.

Field testing is also necessary to check, calibrate and verify equipment operation. Efficiency in operation and design will derive mostly from experience in different formations with different structure and fluid compositions.

Testing at different scales is important, particularly for seismic geophysical techniques. Energy is dissipated with propagation distance, but this dissipation is not usually included in numerical simulation models. In addition, it is difficult to explicitly model source characteristics and energy transfer from the source to the formation. Hence, field testing is necessary to establish scales and conditions under which acceptable signal to noise ratios will be achieved.

Due to recent advances in technology for oil and gas applications, a number of high resolution geophysical techniques are available which can be optimized and improved for subsurface monitoring of CO_2 in the region between wells. These are single-well, crosswell, and surface to borehole seismic, and crosswell electromagnetic and electrical resistance tomography. Electrical and electromagnetic methods have been used to monitor water and steam injection into oil reservoirs, but not CO_2 (4, 5). A very limited number of tests of monitoring CO_2 injection with crosswell seismic. More tests need to be performed in different formations and at different scales to evaluate appropriate frequency ranges for monitoring applications.

It is envisioned that high resolution subsurface geophysical measurements would be combined with lower resolution surface geophysical techniques such as 3D seismic. The surface measurements provide more economic spatial coverage than the subsurface techniques. Microseismic monitoring is another cost-effective seismic measurement which could be combined with high resolution measurements. Finally, in addition to geophysical measurements, hydrologic and geochemical measurements will provide information about the distribution of CO_2 in the interwell region. Downhole measurement of fluid pressure and other hydrodynamic properties can be made and will become even more cost effective as sensor technology advances. Use of natural and introduced tracers can also provide information on the fate and transport of CO_2 in the subsurface. These can be used to estimate CO_2 residence time and storage mechanisms, evaluate process optimization and assess potential leakage.

Data Analysis and Integration:

The third element of a cost-effective monitoring strategy is the development of efficient methods for analysis and interpretation of geophysical, hydrological and geochemical field data. Hence again, the oil and gas industry provides extensive experience in imaging technology. These technologies can be optimized for application to CO_2 monitoring in the interwell region. Techniques are checked and validated by using them first to process data generated by numerical simulation and second, to process data generated by field tests at different scales in different formations.

One of the most important innovations in imaging technology is the simultaneous use, or co-inversion, of data from more than one type of measurement. This approach takes advantage of the fact that different geophysical techniques provide complementary information. For example, since seismic velocities are directly related to density and stiffness of the formation (and its contained fluids) seismic methods are sensitive to gas saturation. electrical conductivity, on the other hand, is directly related to the properties and connectivity of the liquid phase, and thus electrical properties are sensitive to liquid saturation. Tracers, while being sensitive to the hydrodynamic conductivity and connectivity of the formation, are also sensitive to chemical processes.

Oil and gas applications have lead to the development of sophisticated codes for inversion of seismic, electromagnetic, and electrical geophysical data (6, 7, 8, 9, 10). Vasco et al (11) developed a method to invert hydrologic data such as watercut, together with transient pressure and tracer data. The state-of-the-art in inversion can be advanced by combining geophysical, hydrodynamic, production or tracer data, optimized for imaging of CO_2 in the subsurface.

Summary and Conclusions:

Monitoring needs are diverse, requiring measurements of many different parameters and processes both on the surface and in the subsurface. Surface facility monitoring technology is sufficiently well developed for industry to implement immediately. Subsurface measurements need testing, evaluation and improvements in a number of areas, including greater detection sensitivity, higher spatial resolution, better quantification and lower costs. Particular focus needs to be placed upon monitoring of CO_2 in the subsurface in the interwell region. Though further work is needed, extensive experience exists in the oil and gas industry in use of geophysical techniques for subsurface characterization. These techniques can now be optimized for cost-effective methodologies for monitoring of hydrodynamic trapping processes. More R&D will be required to develop reliable methods for monitoring solubility and mineral trapping.

The strategy for development of a monitoring technology with a focus on the subsurface, interwell region, is a three step approach involving (1) numerical simulation and laboratory experiments to assess technique sensitivity, (2) field testing at different scales in different formation, and (3) analysis and integration of complimentary data. This iterative approach will permit selection of the most cost-effective combination of techniques for the particular formation and sequestration activity being considered.

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