PROGRAM facts

Sequestration

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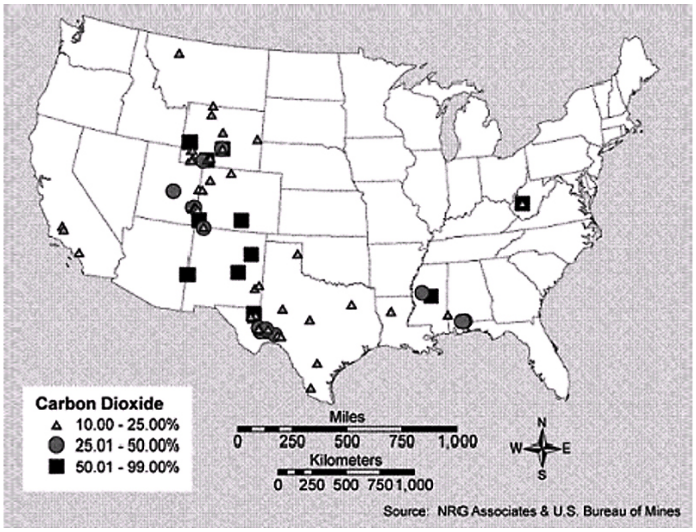
U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

RISK ASSESSMENT FOR LONG-TERM STORAGE OF CO_2 IN GEOLOGIC FORMATIONS

The aim of geologic sequestration is to identify and properly utilize formations that will store CO_2 securely — in much the same way as underground formations have stored oil and natural gas for hundreds of millions of years. Yet CO_2 in an underground formation is buoyant and exhibits low viscosity. If unconstrained, it will flow upwards through rock pores and channels until it reaches the atmosphere. Thus there is a fundamental risk of CO_2 escape, particularly low seepage of CO_2 from a storage reservoir. Although highly improbable, large releases of CO_2 are theoretically possible and risk assessment approaches must address this remote possibility. Large scale releases that escape via a fast pathway may damage trees and other plants via elevated concentrations of CO_2 in soil, present asphyxiation hazards through pooling of CO_2 in low-lying areas and confined spaces, and possibly be harmful to drinking water supplies. Risk assessment must be designed to account for all of these possibilities.

The United States Department of Energy's Office of Fossil Energy has developed a clear vision for the safe and environmentally sound operation and management of geologic CO_2 storage facilities over the long term. This vision is rooted in a science-based technology development effort aimed at fully understanding and effectively managing the risks associated with CO_2 storage. The Department's Sequestration Program has a risk assessment R&D component called "Monitoring, Mitigation, and Verification (MM&V). MM&V is defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is stored in a



Scientists are studying natural underground deposits of CO_2 to better understand factors affecting storage permanence. The map above shows the locations of geologic formations in the United States that have contained natural deposits of CO_2 for millions of years.

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way that is permanent and not harmful to the host ecosystem. Mitigation capability will provide a response to CO_2 leakage or ecological damage in the unlikely event that it should occur. It is likely that all large scale sequestration deployments will have a mitigation plan in place before operations begin.

MM&V standards and protocols are being developed to ensure permanence, to ensure that the risk of any leakage is minimal, and should it occur, leakage can be safely mitigated. MM&V can be broken into three broad categories: Subsurface, Soils, and Above-ground. Subsurface MM&V involves tracking the fate of the CO_2 within the geologic formations underlying the earth and possible migration to the surface. This area also encompasses developments to mitigate leakage, should it occur. Soils MM&V involves tracking carbon uptake and storage in the first several feet of topsoil and tracking potential leakage pathways into the atmosphere from the underlying geologic formation. This area is especially challenging due to the difficulty in detecting small changes in concentration above the background emissions (~370 ppm) that already exist in the atmosphere. Aboveground MM&V is specific to terrestrial sequestration and involves quantification of the above-ground carbon stored in vegetation. The Sequestration Program is developing instrumentation, detailed computer models and protocols for each of these areas.

The aim of geologic sequestration is to identify and properly utilize formations that will store CO_2 securely.

Risk management efforts are being developed to encompass the life of a CO_2 storage project as described below:

Pre-injection. A clear picture of the target formation prior to injection (i.e, a baseline) is developed using core samples, fluid samples, and seismic evaluations. Optimal strategies for CO_2 injection are identified, and the flow of injected CO_2 is modeled over long time frames. As a part of the pre-injection assessment, developers consider different CO_2 leakage scenarios. Categories of leakage events include: (1) cap rock or seal failure through capillary failure, faults, or fractures; (2) CO_2 bypass of the cap rock via spillage or migration outside of the target reservoir; and (3) wellbore failure. Particularly in depleting gas or oil formations where many wells have been drilled and abandoned, wellbore failure may represent the highest CO_2 leakage risk. Both the amount of CO_2 leakage and the path that it travels are assessed. In preferred storage formations, a significant portion of any CO_2 leakage becomes trapped in overlying formations. The viability of a system will be judged based on the results of this pre-injection evaluation and only projects that promise very low risk of leakage will be pursued.

Operation. Once CO_2 injection begins, the transport of CO_2 into the formation will be monitored closely using time-lapse seismic, fluid samples from observation wells, and other data. The monitoring results will be used to both detect any CO_2 leaks or unexpected flow patterns and also to ground truth the reservoir models and hone their predictive capability.

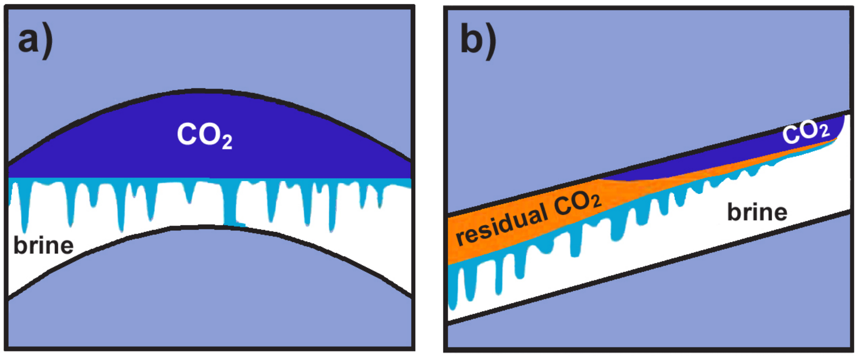
Closure. CO_2 monitoring will be continued after injection is completed until such a time as it is shown that the stored CO_2 is stable. This may be five to ten years after injection has ceased. A combination of reservoir modeling and CO_2 monitoring snapshots will enable verification of long-term CO_2 storage permanence.

Post-closure. Protocols for long-term monitoring are currently under development. Long term monitoring will likely include a complete set of characterization and monitoring data which will be invaluable to ensure permanent storage of the sequestered CO_2.

Trapping Mechanisms and Mitigation of Leakage

Scientists have studied the behavior of CO_2 in underground formations and are developing methods for proactively minimizing the risk of CO_2 leakage. This work centers on an improved understanding of the mechanisms for CO_2 storage. The following is a list of key mechanisms.

- ***Cap rock trapping.*** A layer of low-porosity rock serves as a barrier to upward migration of CO_2.
- ***Pore trapping.*** Through capillary and surface tension forces, droplets of CO_2 become affixed into a rock pore space.
- ***Dissolution in brine solution.*** CO_2 is soluble in brine. At 1,900 psi and 30,000 ppm total dissolved solids, one gallon of brine holds 0.4 lbs CO_2.
- ***Mineralization.*** Once in solution CO_2 will react, albeit at a slow rate, with dissolved minerals to form solid mineral carbonates.
- ***Adsorption.*** Unmineable coal seams offer a unique storage mechanism as CO_2 molecules are adsorbed onto the surface of the coal. Adsorbed CO_2 exists as a condensed liquid and is immobile as long as the formation pressure is maintained.



An understanding of CO_2 storage mechanisms will enable CO_2 injection field practices that enhance storage permanence. The figure above, taken from Stanford University, Global Climate Energy Project, June 2004, "Technical Report 2003-2004" <u>http://gcep.stanford.edu/pdfs/technical_report_2004.pdf</u>, is a schematic of CO_2 dissolution in two aquifers. The mobile CO_2 gas phase is dark blue, the dissolved aqueous CO_2 is light blue, residual CO_2 is orange, and the brine is not colored. a) CO_2 gas is held under a structural trap. Dissolution of CO_2 into the brine reduces the CO_2 gas phase volume. b) The CO_2 gas phase migrates along the top of a sloping aquifer, and leaves behind a region of residual CO_2 (i.e., CO2 trapped in pore space). In this case both dissolution and residual CO_2 saturation contribute to the decrease of the mobile CO_2 phase.

CO_2 that is trapped in pores, dissolved in brine, and mineralized will remain immobile and permanently sequestered. Research is aimed at developing injection techniques that maximize secure CO_2 storage via the trapping mechanisms described above. If CO_2 leakage occurs, steps can be taken to arrest the flow of CO_2 or mitigate negative effects. Examples include, lowering the pressure within the CO_2 storage formation to reduce the driving force for CO_2 flow and possibly reverse faulting or fracturing; increasing the pressure in the formation into which CO_2 is leaking, forming a pressure plug; intercepting the CO_2 leakage path; and plugging the region where leakage is occurring with low permeability materials. Additionally, research is underway to develop mitigation techniques that involved "controlled mineral carbonation" or "controlled formation of biofilms" that could be used to plug seepage/leakage points in a geologic formation.

Research is underway to develop mitigation techniques that could be used to plug seepage/ leakage points in a geologic formation.

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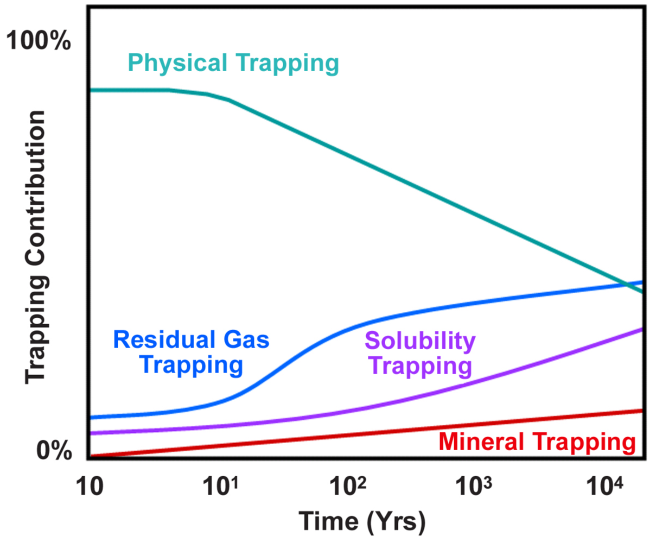
Important for consideration of long term CO_2 storage permanence is the understanding that CO_2 stored in a porous rock formation will tend to become more secure over time (100s of years) as these trapping mechanisms become more predominant, such as CO_2 becomes dissolved into brine or fixed into a mineral carbonate solid. Brine-containing dissolved CO_2 is slightly denser than brine without CO_2 and CO_2-saturated brine will migrate downward in a reservoir, displacing the lighter brine below it. This density effect causes a natural convection that brings the free CO_2 in contact with unsaturated brine. Directionally, mineralization will remove CO_2 from solution and drive further dissolution of CO_2, but the reactions are very slow and less understood.

In summary, the risks of long-term CO_2 storage in geologic formations can be addressed and managed as research provides improved rigorous pre-injection site characterization, close monitoring and accurate modeling of the fate and transport of injected CO_2, field practices to enhance the permanence of CO_2 storage, and capability to reliably detect and mitigate CO_2 leaks in the unlikely even that they occur.



Stable CO_2 stotage mechanisms dominate underground storage over long time frames, providing the promise of secure storage. Source; Sally Benson, 2004, plenary presentation GHGT-7