

# Risk and Monitoring Risk for CO<sub>2</sub> Sequestration in Deep Brine Reservoirs

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# Requirements for Developing a Deep Brine Carbon Sequestration Project

by Ian Duncan

**Photo:** The U.S. Gulf Coast region could ultimately involve tens if not hundreds of CO<sub>2</sub> storage sites.

Carbon capture and storage (CCS) is the storage of carbon dioxide (CO<sub>2</sub>; captured predominantly from coal-fired power plants) in deep brine, depleted oil, and natural gas reservoirs. If CCS is to have a significant impact on CO<sub>2</sub> levels in the atmosphere, on a time scale that will make a difference to global climate change, then an adequate regulatory framework must be put in place as soon as possible.

A viable and effective policy and regulatory framework for geologic carbon sequestration must strike a delicate balance between making a system that minimizes the burden on the companies involved (to both encourage private enterprise to be involved in implementing CO<sub>2</sub> sequestration and to encourage innovation), and has sufficient rigor to ensure the health and safety of the public, the environmental integrity of sequestration projects, public confidence and support, and a project's effectiveness in mitigating atmospheric CO<sub>2</sub>.

These factors are, in part, tied to the issue of CO<sub>2</sub> leakage from geologic reservoirs. Very slow leakage from CO<sub>2</sub> sequestered in deep brine reservoirs poses no immediate threat to public health and safety, but does threaten to undo the beneficial effect of CO<sub>2</sub> sequestration on global warming. Very slow leakage could also result in the contamination of fresh water aquifers. Catastrophic leakage of CO<sub>2</sub> (though extremely unlikely) could threaten public

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health and safety. In addition to CO<sub>2</sub> leakage, large-scale CO<sub>2</sub> sequestration in brine reservoirs could displace brines or brackish water into fresh water. These risks, even if statistically minute, have rightfully drawn attention to the importance of developing an appropriate regulatory framework for geologic sequestration that directly takes on the leakage issue. With that in mind, this article focuses on the following question: What scientific and engineering studies will likely be required for CO<sub>2</sub> sequestration in brine reservoirs?

## Site Selection and Evaluation

### Regional Evaluation of Alternative Sites

Site selection for a carbon sequestration project should be based on a regional evaluation of alternative sites to demonstrate that the proposed storage site is the best available, given all constraints. Selected sites should have sufficient injectivity to enable a cost-effective injection plan; the capacity to store the anticipated volume of CO<sub>2</sub>; a natural containment system or seal capable of retaining CO<sub>2</sub> for time scales of 1000 years; and the existence of laterally extensive sealing formations that can ensure long-term containment. In the future, governments may take a proactive role in predefining and characterizing the best regional brine reservoirs for CO<sub>2</sub> sequestration.

### Geological Characterization

Site characterization should focus on three key issues: sustainable injectivity, capacity, and the effectiveness of containment. Injectivity is the rate CO<sub>2</sub> can be pumped into the reservoir, which is affected by nature of the reservoir rock (i.e., porosity, permeability, natural fractures), formation damage caused by drilling and completion fluids, and injection pressure. Capacity assessment is based on not only the volume and structure of the reservoir, but also its heterogeneity, channelization of CO<sub>2</sub> flow (i.e., sweep efficiency), and constraints on maximum injection pressure from geomechanics. Confinement requires a laterally extensive seal rock (or cap rock) that prevents buoyant CO<sub>2</sub> from flowing upward into aquifers containing underground sources of drinking water (USDWs).

The minimal requirements for an adequate reservoir characterization include:

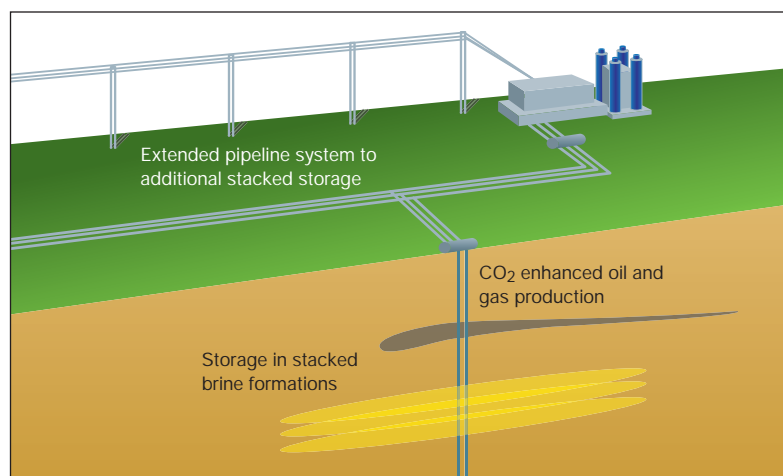
1. A basic static geological model of the reservoir, including stratigraphic correlations, structural cross-sections, a model for porosity, and permeability variation in the reservoir based on well log data extrapolated by use sedimentary facies interpretations and/or three-dimensional seismic data. Particular attention should be paid to the nature and location of faults and existing wells that penetrate the primary seal and could potentially act as conduits for CO<sub>2</sub> leakage.
2. A dynamic reservoir model or flow simulation using a multiphase flow simulator (including reasonable estimates for residual saturation) to predict the nature and extent of the CO<sub>2</sub> plume and its associated pressure anomaly in the brine.

Important issues during the site screening and selection process for CO<sub>2</sub> storage include storage capacity and injectivity of the brine reservoir; integrity of the containment zone, particularly the integrity of the top (or overlying) seal; and potential leakage pathways and the possible impacts of leakage of CO<sub>2</sub> from these pathways, including locating all abandoned and operating wells within the projected zone of anomalous pressure.

The model regulations published by the Interstate Oil and Gas Compact Commission (IOGCC)<sup>1</sup> state that the site characterization of a CO<sub>2</sub> storage reservoir should include a description of mechanisms of geologic confinement (i.e., rock properties, regional pressure gradients, structural features, and absorption characteristics) and the capability of the confinement system to prevent migration of CO<sub>2</sub> beyond the proposed storage reservoir (see "State-Based Developments in Regulating CO<sub>2</sub> Sequestration" by Ian Duncan, J.P. Nicot, and Scott Anderson on page 12).

### Risk Assessment

Risk assessment should focus on potential negative outcomes from the proposed sequestration project. The nature and magnitude of these potential adverse outcomes should play a key role in approving a permit and for approving the monitoring program. Key factors that should be considered in the risk characterization include the composition of the injected CO<sub>2</sub>; the nature and location of potential leakage pathways relative to the location of risk receptors; the potential impact on health and public safety, sensitive ecologies, endangered species, and migratory bird nesting areas; the quality of containment (particularly the quality of the seal) and the number (and characteristics) of well penetrations through the seal within the projected area of the CO<sub>2</sub> plume and its associated zone of anomalously high pressure; the capacity of the site relative to the proposed injection volume (paying particular attention to the percentage of CO<sub>2</sub> that modeling shows will be immobile by the time of closure of the project); and the percentage of the maximum allowable injection pressure proposed for project injection program. Once the key risks and leakage



Model for stacked storage in the Gulf Coast.

Source: [www.gulfcoastcarbon.com](http://www.gulfcoastcarbon.com)

scenarios have been identified, an attempt should be made to quantitatively assess their likelihood. It is important that at this stage risk assessment involve stakeholder input. Transparent interactions with the local community at this stage can avoid problems later. The risk assessment should have sufficient resolution and precision that the approach needed for monitoring is clear.

## Requirements for Initiation of Site Operations

### Injection and Pressure Management Plan

Pressure management during injection is key to minimizing the risk of CO<sub>2</sub> leakage. A careful, reliable approach to pressure management, consistent with sound engineering and scientific principle, should be a requirement of any regulatory system. The main concerns related to the pressures attained in CO<sub>2</sub> injection are that fluid pressures will get high enough to either reactivate existing faults or to create new faults or fractures underground. The fluid pressures necessary to reactivate faults and to create new faults depend on the state of stress in the rock prior to injection, the mechanical strength of the reservoir and cap rocks, and their poroelastic character. These complexities mean that no simple set of prescriptive pressure limits can adequately address these issues.

### MMV Plan

An adequate monitoring, modeling, and verification (MMV) plan to establish risk and to project leak rates both pre- and post-project closure is essential. A key part of any CO<sub>2</sub> sequestration permit requirement is an effective and accurate approach to monitoring. Monitoring should focus on protecting natural resources (particularly groundwater) and ensuring the health and safety of the local population. A wide range of approaches to monitoring have been used in pilot projects in the United States and elsewhere. For example, the Bureau of Economic Geology's Frio Pilot Injection Project (2004–2006) near Houston, TX, used four types of monitoring:

1. Geochemical techniques included sampling of (1) deep subsurface brines; (2) shallow groundwater aquifers; and (3) near surface groundwater.
2. Hydrological techniques based on integrating measurement of pressure and flow-rate with multiphase flow simulation.
3. Geophysical monitoring techniques included: (1) use of a monitoring well down-the-well a neutron probe to directly estimate the CO<sub>2</sub> saturation inside the plume; (2) vertical seismic profiling; and (3) inter-well seismic tomography.
4. Surface-based technologies included measurement of soil gas flux of CO<sub>2</sub> and soil gas chemistry.

One important lesson learned during the Frio project was the critical importance of conducting computer simulations both before and during the injection to aid in design of the monitoring program. Conducting a range

of simulations prior to initiation of injection can help establish the expected magnitude of change in key parameters such as the saturation of CO<sub>2</sub>, the state of stress and fluid pressure in the reservoir, the temperature distribution within the reservoir, and the variation of water chemistry within the reservoir, particularly the pH.

A carefully designed monitoring program will provide information that can be used to refine the computer simulations of CO<sub>2</sub> flow in the reservoir.

Specific monitoring strategies should be developed for each of the four life-cycle phases of a subsurface storage project: pre-operation, operation, closure, and post-closure phases.

**Pre-Operation Phase.** The period of reservoir characterization, establishing a baseline for monitoring measurements. During this phase, the physical and chemical parameters to be monitored are identified and the expected range in magnitude of these parameters over the life of the project is estimated. Based on these estimates, appropriate monitoring systems can be selected and spatial and temporal measurement strategies developed.

**Operation Phase.** The period of active injection. The most extensive monitoring phase in which monitoring focuses on the integrity of the injection, shut-in, plugged, or abandoned wells; and determining the evolving geometry of the plume of injected CO<sub>2</sub>.

**Closure Phase.** The period of monitoring after sealing of the engineered reservoir to ensure the integrity of the well closure.

**Post-Closure Phase.** The period of long-term monitoring after well closure. A limited range of monitoring, with lengthening time intervals after the reservoir has been sealed. The level of monitoring activities should be greater if CO<sub>2</sub> leakage is detected in earlier phases of the project or if there is a legal dispute, or some other problem.

Any MMV plan should

- begin with baseline measurements over the entire project prior to the initiation of CO<sub>2</sub> injection;
- be sufficient to demonstrate that the project meets all performance standards entailed in the permit;
- be sufficient to detect threats to USDWs and enable timely remediation aimed at preventing such contamination;
- enable verification of injected volumes for CO<sub>2</sub> credits;
- be risk-based in striving to detect most likely hazard and leakage;
- facilitate operation in a "learn-as-you-go" environment by providing a quantitative basis for appropriate improvements in injection strategies; and
- include an ongoing evaluation of the accuracy of the initial capacity estimates.

It is important that the regulatory framework be flexible





enough to recognize that there will be no single geochemical, geophysical, or geological approach that will be appropriate for all projects. For this reason, requirements for the nature of MMV plans in the permitting rules are best directed by expectations on performance rather than specification of technologies. For example, Washington State's proposed regulations require owners/operators of sequestration projects to develop a monitoring program that is designed to identify CO<sub>2</sub> leakage from the geologic containment system to the atmosphere, surface water, and groundwater. The monitoring program must be able to identify groundwater quality degradation in aquifers prior to degradation of any potable aquifer and must include observations in the monitoring zone(s) that can identify migration to aquifers as close stratigraphically to the geologic containment system as possible.<sup>2</sup> Again, this regulation is formed as a series of expectations or performance standards rather than a set of specifications.

### Remediation Plan

The main focus of a remediation plan should be to protect groundwater resources. The greatest need for remediation if CO<sub>2</sub> leaks into USDWs may be created by heavy metals (e.g., Fe, Mn, Pb, As) that are mobilized by low-pH fluids. Approaches to remediation might include a pump-and-treat approach; treatment barriers for the removal of acid mobilized trace metals; containing the plume by manipulating pressure gradients in the aquifer to constrain the movement of contaminated water; and removing accumulations of CO<sub>2</sub> gas in groundwater by drilling wells through the accumulations and producing CO<sub>2</sub>.

Under Washington State's proposed regulations, each plan is required to identify trigger thresholds that, if exceeded, will instigate corrective action. The regulations suggest that mitigation and remediation plans should address responses to the failure of the geologic containment system. The areas for concern for remediative action are listed in the draft regulations as degradation of water quality outside the geologic containment system; release of CO<sub>2</sub> to the atmosphere; or any other outcome that poses an unacceptable risk to public health or the environment. The regulations outline possible remediative action as conducting well repairs; reducing injection pressure, reservoir, or formation pressure; creating a pressure barrier through increased pressure above geologic containment system; the interception, recovery, and re-injection of CO<sub>2</sub>; and the removal of injected materials.

### Summary

To have a significant impact on decreasing atmospheric CO<sub>2</sub> levels, geologic sequestration in deep brine reservoirs will have to occur on a very large scale. For example, the Gulf Coast region of the United States could ultimately involve tens if not hundreds of storage sites with injection projects creating CO<sub>2</sub> plumes with a cumulative surface area amounting to hundreds of square kilometers. The scale of individual injection projects is likely to be as large as or larger than any fluid injection projects previously permitted under

the existing U.S. Environmental Protection Agency's Underground Injection Control (UIC) Program. In addition, CO<sub>2</sub> is more buoyant (and therefore more upwardly mobile) than other fluids regulated by the UIC Program. All these factors combined lead us to the conclusion that the regulatory framework for geologic sequestration in deep brine reservoirs should be comprehensive and take into consideration concepts and approaches that significantly extend the scope of the current UIC framework.

Any regulatory framework for CO<sub>2</sub> sequestration should pay careful attention to relative risks. A key factor should be both the severity and probability of leakage and the scale of the potential impact on the local residents and ecology (e.g., the regulatory approach to permitting a 15-million ton/yr injection in the vicinity of a major metropolitan area vs. a similar injection in an area with very sparse population and very low biological diversity). The risk profile of large CO<sub>2</sub> injection projects differ from contaminated water injections due to the buoyancy of CO<sub>2</sub>. As a result, the decades of UIC experience in permitting and monitoring such injection projects gives us limited insights into the behavior of large CO<sub>2</sub> plumes. Numerical simulation should be an important tool in identifying potential risks.

Comprehensive education and training of regulatory agency staff will be a prerequisite to effective implementation of any performance-based regulatory regime. Geologic CO<sub>2</sub> sequestration is a new technology that justifies and, arguably, requires a new approach to regulation and permitting. Development of a regulatory framework for geologic CO<sub>2</sub> sequestration provides an opportunity to implement new approaches to permitting and to enable improved accountability. em

### References

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### Further Reading

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