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Underground Carbon Dioxide Sequestration: Frequently Asked Questions

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Summary

This report answers frequently asked questions about the geologic sequestration of carbon dioxide (CO_2). The questions are broadly representative of typical inquiries regarding the process and mechanics of storing CO_2 underground, how much might be stored, and what might happen to CO_2 once it is injected underground. Geologic sequestration is one step in a process termed *carbon capture and sequestration*, or CCS. Following capture and transportation, CO_2 would be injected into geologic formations that have suitable volume, or pore space, to retain large quantities of the captured gas. Currently, the most promising reservoirs for storing CO_2 are oil and gas fields, deep saline reservoirs, and unmineable coal seams.

Preventing CO_2 from escaping a geologic formation would require careful reservoir characterization in advance of the injection phase of a project, as well as monitoring during and after CO_2 injection. Knowledge gained from over 30 years of injecting CO_2 underground to enhance oil recovery would be applied to storing CO_2 for CCS purposes. In addition, a variety of techniques are currently available for monitoring leaks from a reservoir, and knowledge gained from field testing may lead to improved or new technologies for detecting CO_2 leakage. Given the complexity of most geologic reservoirs, and the potentially huge volumes of CO_2 that may be injected, risk of some CO_2 leakage over time may never completely be eliminated. Even with careful characterization of a potential reservoir and monitoring of CO_2 migration during and after injection, the detailed fate of CO_2 stored underground may not be thoroughly understood.

The U.S. Department of Energy (DOE) has made an assessment of the potential sequestration capacity across the United States and parts of Canada and has determined that there exists sufficient volume to store approximately 600 years of CO_2 produced from total U.S. fossil fuel emissions (at current rates). The sequestration capacity estimate is primarily drawn from existing information on the geology and depends on several assumptions about geologic sequestration mechanisms. How the DOE estimate will compare to the actual sequestration capacity will depend, in part, on the results from a series of seven large-scale CO_2 injection experiments to be conducted by seven regional carbon sequestration partnerships across the United States. DOE has awarded funds totaling $456.7 million for the seven injection tests, which are scheduled to begin in 2009.

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Many people are unfamiliar with the concept of sequestering carbon—most likely in the form of carbon dioxide (CO_2)—underground in geologic reservoirs. This report answers questions broadly representative of typical queries about why, where, and how CO_2 may be stored underground, as well as how much CO_2 might be stored. In addition, this report answers several questions about what might happen if CO_2 escapes from underground storage. The term *carbon sequestratio*n includes carbon capture and sequestration (CCS), but it is also used to refer to the biological uptake of carbon from the atmosphere through photosynthesis. This report does not discuss biological sequestration.[1] Capturing and storing CO_2 in the oceans is another possible option for carbon sequestration, although currently it is not deemed as promising as underground sequestration.[2]

The only operating major commercial project dedicated solely to CO_2 sequestration in a geologic reservoir today is the Sleipner Project, located approximately 150 miles off the coast of Norway in the North Sea. Two other operating commercial-scale CO_2 sequestration ventures—the Weyburn Project in south central Canada and the In Salah Project in Algeria—use the injected CO_2 to help recover oil and natural gas, respectively. In the United States, the oil and gas industry injects approximately 48 million metric tons of CO_2 each year for enhanced oil recovery (EOR), but permanently sequestering CO_2 has not been a focus of these EOR activities to date. The U.S. Department of Energy (DOE) has sponsored carbon sequestration research and development since 1997, and is embarking on a third phase of its geologic carbon sequestration research and development program. DOE is planning seven large-scale CO_2 sequestration injection experiments beginning in 2009.

Background

What Is Sequestration?

Sequestration is a final step in a carbon capture and sequestration (CCS) process: capturing carbon—usually carbon dioxide (CO_2)—at its source and storing it instead of releasing it to the atmosphere. The first step in CCS is to capture CO_2 at the source and produce a concentrated stream for transport and sequestration. Currently, three main approaches are available to capture CO_2 from large-scale industrial facilities, such as cement plants or fossil fuel power plants: (1) post-combustion capture, (2) pre-combustion capture, and (3) oxy-fuel combustion capture. Transportation of captured CO_2 is the second step in CCS. Pipelines are currently the most common method for transporting CO_2 in the United States, and would likely be used for CCS unless the CO_2 could be stored directly beneath the emission source. Injecting CO_2 underground into a geologic formation is the likely third step in the process, where the carbon would remain out of contact with the atmosphere.

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[1] For information on biological uptake of carbon, see CRS Report RS22964, *Measuring and Monitoring Carbon in the Agricultural and Forestry Sectors*, by Ross W. Gorte and Renée Johnson.

[2] This report only discusses underground sequestration of CO_2. For a broader discussion of CCS, see CRS Report RL33801, *Carbon Capture and Sequestration (CCS)*, by Peter Folger; CRS Report RL34621, *Capturing CO_2 from Coal-Fired Power Plants: Challenges for a Comprehensive Strategy*, by Larry Parker, Peter Folger, and Deborah D. Stine; and CRS Report RL33971, *Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues*, by Paul W. Parfomak and Peter Folger.

Why Is CCS of Interest in the Debate over Global Warming?

CCS is attracting interest as a measure for mitigating global climate change because large amounts of CO_2 emitted from fossil fuel use and other industrial processes such as cement manufacturing could potentially be captured and stored underground. Most scientists have concluded that greenhouse gases (GHG) emitted by humans are influencing the global climate. Although natural events such as volcanic eruptions or variability in the sun's energy output also contribute to climate variability, scientists cannot explain the climate changes in the past few decades without including the effects of elevated GHG concentrations from fossil fuel use, land clearing, and industrial and agricultural emissions.[3] Of all the GHGs emitted by humans, CO_2 is considered most important, in part because large volumes of the gas are released to the atmosphere each year. A large fraction of CO_2 emitted by human activities remains in the atmosphere; in fact, CO_2 concentrations in the atmosphere have increased by one-third since the Industrial Revolution, from about 280 parts per million (ppm) in 1750 to over 380 ppm today.[4] In the United States, fossil fuel combustion accounts for 94% of all CO_2 emissions. One-third of U.S. CO_2 emissions come from fossil-fueled electricity generating power plants. These plants may be the most likely initial candidates for CCS because they are predominantly large, single-point sources of emissions. An assumption inherent in CCS is that CO_2 will be stored underground in sufficient quantity, and for sufficient time, to significantly ameliorate impacts of GHG-influenced climate change.

Storing CO_2 Underground

What Is a Geologic Formation and How Would It Sequester CO_2?

CO_2 would need to be stored underground in *geologic formations*[5] with characteristics that would trap large volumes of CO_2 and not allow significant leakage from the formation. Some of these characteristics include open spaces, known as *porosity;* sufficient interconnectivity between the open spaces so that CO_2 can flow laterally or migrate within the formation, known as *permeability*; and a layer or boundary that is impermeable to upward flow so that CO_2 is trapped underground. Many types of geologic formations have these features, such as sandstones and limestones, and some geologic formations are tens to hundreds of feet thick and may extend laterally for miles. Geologic formations that are potential CO_2 reservoirs may be analogous to reservoirs that trap oil and gas. Oil and gas can be found in sandstones, limestones, and other permeable formations, trapped for millions of years until tapped by wells drilled from the surface to extract the hydrocarbons. An overlying layer of low permeability, commonly referred to as a *caprock* or *geologic seal* (such as shales or siltstones), prevents oil and gas from migrating out of the permeable formation. Similarly, a caprock or geologic seal would be expected to trap CO_2 and prevent it from leaking upwards.

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[3] For more information on the science and policy of climate change, see CRS Report RL34513, *Climate Change: Current Issues and Policy Tools*, by Jane A. Leggett.

[4] For more information on why CO_2 concentrations are increasing in the atmosphere, see CRS Report RL34059, *The Carbon Cycle: Implications for Climate Change and Congress*, by Peter Folger.

[5] A geologic formation refers to a body of rock, igneous, metamorphic, or sedimentary, that can be identified by its geologic characteristics (e.g., types of minerals, age, chemical composition) and can be mapped at the Earth's surface or traceable in the subsurface.

Other types of geologic formations may possess characteristics that could trap CO_2 underground. For example, coal beds are commonly porous and permeable and are viewed as potential reservoirs for storing CO_2. In addition, methane gas—which forms naturally from the coal—often remains bound to the organic molecules within the coal seam. Experiments have shown that coal also can bind CO_2 to its mineral surfaces, and the organic molecules may actually prefer to trap CO_2 instead of the naturally occurring methane. Other types of geologic formations, known as black shales, also possess this binding ability, and may be potential reservoirs for CO_2 sequestration. Shales typically have low permeability, however, which may make it difficult to inject large volumes of CO_2 at rates comparable to other types of geologic formations.

Another type of geologic formation that may be a candidate for CO_2 sequestration is known as flood basalt,[6] such as that found on the Columbia River Plateau. Large and thick formations of flood basalts occur globally, and may have favorable characteristics for CO_2 sequestration, such as high porosity and permeability. Of further interest is the capacity for the minerals in these flood basalts to chemically react with CO_2, which could result in a large-scale conversion of the gas into stable, solid minerals that would remain underground for thousands of years.

Where Would Large Amounts of CO_2 Likely Be Sequestered?

It is generally agreed that the most promising underground locations for storing CO_2 underground fall into three categories: (1) oil and gas reservoirs; (2) deep saline reservoirs[7]; and (3) unmineable coal seams. Oil and gas reservoirs and deep saline reservoirs are composed of porous and permeable geologic formations, as discussed above, whose pore space is filled either with hydrocarbons, saline water (brine), or some combination of both. Coal that is not economically mineable because the beds are not thick enough, the beds are too deep, or the structural integrity of the coal bed[8] is inadequate for mining may have the properties discussed above, making them amenable to CO_2 sequestration.

According to a U.S. Department of Energy (DOE) report,[9] at least one of each of these three types of potential CO_2 reservoirs occur across most of the United States in relative proximity to many large point sources of CO_2, such as fossil fuel power plants or cement plants. Deep saline formations are the most widespread, and have the most potential sequestration capacity compared to oil and gas reservoirs or unmineable coal seams. Oil and gas fields or unmineable coal seams, however, could produce incremental amounts of crude oil or methane with CO_2 injection, which could offset some of the costs of storing CO_2. These techniques are referred to as enhanced oil recovery (EOR) and enhanced coal bed methane recovery (ECBM). Not all power plants, cement plants, and other large, stationary CO_2 emitters are close to potential reservoirs, however.

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[6] Flood basalts are vast expanses of solidified lava that erupted over large regions in several locations around the globe. In addition to the Columbia River Plateau flood basalts, other well-known flood basalts include the Deccan Traps in India and the Siberian Traps in Russia.

[7] Sometimes the term *saline aquifer* is used in this context, which is probably a misnomer, because the saline formations being discussed for CO_2 sequestration are typically too saline for drinking or agricultural use. Shallow aquifers that are brackish might be used as drinking water or agricultural resources with some treatment, such as desalination, but such aquifers probably would not be considered as prime targets for storing CO_2.

[8] *Coal bed* and *coal seam* are interchangeable terms.

[9] U.S. Dept. of Energy, National Energy Technology Laboratory, *2008 Carbon Sequestration Atlas of the United States and Canada*, 2nd ed. (November 2009), 140 pages. Hereafter referred to as the 2008 Carbon Sequestration Atlas. See http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasII/.

Captured CO_2 from sources in New England and portions of the mid-Atlantic seaboard, for example, might have to be transported over long distances to reach a suitable sequestration site.

How Much CO_2 Can Be Sequestered Underground?

Table 1 shows estimates for CO_2 sequestration capacity in the United States and parts of Canada for the three reservoir types discussed above, according to the DOE 2008 Carbon Sequestration Atlas.

Table 1. Geological Sequestration Capacity for the United States and Parts of Canada

Reservoir type	Lower estimate of sequestration capacity ($GtCO_2$)	Upper estimate of sequestration capacity ($GtCO_2$)
Oil and gas fields[a]	138	—
Deep saline formations	3,297	12,618
Unmineable coal seams	157	178

Source: 2008 Carbon Sequestration Atlas.

Note: $GtCO_2$ equals a billion metric tons of CO_2. A metric ton is approximately 2,200 pounds.

a. According to DOE, oil and gas fields are sufficiently well-understood so that no range of values for sequestration capacity is given.

Even the lower estimates of sequestration capacity, when added together, indicate that the United States has enough potential capacity to store its total CO_2 emissions from fossil fuels for over 600 years (at the current rate of emissions).[10] Excluding CO_2 emissions from fossil fuels used for transportation, which, because of the millions of small and dispersed sources, would likely *not* be captured and stored underground, these estimates suggest the United States could store over 900 years of CO_2 emitted from sources like power plants, factories, and cement manufacturers.[11] Whether CO_2 can be economically captured, transported, and stored underground, however, remains an open question.

Can the Sequestration Capacity Estimates for CO_2 Be Confirmed?

The sequestration estimates are primarily drawn from existing information on the geology of the formations and various assumptions about the geologic sequestration mechanisms. Key considerations in the estimates include (1) how much total sequestration space is available for each type of reservoir, and (2) what is the efficiency of storing CO_2 in the available sequestration space (i.e., what fraction of the total pore space could actually be occupied by CO_2). The accuracy of the sequestration capacity estimates of the reservoirs will be tested, in part, by a series of planned experiments: large-volume injection tests whereby CO_2 is injected into a formation and its behavior monitored (discussed below). The experiments could produce results that will enable

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[10] In 2006, the United States emitted approximately 5.6 $GtCO_2$ from the combustion of fossil fuels. See http://epa.gov/climatechange/emissions/usinventoryreport.html.

[11] The estimates for potential sequestration capacity provided in the 2008 Sequestration Atlas are more than triple the estimates provided in the 2007 version of the atlas.

researchers to test their assumptions about the sequestration properties of the geologic formations.[12]

How Is CO_2 Injected Underground and How Deep Will It Be Sequestered?

In a CCS operation, after CO_2 is captured from its source, it would be compressed, transported, and injected via wells into the sequestration reservoir. Compressing CO_2 is important because it becomes denser and occupies less space with increasing pressure. The denser it becomes, the more CO_2 can be stored within the pore space of a geologic reservoir. Also, with enough pressure and at a high enough temperature, CO_2 becomes *supercritical*, and is dense like a liquid, but flows like a gas. The ability of CO_2 to disperse efficiently through the interconnected pore spaces of a geologic reservoir increases significantly if it is under enough pressure to be a supercritical fluid.

The density of CO_2 increases still further if injected deeper due to the pressure of the overlying rocks. The denser it becomes, the more likely the CO_2 may stay underground. Conversely, if CO_2 is injected at shallow depths, it may be more likely to escape the reservoir. Above a depth of 2,500 feet, the chances increase that CO_2 would tend to rise towards the surface as a buoyant gas. Thus, it is likely that oil and gas reservoirs and saline formations located deeper than 2,500 feet would be preferred over shallower geologic formations. It is also recognized that injecting CO_2 deeper increases the distance between the sequestration reservoir and fresh water aquifers—used for drinking water or agricultural purposes—that are usually located at shallower depths.

Is CO_2 Currently Stored Underground?

The petroleum industry in the United States injects approximately 48 million metric tons of CO_2 underground each year to help recover oil and gas resources (enhanced oil recovery, or EOR).[13] Injected CO_2 expands and helps drive oil that is not recovered by primary or secondary recovery towards a production well.[14] Also, the CO_2 can dissolve in the oil, making it less viscous and able to flow more easily in the geologic formation. Some of the CO_2 is trapped in the reservoir during EOR; however, a large fraction of the injected gas may be pumped to the surface with the recovered oil, where it is usually separated from the oil and reinjected.[15] Approximately 75% of the CO_2 injected for EOR in the United States comes from naturally occurring underground deposits; only about 12 million metric tons of CO_2 comes from manmade sources like fertilizer or gas-processing plants.[16] Thus, only small amounts of CO_2 produced by industrial processes are currently injected underground in EOR operations.

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[12] See the DOE National Energy Technology Laboratory FAQ Information Portal, at http://www.netl.doe.gov/technologies/carbon_seq/FAQs/project-status.html#Geologic_Field.

[13] U.S. DOE, *Carbon Sequestration Through Enhanced Oil Recovery*, National Energy Technology Laboratory (March, 2008), at http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf.

[14] Primary recovery relies on the natural pressure of the reservoir to drive the oil or gas to the production well; secondary recovery uses water or gas to produce more petroleum. EOR is known as a tertiary recovery technique. See http://www.fossil.energy.gov/programs/oilgas/eor/index.html.

[15] According to DOE, approximately 9 million metric tons of the CO_2 used for EOR, or approximately 20% of the total injected each year, remains trapped underground.

[16] U.S. DOE, *Carbon Sequestration Through Enhanced Oil Recovery*, National Energy Technology Laboratory (March, 2008).

The United States leads the world in EOR activities and the petroleum industry has over 30 years of EOR experience. Engineering techniques and knowledge acquired since the early 1970s may be directly applicable to CCS. In fact, the amount of CO_2 produced from a typical 500 megawatt coal-fired power plant—about 10,000 metric tons per day—is comparable to the daily injection rates for some EOR operations.[17] However, because the purpose of EOR is to extract oil and gas not normally recoverable, the net sequestration of CO_2 in EOR operations may be negligible, because the extracted oil and gas is burned for energy which releases CO_2 to the atmosphere. Moreover, even if all of the CO_2 used in U.S. EOR operations today remained trapped underground, it would represent a small fraction of the current U.S. emissions: fossil fuel power plants alone emit to the atmosphere nearly 50 times the EOR amount of CO_2 each year.

The only operating major commercial project dedicated to CO_2 sequestration in a geologic reservoir today is the Sleipner Project, located approximately 150 miles off the coast of Norway in the North Sea.[18] Over 2,700 metric tons of CO_2 per day—separated from natural gas at the Sleipner West Gas Field—is injected 2,600 feet below the seabed. Over the lifetime of the project, over 20 million metric tons of CO_2 are expected to be injected into the saline formation, which is sealed at the top by an extensive and thick shale layer.[19] Monitoring surveys of the injected CO_2 indicate that the gas has spread out over nearly two square miles underground without leaking upwards. Long-term simulations also suggest that over hundreds to thousands of years the CO_2 will eventually dissolve in the saline water, becoming heavier and less likely to migrate away from the reservoir.

What Are the Regulations for Geological Sequestration of CO_2?

No existing federal regulations govern the injection and storage of CO_2 for the purposes of carbon sequestration. But in July 2008 the U.S. Environmental Protection Agency (EPA) released a draft rule that would regulate CO_2 injection for the purposes of geological sequestration under the authority of the Safe Drinking Water Act, Underground Injection Control (UIC) program.[20] Under the proposal, the EPA would create a new class of injection wells (Class VI) and establish national requirements that would apply to the Class VI wells.[21] EPA accepted public comments through December 2008, and expects to promulgate a final rule in 2010 or 2011. Some observers have noted that regulating CO_2 injection solely to protect groundwater, which is the focus of the EPA Class VI requirements, may not fully address the primary purpose of storing CO_2 underground, which is to reduce atmospheric concentrations.[22]

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[17] Intergovernmental Panel on Climate Change (IPCC) Special Report: *Carbon Dioxide Capture and Storage*, 2005, p. 233. Hereafter referred to as IPCC Special Report.

[18] The Weyburn and In Salah Projects, mentioned earlier, use the injected CO_2 to enhance oil and gas recovery as well as for carbon sequestration. At Sleipner, the CO_2 is injected solely for the purpose of permanent storage.

[19] IPCC Special Report, Box 5.1.

[20] *Federal Register*, pp. 43491-43541 (July 25, 2008).

[21] The UIC program currently includes five classes of injection wells (I-V). For more information about the Safe Drinking Water Act and the UIC program, see CRS Report RL34201, *Safe Drinking Water Act (SDWA): Selected Regulatory and Legislative Issues*, by Mary Tiemann.

[22] See, for example, *Carbon Capture and Sequestration: Framing the Issues for Regulation*, an Interim Report from the CCSReg Project (December 2008), pp. 73-90; at http://www.ccsreg.org/interimreport/feedback.php.

Oil and gas operators that inject CO_2 for the purposes of EOR are regulated under the UIC program Class II wells. It is expected that they will continue to inject CO_2 using Class II wells unless the purpose of the injection changes from EOR to geological sequestration.

A few states are also moving ahead with state-level geological sequestration regulations for CO_2. For example, Washington state has adopted rules coupling climate policy to geological sequestration of CO_2, and Wyoming has defined rules for ownership of its pore space that could be used for CO_2 storage.

What Could Go Wrong with Sequestering CO_2 Underground?

Can CO_2 Leak from Geologic Formations?

It is expected that the reservoir characterization process would rule out geologic formations that are too shallow, do not have adequate caprocks or other geologic seals, are intersected by permeable faults or fractures that might be pathways for escaping CO_2, or are in tectonically active areas. Characterizing geologic reservoirs for the purposes of CO_2 sequestration is an ongoing research effort, and laboratory experiments, field projects, and modeling studies may reveal new challenges or breakthroughs. Abandoned oil and gas fields are often considered first targets for CO_2 sequestration to take advantage of the natural configuration of permeable reservoir and overlying caprocks. Oil and gas reservoirs trapped hydrocarbons for millions of years before wells drilled into the reservoir produced the petroleum. Conversely, oil and gas fields typically contain abandoned wells that may penetrate the target reservoir and potentially provide a continuous pathway from the reservoir to the surface. Any geologic sequestration project would likely identify old or abandoned wells and evaluate whether the wells had been properly plugged and sealed so as to prevent migration of CO_2 from below.

Large-scale injection tests planned for the next several years should also provide information that would be used to guide site selection for full-scale CCS operations in the future, especially for deep saline reservoirs and unmineable coal seams, which do not have the same level of engineering experience as oil and gas fields.[23] All of these considerations, however, do not rule out the chance that CO_2 could leak from geologic formations. Even when CO_2 is compressed and injected as a supercritical fluid, it will likely remain less dense than the surrounding fluid it displaces, and rise buoyantly to spread out laterally beneath the overlying caprock. Permeable cracks or other leaks in the caprock could allow the buoyant fluid CO_2 to migrate upward. How much could leak, over what duration, and what the effects might be are key questions.

Can Injecting CO_2 Underground Cause Earthquakes?

The possibility for earthquakes, or *induced seismicity,* resulting from underground injection of CO_2 must be considered in carbon capture and sequestration activities. Instances of induced seismicity from deep underground injection of hazardous waste, from oil and gas operations, and

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[23] U.S. DOE Carbon Sequestration Technology Roadmap and Program Plan (2007), p. 22; at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf.

from other activities have been documented in locations where the injected fluids interacted with previously existing faults. The most notable example in the United States occurred in the early 1960s when scientists recognized a relationship between earthquakes and the deep injection of hazardous waste fluids near the Rocky Mountain Arsenal northeast of Denver, CO.[24] The likelihood of induced seismicity from deep CO_2 injection is probably greatest in seismically active areas with a recent history of faulting and earthquakes.[25] The possibility of CO_2 injection-triggered earthquakes has been recognized for some time; thus it is likely that precautions would be observed in the characterization of the potential CO_2 reservoir and in the regulatory structure governing CO_2 injection schemes. For example, the EPA's UIC program currently contains provisions addressing induced seismicity (40 C.F.R. 46.13 and 40 C.F.R. 46.68).

The most likely problem associated with induced seismicity would not be shaking hazards at the ground surface that are normally associated with earthquake-related damage. Rather, small earthquakes induced by CO_2 injection could fracture the rocks in the reservoir or, more importantly, the caprock above the reservoir. The EPA proposed rule for geologic sequestration (Class VI wells), discussed above, would require that owners or operators not exceed injection pressures that would induce seismicity and initiate or propagate fractures across the geologic seal or confining zone. Creating or reactivating permeable faults might provide a conduit for injected CO_2 to escape upwards from the sequestration formation through the caprock—if the fault extends through the entire caprock formation.

Can CO_2 Harm People?

A likely public concern would be the potential for large volumes of CO_2 to leak to the ground surface and accumulate in low-lying, inhabited areas. CO_2 is not toxic, flammable, or explosive (like methane or propane gas, for example), but if allowed to accumulate in enclosed spaces at high concentrations (e.g., 40,000 parts per million or more), CO_2 could displace oxygen and cause unconsciousness or asphyxiation.[26] If CO_2 leaks into the soil and root zone at high enough concentrations, it may also harm vegetation and crops. The chances of such high concentrations forming during CO_2 injection for CCS are remote, assuming the reservoir is well characterized, and "fast pathways" such as unidentified and abandoned wells, or unidentified permeable fractures and faults, do not intersect the injection site and connect to occupied, low-lying, unventilated structures. The chances are probably higher for small amounts of leakage during injection, or leakage over time, given the complexity of most geologic formations, although it is also likely that some reservoirs may never leak CO_2.

What Is at Risk If CO_2 Leaks?

In addition to the remote chance for affecting human health directly, discussed above, another possible risk is the chance of CO_2 leakage into an aquifer used for drinking water or as a supply for agriculture. If that occurs, contaminants that may be contained in the injected CO_2 could pollute the drinking water supply. It is unlikely CO_2 would be injected close to a critical aquifer;

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[24] J. H. Healy et al., "The Denver Earthquakes," *Science*, v. 161, no. 3848 (Sept. 1968), pp. 1301-1310.

[25] Joel Sminchak and Neeraj Gupta, "Aspects of Induced Seismicity and Deep-Well Sequestration of Carbon Dioxide," *Environmental Geosciences*, v. 10, no. 2 (2003), pp. 81-89.

[26] 40,000 ppm is the value listed as immediately dangerous to life and health (IDLH) by the National Institute for Occupational Safety and Health. See http://www.cdc.gov/niosh/idlh/intridl4.html.

it would likely be injected deep enough so that the possibilities of upward leakage are fairly remote. The same precautions would apply: adequate caprock, deep reservoir, lack of "fast pathways" to the aquifer, as well as engineering expertise to inject the CO_2 without "overpressuring" the reservoir, which could create fractures or increase the chances of leakage around wells. Over the lifetime of an injection project, the chances of the injected CO_2 encountering unidentified faults or fractures in the reservoir may increase, as the CO_2 disperses laterally from the injection point and fills pore spaces throughout the geologic formation. However, the pressure of the injected CO_2 also decreases laterally from the injection point, so that the likelihood of large releases over a short timespan also decreases with distance from where the CO_2 is injected. Some observers conceptualize the risk of leakage as increasing to a peak during the injection phase, and then decreasing after injection stops as the CO_2 becomes more permanently trapped in the subsurface over time.[27]

Injecting CO_2 into saline formations lowers the pH (increases the acidity) of the formation water. More acidic waters may dissolve minerals in the formation such as calcium carbonate and release metals, such as iron and manganese, or other elements contained within those minerals. The increased acidity could also increase the permeability of the formation, allowing the injected CO_2 to migrate more readily. Initial results from injection experiments that observed this process seem to indicate that the reservoir integrity remained intact and CO_2 did not leak.[28] Additional injection experiments may help understand whether increased acidity following CO_2 injection is a significant issue.

How Would Leaks Be Detected?

Geophysical techniques, such as seismic imaging, have been used at the Sleipner sequestration project, discussed above, to map the shape of the CO_2 plume at depth and plot its migration over time as CO_2 is injected. These techniques could be useful for detecting leakage from the reservoir, especially if the CO_2 concentrations were high enough to distinguish them from the saline formation water, although seismic monitoring could be costly compared to other techniques. To help detect leaks around wells, or into nearby structures or dwellings, tracer compounds—which are detectable at very low concentrations—could be added to the injected CO_2 and then monitored.[29] If shallow aquifers are a concern, monitoring wells can be installed above the CO_2 sequestration reservoir, and below the drinking water aquifer, to measure changes in pressure, temperature, and chemistry that may indicate CO_2 is escaping the reservoir. Also, changes to vegetation at the ground surface could be monitored over time, which may indicate CO_2 leakage into the soil from below.

The terms *measurement*, *monitoring*, and *verification* (or MMV) are typically used to describe the plan, system, and tools for characterizing the subsurface reservoir and for detecting changes throughout the injection, closure, and long-term care phases of a geologic sequestration project. There is no universal agreement on the specific elements that should be included in MMV for all large-scale geologic sequestration projects. Because the geology varies from site to site, a different set or combinations of techniques may be required for each project.

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[27] World Resources Institute, *CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage*, Washington, DC: WRI (2008), p. 55.

[28] Y. K. Kharaka et al., "Gas-water interactions in the Frio Formation following CO_2 injection: implications for the storage of greenhouse gases in sedimentary basins," *Geology*, v. 34, no. 7 (July 2006), pp. 577-580.

[29] Similarly, chemicals added to propane or natural gas are "tracers" detectable by smell that could indicate leaks.

How Long Will CO_2 Stay Underground?

When CO_2 is injected into an oil and gas reservoir or a deep saline formation, it is expected to occupy some portion of the pore space, and displace the saline water, oil, gas, or some combination of the natural formation fluids. Initially, the injected CO_2 would occupy the pore space as a liquid or supercritical fluid, as discussed above, and remain in the geologic formation unless one or more of the possible leakage scenarios outlined above occurs. This is commonly referred to as *volumetric storage*.

Over hundreds or thousands of years, however, the injected CO_2 would start to dissolve into the formation fluids, further decreasing its chances of leaking out of the reservoir. This is known as *solution storage*. Solution storage would effectively trap the CO_2 underground for a long time, but the rate at which CO_2 dissolves into the saline water decreases as the salinity increases; CO_2 would dissolve only very slowly in deep, highly saline formations.

CO_2 injected into coal seams could be tightly bound, or *adsorbed*, onto the coal surfaces, and would likely stay bound to the coal for a long time unless further disturbed. Studies indicate that CO_2 could displace methane (and the methane recovered at the surface) which occurs naturally in many coal seams. Other studies indicate that injecting CO_2 into coal seams may cause the coal to swell, however, which could reduce the permeability of the coal seam and limit its effectiveness for sequestering large amounts of CO_2.[30]

Injecting CO_2 into deep flood basalts, such as those found in the Columbia River Plateau occupying portions of Washington, Oregon, and Idaho, may cause the minerals in the basalt to react with the CO_2 and form solid minerals (known as *mineral storage*). The minerals would likely stay underground in the flood basalts for thousands to millions of years, essentially trapping the injected CO_2 for geologic time. Flood basalts are attracting attention for CO_2 sequestration in part because of their potential for mineral storage, and because basalts commonly possess good porosity and permeability. However, unlike oil and gas reservoirs and deep saline formations, which form in sedimentary basins and are often overlain by impermeable cap rocks, flood basalts are composed of multiple layers of erupted lava flows. Lava flows may not provide the same degree of geologic seal as sedimentary rocks, like shales. Of possible concern is whether the injected CO_2 will have sufficient time to react with the basalts and form stable minerals before the CO_2 migrates to the surface.

What Happens to Reservoir Fluids Displaced by Injected CO_2?

In most of the depleted oil and gas reservoirs and deep saline formations under consideration for geologic CO_2 sequestration, saline water or brine occupies the pore spaces in the reservoir. Carbon dioxide injected as a supercritical fluid would likely displace some portion of the brine (volumetric storage), which means that the displaced brine would flow elsewhere. Where and how fast the brine would flow, and how much would be displaced, depends on the characteristics of the formation, including its porosity and permeability, as well as how much CO_2 is injected. In large potential CO_2 reservoirs, such as the Mt. Simon sandstone that underlies parts of Ohio, Pennsylvania, and Illinois, the amount of brine displaced would likely be small relative to the

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[30] X. Cui, R. M. Bustin, and L. Chikatamarla, "Adsorption-induced coal swelling and stress: Implications for methane production and acid gas sequestration into coal seams," *Journal of Geophysical Research*, vol. 112, B10202 (2007).

huge volume contained throughout the formation. In those cases, the likelihood of substantial migration of brine outside the formation is relatively small. For formations with less volume, relatively greater amounts of brine would be displaced compared to the initial volume in the reservoir. Any risk to underground sources of drinking water from the displaced brine would depend, in part, on proximity of the boundary of the CO_2 reservoir to a freshwater aquifer. It is likely that reservoir characterization prior to injection, as well as monitoring during the injection phase, would provide needed information on the likelihood of brine migration into a drinking water source. After injection ceases, the likelihood of additional brine migration decreases rapidly as the added pressure from the injected CO_2 dissipates, and as CO_2 dissolves into the formation brine.

What Is the Status of U.S. Demonstration Projects for Underground CO_2 Sequestration?

Beginning in 2003, DOE created seven regional carbon sequestration partnerships to identify opportunities for carbon sequestration field tests in the United States and Canada.[31] The regional partnerships program is being implemented in a three-phase overlapping approach: (1) characterization phase (from FY2003 to FY2005); (2) validation phase (from FY2005 to FY2009); and (3) deployment phase (from FY2008 to FY2017).[32] According to the 2008 Carbon Sequestration Atlas, the first phase of the partnership program identified the potential for sequestering over 3,000 $GtCO_2$ across the United States and parts of Canada.

The third phase, deployment, is intended to demonstrate large-volume, prolonged injection and CO_2 sequestration in a wide variety of geologic formations. According to DOE, this phase is supposed to address the practical aspects of large-scale operations, presumably producing the results necessary for commercial CCS activities to move forward. On November 17, 2008, DOE announced it was awarding the seventh, and last, award for the large-scale carbon sequestration projects under phase three of DOE Carbon Sequestration and Technology Roadmap and Program Plan.[33] DOE has now awarded funds totaling $457.6 million (an average of $65 million per project) to conduct a variety of large-scale injection tests over several years. In addition to DOE funding, each partnership also contributes funds ranging from 21% to over 50% of the total project costs.[34]

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[31] The seven partnerships are Midwest Regional Carbon Sequestration Partnership; Midwest (Illinois Basin) Geologic Sequestration Consortium; Southeast Regional Carbon Sequestration Partnership; Southwest Regional Carbon Sequestration Partnership; West Coast Regional Carbon Sequestration Partnership; Big Sky Regional Carbon Sequestration Partnership; and Plains CO_2 Reduction Partnership; see http://www.fossil.energy.gov/programs/sequestration/partnerships/index.html.

[32] DOE Carbon Sequestration Technology Roadmap and Program Plan 2007, p. 36.

[33] DOE awarded $66.9 million to the Big Sky Carbon Sequestration Partnership. See http://www.fossil.energy.gov/news/techlines/2008/08059-DOE_Makes_Sequestration_Award.html.

[34] For more information about specific sequestration projects, see the DOE Carbon Sequestration Regional Partnerships website, at http://www.fossil.energy.gov/programs/sequestration/partnerships/index.html.

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