The Hydrology of Geologic Sequestration

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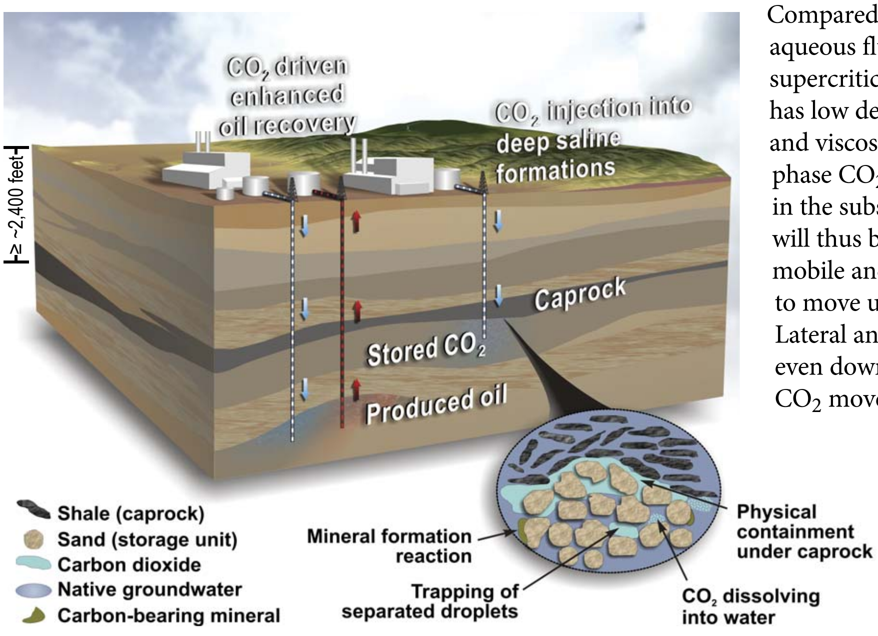
Although somewhat controversial, geologic sequestration of carbon dioxide (CO_2) is poised to become a key component of the global response to climate change. In the United States, geologic sequestration is now recognized as the only feasible approach to continued dependence on coal while mitigating CO_2 emissions. Understandably, the popularity of geologic sequestration has increased among researchers, industry, and policy advocates in the last several years, as a U.S. Department of Energy-directed research program has moved forward and the U.S. Environmental Protection Agency has begun to build a regulatory approach for these projects. However, concerns remain that geologic sequestration projects may pose a threat to groundwater and in the long-term may prove ineffective for isolating CO_2 from the atmosphere.

CO_2 has been injected underground for over 30 years to enhance oil and gas recovery, so much of the necessary infrastructure, technology, and expertise already exist. However, the gargantuan volumes of CO_2 that will have to be injected in order to mitigate anthropogenic atmospheric emissions (see sidebar) dwarf the scale of existing projects and pose several unique challenges. CO_2 injection for geologic sequestration will likely be more closely regulated than enhanced oil and gas recovery projects, requiring substantial characterization and monitoring of the site. For example, proposed EPA regulations under the Underground Injection Control (UIC) program require the demonstration of site injectivity and long-term storage effectiveness, as well as delineation of the three-dimensional area of impact, through an iterative approach of site characterization, multiphase fluid modeling, and monitoring (EPA, 2008).

Trapping Mechanisms

CO_2 will in most cases be injected underground as a supercritical fluid—a phase state exhibiting properties of both a liquid and vapor. The injected CO_2 remains a supercritical fluid at depths greater than around 2,600 feet due to elevated temperature and pressure. At lesser depths, CO_2 exists in either liquid or gaseous form. Maintaining CO_2 as a supercritical fluid is ideal, as this results in the maximum storage of CO_2 per volume of porous media. CO_2 injectate may contain impurities, including mercury, hydrogen sulfide, and sulfur dioxide. At sufficient concentrations, these impurities may significantly alter the physico-chemical properties of the injectate.



Schematic diagram illustrating the geologic sequestration of CO_2.

Compared to aqueous fluids, supercritical CO_2 has low density and viscosity. Pure-phase CO_2 plumes in the subsurface will thus be highly mobile and tend to move upward. Lateral and even downward CO_2 movement is also expected in response to pressure differentials between the injectate and native fluids.

Several subsurface processes, collectively referred to as trapping mechanisms, may promote long-term sequestration of CO_2. These include physical containment beneath low-permeability geologic strata (caprock); trapping as a residual, non-mobile fluid phase in formation pore space (capillary trapping); dissolution of CO_2 into native groundwater; precipitation of carbon-bearing minerals (mineralization), and sorption of CO_2 onto mineral surfaces (Metz and others, 2005). In the short term, physical containment beneath caprock is essential for isolating CO_2 from overlying aquifers and the atmosphere. Over longer periods, a combination of these trapping mechanisms is expected to permanently sequester the injected CO_2.

There is some risk that injected CO_2 could escape the target storage formation and move upward toward drinking-water aquifers and the atmosphere. Abandoned well bores that penetrate the storage formation are recognized as the most likely leakage pathway for CO_2. However, CO_2 may also migrate through faults or fractures in the caprock system. Saripalli and McGrail (2002) demonstrated that an accumulated CO_2 thickness of approximately 60 feet beneath the caprock is sufficient to cause leakage into caprock microcracks or crevices 2 microns in diameter.

Project Siting

Geologic sequestration is envisioned to take place primarily in deep saline formations and oil reservoirs. More than 90 percent of storage capacity is projected to be in saline formations (Dooley and others, 2006), which are predominantly sandstone and carbonate strata containing groundwater unsuitable for drinking water (>10,000 milligrams per liter total dissolved solids). Other geologic formations of interest for sequestration include natural-gas reservoirs, unmineable coal seams, saline-filled basalts, salt caverns, and organic shales.

Although they account for less than 10 percent of potential storage capacity, oil reservoirs may be the focus of early geologic sequestration projects. Actively produced fields and so-called "depleted" reservoirs are both of interest for CO_2 storage, and some well fields may already have the required infrastructure for CO_2 injection. Oil reservoirs are also generally better characterized than deep saline formations, and are overlain by caprock sufficient to restrict the upward movement of oil and gas.

Regardless of the type of formation, a promising geologic sequestration site must have a target formation with sufficient injectivity to receive the amounts of CO_2 to be injected and be overlain by at least one caprock layer that will restrict upward flow of CO_2. The caprock structure is also important. For instance, if the strata dip too steeply, CO_2 could migrate laterally along the target formation/caprock interface. Anticlinal formations are ideal physical traps for geologic sequestration sites.

Can We Make a Difference?

CO_2 is released to the atmosphere by many sources, but most estimates are that around 95 percent comes from natural processes, primarily the decay of organic material. How, then, can the small fraction generated by humans make any difference? Most scientists think that until recently, the rate of CO_2 release was balanced by its absorption, primarily by plants and the ocean, keeping the atmospheric concentration relatively stable. But anthropogenic sources have upset this balance, resulting in steadily increasing concentrations that affect global climate. Thus, the focus on reducing these sources is an attempt to regain the balance. Some figures:

- Global CO_2 anthropogenic emissions, 2006: 29.2 billion metric tons (bmt) (EIA, 2009)
- U.S. CO_2 anthropogenic emissions, 2006: 6 bmt (EIA, 2009)
- U.S. CO_2 emissions from nontransportation (potentially capturable) sources, 2006: 4 bmt (EIA, 2009)
- More than 8,100 large CO_2 point sources (potentially capturable) worldwide account for more than 60 percent of all anthropogenic CO_2 emissions; they are predominantly fossil-fueled electric power plants (GTSP, 2006).
- The cumulative amount of CO_2 that would need to be stored over the next century to to achieve atmospheric CO_2 stabilization is estimated to be 20 bmt in the United States and more than 100 bmt worldwide—this would require increasing current sequestration deployment by three to four orders of magnitude (GTSP, 2006).

Based on these figures, if all 8,100 large sources were captured at 80% efficiency, that would represent less than 14% of the amount needed to achieve stabilization.

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Site Monitoring

Monitoring is an essential component of the management of a geologic sequestration site, providing data related to the effectiveness of CO_2 storage as well as any risks to drinking-water aquifers and the atmosphere. Monitoring programs at geologic sequestration sites will be designed to track the evolution of injected CO_2 and any mobilized constituents, as well as formation pressure. A variety of techniques, developed for use at oil and gas well fields and contaminated sites, are available to monitor these parameters.

Monitoring for changes in pressure, aqueous geochemistry, salinity, or the presence of drinking-water contaminants will require direct access to the target formation and overlying strata via monitoring wells. However, installation of monitoring wells will be a relatively expensive part of these projects, and there is some risk that the monitoring wells themselves could become conduits for fluid movement. Therefore, a limited number of monitoring wells will likely be placed strategically in areas predicted to overlie the eventual CO_2 plume and area of elevated pressure.

Geophysical techniques have been used to monitor changes in CO_2 saturation at geologic sequestration projects (such as Doughty and others, 2008, and Bickle and others, 2007), including seismic and electromagnetic surveys. These techniques have been employed both at the ground surface and down-hole, and are capable of providing monitoring data over much larger areas than could reasonably be accessed with monitoring wells. Although geophysical methods in general will be a key component of monitoring geologic sequestration sites, no single technique is applicable to all sites. An evaluation will need to be conducted for each geologic sequestration site to determine the appropriate suite of monitoring technologies to be used.

Because leakage of CO_2 to the atmosphere and into buildings is of concern, it is likely that surface air and soil gas will be monitored in the vicinity of geologic sequestration projects. Monitoring at the surface and in the vadose zone can detect and quantify leakage of CO_2 from the target formation, and will also indicate if CO_2 has leaked into drinking-water aquifers. Surface monitoring for CO_2 may be accomplished using an infrared gas analyzer attached to an eddy covariance tower. Soil gas may be sampled using vapor monitoring wells, and flux of CO_2 from the soil to surface air can be measured using soil-flux chambers. In each of these applications, it is important to characterize natural variability in CO_2 concentrations for comparison to monitoring data, and to collect sufficient spatial data to account for this variability.

Computational Modeling

CO_2 flow through the subsurface is extremely complex, involving multiphase fluid flow, CO_2 dissolution into groundwater, mineral precipitation and dissolution, and in some cases, geomechanical impacts. The fate and transport of CO_2 will be very site-specific, depending on geological structure and mineralogy. The transport properties of CO_2 also vary greatly with temperature and pressure. For these reasons, state-of-the-art computational modeling has been advocated as an integral tool for

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managing geologic sequestration projects and understanding associated risks. Proposed U.S. EPA regulations require computational modeling results to be provided in permit applications, and ongoing model calibration to monitoring data during the lifetime of the project.

Existing model frameworks developed for multiphase flow and reactive transport problems can be applied to modeling the injection of CO_2. Modeling CO_2 injection and sequestration poses several challenges, however, such as the need to properly characterize CO_2 transport properties across a large range of temperatures and pressures, and to adequately characterize the vast subsurface areas considered for injection.

Several research studies published in the last several years have modeled the subsurface injection of CO_2 for geologic sequestration (Schnaar and Digiulio, 2009). The most comprehensive numerical models reported in peer-reviewed literature are capable of replicating formation heterogeneity using statistical routines, CO_2 migration through artificial penetrations, hysteretic relative permeability curves and residual CO_2 trapping, and mineral precipitation and dissolution reactions and subsequent changes in formation porosity and permeability. Somewhat simpler analytical and semi-analytical models have been developed for initial site screening.

A limited number of studies (such as Doughty and others, 2008) have compared initial modeling predictions to monitoring data collected from early geologic sequestration pilot projects. These studies have demonstrated the necessity of calibrating models to monitoring data whenever feasible. For example, CO_2 is prone to traveling through high-permeability channels that may not have been identified during initial site characterization and included in the model grid. The most comprehensive understanding of the migration of CO_2 and mobilized constituents will be obtained through an integrated site characterization, monitoring, and modeling approach. ■

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