Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Carbon Dioxide Capture for Storage in Deep Geologic Formations, Volume 2
D.C. Thomas and S.M. Benson (Eds.)

Chapter 28

PROSPECTS FOR EARLY DETECTION AND OPTIONS FOR REMEDIATION OF LEAKAGE FROM CO_2 STORAGE PROJECTS

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ABSTRACT

Geologic storage projects of CO_2 should be designed to maintain secure storage thousands of years or longer. However, in some cases, leakage may occur and remediation measures, either to stop the leak or to prevent human or ecosystem impacts will be needed. Moreover, the availability of remediation options will reassure the public that geologic storage can be safe and effective and help build confidence in carbon capture and storage.

This study reviews the remediation options available for many of the types of leakage that may occur based on analogous situations in natural gas storage, oil and gas production, groundwater remediation, and soil gas and vadose zone cleanup. Remediation options are discussed for damaged injection wells, leaking abandoned wells, over pressured reservoirs, carbon dioxide accumulations in shallow groundwater, secondary contamination of groundwater by acidification, vadose zone and soil gas accumulations, and surface releases. Examples of remediation options for buildings and surface water are also discussed. This study demonstrates that remediation options are available for many of the leakage scenarios that can be envisioned.

INTRODUCTION

The need for methods of early detection, intervention measures to prevent leakage and remediation of leakage from CO_2 storage projects is a recurrent theme in discussions about the acceptability of geologic storage of CO_2 as an approach to emission reduction. To date, little, if any, research has been done that addresses this issue. The purpose of this study is to identify intervention options to prevent leakage and remediation options that could be used to eliminate or manage risks after leakage has been detected. The approach taken in this study is as follows:

- Identify and develop the leakage scenarios and consequences that are most likely to occur in geologic storage projects (e.g. leakage up abandoned wells, leakage up undetected faults or fractures in the reservoir seal, etc.).
- Calculate a range of hypothetical leakage rates from prototypical storage projects, including those performing effectively and those leaking at unacceptable rates.
- Survey and document remediation practices currently used in natural gas storage, oil and gas production, groundwater and vadose zone remediation.
- Evaluate how and the extent to which existing remediation practices could be employed to remediate leakage in geologic storage projects.
- Identify potential new approaches for remediation of geologic storage projects for scenarios where existing remediation approaches are not sufficient.
- Identify additional knowledge or information needed to develop and build confidence in the effectiveness of new or improved remediation approaches.

LEAKAGE SCENARIOS AND CONSEQUENCES FOR GEOLOGIC STORAGE PROJECTS

To identify options for remediation of CO_2 storage projects it is necessary to first understand potential failure mechanisms and pathways. Potential leakage scenarios are illustrated in Figure 1, which shows the major leakage pathways and potential consequences of leakage. Beginning with the deepest parts of the geologic storage site, we evaluate the principle components of the system and how they may lead to leakage.

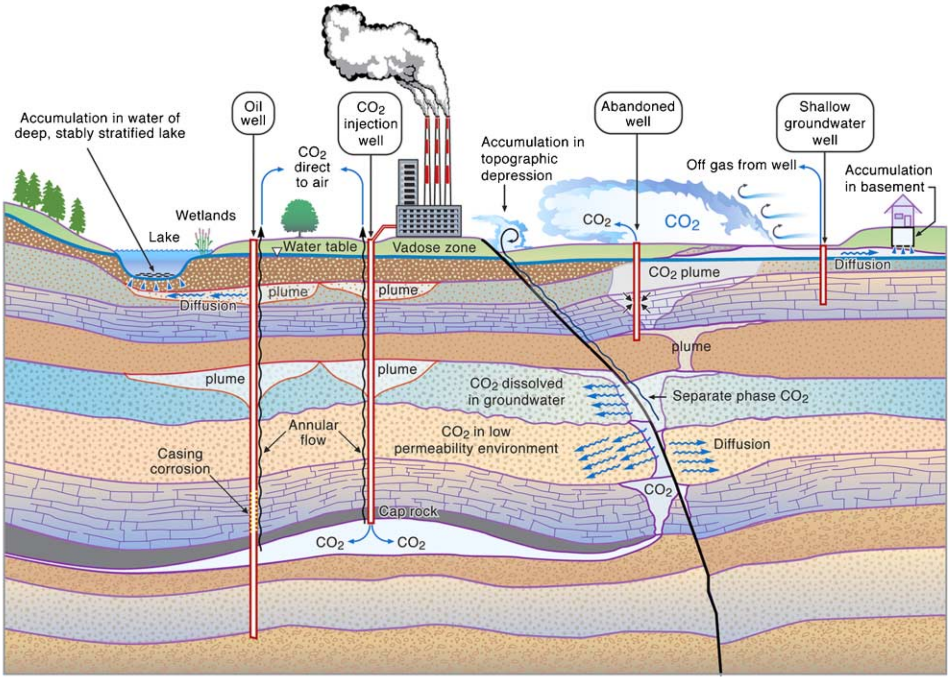

Figure 1: Illustration of potential leakage pathways at poorly selected storage sites and consequences of leakage.

CO_2 will be injected underground using injection wells. Drilling and well completion technology has matured to the point where the wells perform effectively over long periods of time. However, it is possible that poor well construction techniques or inadequate maintenance of those wells can create leakage of CO_2 back to the surface [1–3]. Injection wells may fail in a number of ways: (1) corrosion or mechanical damage to the casing, (2) corrosion or mechanical damage to the injection tubing and packers, and (3) leakage in the annular region between the outside of the casing and the borehole wall. In addition to the injection wells themselves, nearby oil and gas wells, whether used for production, monitoring, injection, or are idle may also provide a leakage pathway towards the surface. One of the greatest uncertainties and potential risk of underground storage is the existence of abandoned wells and the leakage paths they may create [4]. In the past century, millions of wells have been drilled all around the United States, many of which were poorly constructed originally or were never properly plugged and abandoned. Unlike active wells or recently abandoned wells, record keeping on the location and depth of older wells is poor and they will often be difficult to locate. Shallow groundwater wells may also provide a leakage pathway to the surface.

Geologic storage sites will be selected based on careful site investigations which demonstrate the presence of a suitable cap rock or seal for the storage reservoir. The cap rock provides a low permeability barrier that prevents the upward migration of the buoyant CO_2 plume. In some cases, however, it is possible that faults or fractures go undetected or that the CO_2 spreads beyond the intended storage footprint. If the CO_2 plume encounters a permeable fault or fracture it may provide a leakage path of CO_2 towards the surface. CO_2 leakage up faults and fractures is likely to occur as a separate phase. During the process of leakage up faults or fractures, CO_2 may accumulate in secondary, shallower traps such as other subsurface formations or aquifers.

As the CO_2 approaches the land surface, a number of different atmospheric discharge scenarios can be envisioned:

- CO_2 could be directly discharged to the atmosphere through a well;
- CO_2 may accumulate in the vadose zone and be released by advection and diffusion across the land surface;
- in regions with a very shallow water table CO_2 could discharge directly to the atmosphere;
- if overlain by water, CO_2 would dissolve in the ocean or a lake and discharge by diffusion to the atmosphere. If the leakage rate was sufficiently high, CO_2 may bubble through the water column and be discharged to the atmosphere directly. Under unusual circumstances found in deep lakes in the tropics, CO_2 could accumulate in the bottom waters of a deep lake or at sufficient depths in the ocean, possibly leading to eventual eruption following supersaturation or some triggering event—as evidenced at Lake Nyos. If the water was deep and cold enough, the CO_2 may form hydrates that accumulate on the sea floor;
- if overlain by a building, CO_2 could accumulate in the basement or subfloor, leading to the build-up of potentially dangerous concentration of CO_2.

The local health, safety and environmental consequences of each of these discharge scenarios will depend on the size and rate of the release. For example, Oldenburg et al. [5] demonstrate that even large releases from the vadose zone to the atmosphere are unlikely to result in unsafe concentrations of CO_2 in the atmosphere because atmospheric mixing rates are high enough to quickly dilute the CO_2. However, these same scenarios show that even for low release rates, high concentrations of CO_2 can build-up in the soils, exceeding concentrations known to damage vegetation.

POTENTIAL RELEASE RATES FROM LEAKING STORAGE PROJECTS

Estimating the amount of CO_2 that may be released from a failing storage project is an important starting point for assessing detection and remediation options. Two scenarios are examined: (1) a small-scale project storing the emissions from an oil refinery that emits 1 Mt CO_2 per year and (2) a larger scale project storing emissions from a 500 MW coal-fired power plant that emits 3.6 Mt/year. In each case we assume that CO_2 is injected at a constant rate for a 50-year period. For these projects, we calculate how much CO_2 would be released if 0.01, 1 and 10% of the cumulative amount of CO_2 that had been stored was released over a 1-year period. The release rates were selected to cover a broad range of values, not because they are based on actual or calculated release rates from any particular project. Table 1 summarizes the quantity of CO_2 that would be released during a 1-year period after 1, 10 and 50 years of injection.

TABLE 1
SUMMARY OF THE QUANTITY OF CO_2 THAT WOULD BE RELEASED (IN MT/YEAR) FOR LEAKING CO_2 STORAGE PROJECTS FOR LEAKAGE RATES OF 0.01, 1 AND 10% OF THE TOTAL AMOUNT STORED

Scenario	**Refinery (1 Mt CO_2/year)**			**500 MW power plant (3.6 Mt/year)**		
Leakage rate (%stored/year)	0.01	1	10	0.01	1	10
1 year (Mt/year)	0.0001	0.01	0.1	0.00036	0.036	0.36
10 years (Mt/year)	0.001	0.1	1.0	0.0036	0.36	3.6
50 years (Mt/year)	0.005	0.5	5.0	0.0186	1.86	18.6

To put these release rates into perspective it is useful to compare them to the flux of CO_2 that is associated with the natural cycling of CO_2 between the atmosphere and the biosphere. The maximum range of natural ecosystem fluxes between the land surface and the atmosphere is from 10 μmol/m^2/s efflux during the peak of night-time respiration to 30 μmol/m^2/s drawdown during maximal daytime photosynthesis at the height of the growing season but more typically would be 0.5–2 μmol/m^2/s efflux and 2–10 μmol/m^2/s drawdown [6,7]. To directly compare the hypothetical releases from a storage project to these natural fluxes, the area over which the release occurs must be specified. The footprint of the underground plume of CO_2 created by a storage project of this magnitude is expected to be on the order of 50–300 km^2 (equivalent to a radius of 5–10 km), based on capacity estimates developed by Doughty et al. [8]. One meaningful comparison is to assume that the release of CO_2 is evenly distributed over the entire footprint of the plume. For this case the fluxes are provided in Figure 2. As shown, for all but the release rate of 10% per year, these fluxes are much lower than or in the range of the natural ecosystem fluxes. This indicates that for release rates of 1% or less that are evenly distributed over the footprint of the plume, detection of the releases would be difficult. For release rates of 10% or greater, the fluxes are significantly greater than the natural fluxes and consequently would be easily detected and likely to have observable ecosystem impacts (see discussion in Ref. [5]).

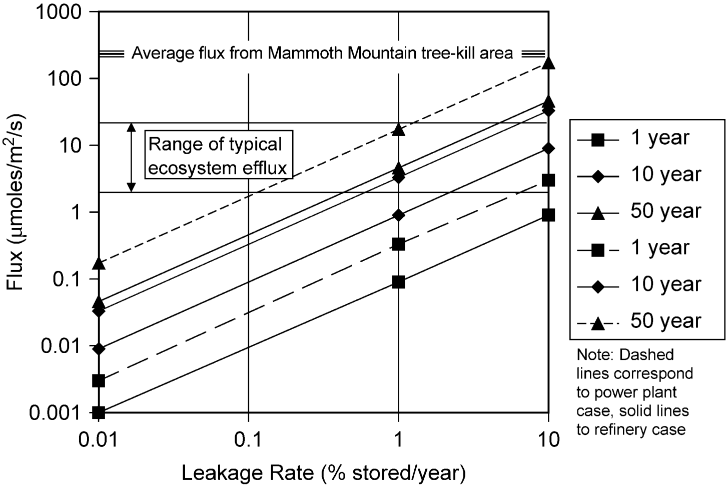

Figure 2: Fluxes of CO_2 for the scenarios listed in Table 1 assuming that the releases are eventually distributed over the footprint of a plume with a radius of 5 km.

In reality, it is very unlikely that a storage site would have leakage that is evenly distributed over the entire footprint of the plume. Instead, as described in the previous section, leakage would be concentrated around aging wells, faults that compromise the integrity of the cap rock, or storage structures with incomplete closure. In each of these cases, leakage would be concentrated within a limited area and therefore, fluxes could be significantly higher than the values shown in Figure 2. To investigate the leakage fluxes for some other scenarios, Figure 3a,b show the estimated flux of CO_2 for each leakage rate at the end of the 50-year project lifetime for four surface release scenarios: radial flux zones with 10 m (area of 300 m^2) and 100 m radius (area of 30,000 m^2) and 1 km linear flux zones either 1, 10, or 100 m wide (areas of 1000, 10,000 and 100,000 m^2, respectively). Note that in all these cases the surface release is concentrated in a very small fraction of the overall dimension of the plume of CO_2 in the storage formation.

For all of the cases provided in Figure 3a,b, the flux is orders of magnitude greater than the natural ecological flux. In fact, at 1% seepage, the fluxes range from 3–6 orders of magnitude greater than background ecological levels and would be greater than those seen at Mammoth Mountain at the height of the flux in the early 1990s—1000–1200 tonnes of CO_2 per day. The area of associated tree-kill is 170 acres (6.9×10^5 m^2) (USGS, http://lvo.wr.usgs.gov/CO2.html, 2003;) leading to an average flux of approximately 400 μmol/m^2/s. Using eddy flux correlation, Anderson and Farrar [9] measured the CO_2 flux as between 180 and 360 μmol CO_2/m^2/s. These calculations suggest that leakage from medium to large size projects, even at rates as low as 0.01%/year could be easily detected if it is confined to relatively small areas because the flux is so much greater than the background rate.

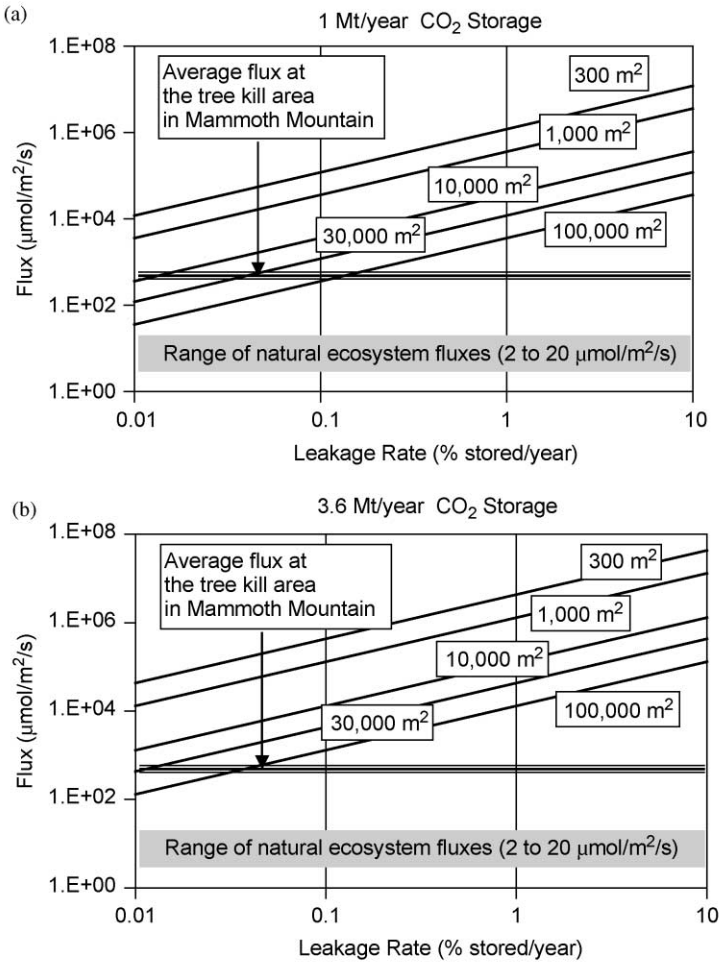

Figure 3: Flux of CO_2 in μmol/m^2/s for several leakage rates. These calculations are for release rates after 50 years of CO_2 injection. (a) Fluxes for a 1 Mt/year storage project. (b) Fluxes for a 3.6 Mt/year storage project.

METHODS FOR EARLY DETECTION OF LEAKAGE

A wide variety of approaches are available for monitoring geologic CO_2 storage operations and potential leakage. Several chapters in this volume summarize these monitoring methods and will not be repeated here [10–16]. Suffice it to say that monitoring approaches are available to monitor the progress of a storage project as the storage reservoir volume fills up and potentially detects leakage long before it approaches the land surface. Early detection of leakage from the storage reservoir will provide the opportunity for intervention and remediation before large amounts of CO_2 are released back into the atmosphere. If CO_2 has migrated to the land surface and is discharged to the atmosphere, methods are available to monitor both the flux and concentration of CO_2 in the atmosphere, soils and surface water [10,11]. As described above, if the release is confined to a limited area, as we expect it to be, fluxes from leaking CO_2 storage projects will be much higher than the natural background flux of CO_2. The high flux, relative to the background rate will make detection relatively easy using commercially available equipment, if the location of the release is known. Subsurface monitoring techniques should be effective in locating the areas where surface leaks are likely to occur. Similarly, understanding of the geologic setting should also provide an indication of the places where leakage is most likely to occur. Remote sensing may also be useful for locating leaks by detecting ecosystem stress from elevated soil-gas CO_2 [12]. In future, remote sensing may also be used to directly monitor CO_2 concentrations if the technology can be improved enough to have sufficient resolution.

REVIEW OF THE RESPONSE TO LEAKAGE IN NATURAL GAS STORAGE PROJECTS

Natural gas storage projects provide a good modern analogue for storage of CO_2 in underground geological formations. The technology for injection, well construction and monitoring is very similar to that which would be used for geological storage of CO_2. It is natural, therefore, to look to these projects for insight into remediation options. In the US alone there are over 450 natural gas storage projects. Of these, a small number have experienced leakage [2]. The projects listed below provide information on how the leakage was managed and what kinds of approaches were used for remediation.

- *Herscher-Galesville, IL.* In mid-1953, several months after natural gas was first pumped into the Galesville formation, bubbles of gas appeared in shallow water wells in the Herscher field. Wells were drilled around the periphery of the field to remove water and thereby minimize the pressure build-up. The water was then reinjected into the Potosi Dolomite (above the Galesville) in order to pressurize the shallower formation. By carefully monitoring the differential pressures and recycling gas from several vent wells in other still shallower formations, the Herscher-Galesville natural gas storage project has been active for almost 50 years. To this day, the cause of the leakage is still not known with certainty [17].
- *Leroy, WY.* At this gas storage site, gas was observed bubbling to the surface; it was reportedly controlled by limiting maximum injection pressures.
- *East Whittier, CA.* In the 1970s, storage gas had migrated out of the original storage footprint and was being produced and sold by another company from a neighboring lease, which according to DOGGR is not an uncommon reason for abandoning storage operations. Currently, this field is in the process of being shut down.
- *West Montebello, CA.* In the 1970s, gas was leaking along old, improperly plugged wells to a shallower zone but not to the surface. Problem wells were plugged and the gas that trapped in the shallower zone may eventually be produced. This field is also being shut down.
- *McDonald Island, CA.* On 17 May 1974, PG&E lost control of a new injection/withdrawal well, Whiskey Slough 14 W, which then caught fire. While pulling out of hole, the well fluid level apparently dropped and was not monitored. The fire was extinguished and the well was controlled after 19 days by drilling a relief well and killing the blowout with heavy mud [18].
- *Indiana.* In the 1960s and 1970s, many water wells in northern Indiana were contaminated with natural gas from a shallow storage aquifer. Under current regulations, such a project would not be allowed.
- *Hutchinson, KS.* Natural gas from the Yaggy gas storage project leaked from an injection/withdrawal well. The storage structure is composed of several mined salt caverns at least 150 m deep. The leaked

gas migrated seven miles to the town of Hutchinson through a 20 ft zone with several dolomite layers interspersed with shale. Within the town, it then flowed up and erupted from old, unplugged wells that no one had known about and that had been used for salt solution mining many decades ago (KGS, www.kgs.ku.edu/PRS/Poster/2002/2002-44/, 2002). Remediation was accomplished by plugging the injection/withdrawal well and the abandoned wells. After this, 12 wells were drilled into the shallow aquifer to intercept gas accumulations and vent the gas into the atmosphere. High-resolution seismic imaging was successfully used to locate gas accumulations in the aquifer and to guide siting the wells used to vent the gas [19]. In addition, electromagnetic and high-resolution magnetic methods were used to locate additional abandoned wells that could provide leakage pathways in the future [20].

These projects demonstrate that each time when a leak was detected, an intervention or remedy was put in place that stabilized the situation. In most cases, the project was able to continue, but in a few others, a decision was made to terminate the project. In the following section, these and other remediation techniques for geologic storage projects are presented.

REMEDIATION OPTIONS FOR LEAKING GEOLOGIC STORAGE PROJECTS

In the process of exploring past practices and potential failure scenarios, seven problems have been identified that require remediation: (1) leaks from the storage reservoir; (2) leakage from active or abandoned wells; (3) contamination of shallow groundwater; (4) vadose zone and soil contamination; (5) localized surface fluxes; (6) leakage of carbon dioxide in indoor spaces, especially basements; and (7) leakage into surface water. Remediation options for each of these types of leaks are described below and summarized in Table 2. In some cases the methods are well established. In others, they are more speculative, but with appropriate research and development, may nevertheless one day become feasible.

Leakage from the Storage Reservoir

There are three basic approaches to stopping leakage from the storage reservoir: (1) the pressure in the storage formation can be reduced; (2) the pressure in the formation into which leakage is occurring can be increased; or (3) the CO_2 plume can be intercepted and extracted from the reservoir before it leaks out of the storage structure. Lowering the pressure in the storage reservoir will help reduce or stop leakage in two ways. First, lowering the pressure will reduce the pressure gradient driving the CO_2 out of the storage reservoir. Second, if faults or fractures have become leakage pathways as a result of the pressure build-up in the storage reservoir, lowering the pressure can mitigate this [21]. Increasing the pressure in the formation into which CO_2 is leaking will decrease the pressure gradient that is causing the storage structure to leak. Finally, extraction of the CO_2 plume before it leaks will directly intercept and prevent leakage. Techniques for accomplishing these three approaches are listed below.

- Lower the reservoir pressure by injecting at a lower rate or through more wells [17].
- Lower the reservoir pressure by removing water or other fluids from the storage reservoir.
- Lower the reservoir pressure by creating a pathway to access new compartments in the storage reservoir, e.g. hydrofracture or a well completion open to two storage zones.
- Increase the upgradient pressure by injecting water or brine ahead of the leak.
- Stop injection in order to lower the reservoir pressure and stabilize the project.
- Stop injection, produce the CO_2 from the storage reservoir and reinject it back into a more suitable storage structure.
- Drill extraction (pumping wells) wells in the vicinity of the leak to stop the leakage and capture the CO_2 before it leaks out of the storage structure. Reinject the CO_2 at a more suitable location.

Leakage from Active or Abandoned Wells

Methods for repairing active and abandoned wells are used on a routine basis in the oil, gas, natural gas storage and waste disposal industries. In addition, for newly drilled wells, federal, state and local regulations have been developed to ensure that wells are drilled and completed safely and will not harm groundwater or other resources. These techniques can be employed to remediate leaking wells in CO_2 storage projects.

Examples of these techniques are provided below.

- Repair leaking injection wells with standard well recompletion techniques such as replacing the injection tubing and packers.
- Repair leaking injection wells by squeezing cement behind the well casing to plug leaks behind the casing.
- Plug and abandon injection wells that cannot be repaired by the methods listed above.
- Stop blowouts from injection or abandoned wells using standard techniques to "kill" a well such as injecting a heavy mud into the well casing. After control of the well is reestablished, the recompletion or abandonment practices described above can be used. If the wellhead is not accessible, a nearby well can be drilled to intercept the casing below the ground surface and "kill" the well by pumping mud down the interception well [18].

Groundwater Remediation

Groundwater remediation methods that may be useful for CO_2 leakage can be categorized as: (1) passive, (2) active, and (3) those meant to deal with contamination caused by dissolution of secondary minerals as a result of groundwater acidification from CO_2. Passive methods utilize natural attenuation of the CO_2 by dissolution in groundwater, dilution and mineralization. Monitoring is used to confirm that the hazard is being remedied at an acceptable rate. Active methods involve injection or extraction of fluids to accelerate removal or stabilization of the CO_2. The most commonly employed method, "pump and treat", removes the groundwater from the aquifer and treats it at the surface to remove the unwanted impurities. For CO_2, this could include both gas phase pumping and groundwater extraction. For gas that remains trapped as a residual and immobile phase, groundwater extraction could also be used to dissolve the plume of CO_2. The greatest need for remediation from the effects of CO_2 leakage may be for removal of elements mobilized by the dissolution of minerals, e.g. arsenic (As) and lead (Pb) caused by acidification of groundwater from CO_2. In addition to the "pump and treat" approach mentioned above, flow-through treatment barriers may be effective for removal of trace elements mobilized by groundwater acidification [22]. Another possible method is to contain the plume of contaminated water by managing hydraulic heads and preventing the flow of contaminated waters [23]. Examples of these approaches are provided below.

- Accumulations of gaseous CO_2 in groundwater can be removed, or at least made immobile, by drilling wells that intersect the accumulations and extract the CO_2. The extracted CO_2 could be vented to the atmosphere or reinjected back into a suitable storage site.
- Residual CO_2 that is trapped as an immobile gas phase can be removed by dissolving it in water and extracting it as a dissolved phase through groundwater extraction wells.
- CO_2 that has dissolved in the shallow groundwater could be removed, if needed, by pumping to the surface and aerating it to remove the CO_2. The groundwater could then either be used directly or reinjected back into the aquifer.
- If metals or other trace contaminants have been mobilized by acidification of the groundwater, "pump-and-treat" methods can be used to remove them. Alternatively, hydraulic barriers can be created to immobilize and contain the contaminants by appropriately placed injection and extraction wells. In addition to these active methods of remediation, passive methods that rely on natural biogeochemical processes may also be used. Treatment walls designed to remove the trace elements could also be used.

Vadose Zone

Vadose zone remediation is a mature field. Similar to groundwater remediation, there is a basic distinction between passive and active methods such as soil vapor extraction (SVE). Passive methods rely on diffusion from the vadose zone to the atmosphere or natural biogeochemical processes to remove the unwanted substance. Passive removal can also be enhanced by using the natural diurnal fluctuations in atmospheric pressure to accelerate diffusive fluxes or accelerated even more by the use of "BaroBalls" [5,24]. Passive methods have the advantage of being less expensive but typically take much longer than active methods.

Active methods of vadose zone remediation that might be applicable to CO_2 removal are generally variations of the industry standard SVE, sometimes with covers or sprinkling/irrigation [25]. The basic mechanism behind SVE is flushing fresh air through the soil and extracting soil gas. SVE systems can be optimized by using vertical wells, horizontal wells, drainage systems or trenches for collection of soil gas, and surface facilities would include a vacuum pump or blower, moisture knockout and treatment facilities. As an alternative, for soluble substances such as CO_2, sprinkling or irrigation can be used to dissolve and move them downward into shallow groundwater which can then be diluted by the groundwater or processed by pump-and-treat. Another alternative method, which is commonly used in landfills, is to cover the surface with an impermeable barrier and install a collection system below the cover. Examples of vadose remediation techniques are provided below.

- CO_2 can be extracted from the vadose zone and soil gas using standard vapor extraction techniques from horizontal or vertical wells.
- Fluxes from the vadose zone to the ground surface could be decreased or stopped using caps or gas vapor barriers. Pumping below the cap or vapor barrier could be used to deplete the accumulation of CO_2 in the vadose zone.
- Since CO_2 is a dense gas it could be collected in subsurface trenches. Accumulated gas could be pumped from the trenches and released to the atmosphere or reinjected back underground.
- Passive remediation techniques that rely only on diffusion and "barometric pumping" could be used to slowly deplete one-time releases of CO_2 into the vadose zone. This method will not be effective for managing ongoing releases because it is relatively slow.
- Acidification of the soils from contact with CO_2 could be remediated by irrigation and drainage. Alternatively, agricultural supplements such as lime could also be used to neutralize the soil.

Large Short Duration Releases of CO_2 to the Atmosphere

Large short duration releases of CO_2 to the atmosphere can be managed by passive or active dilution in the atmosphere. For example

- For releases inside a building or confined space, large fans could be used to rapidly dilute CO_2 to safe levels.
- For large releases spread out over a large area, dispersion from natural atmospheric mixing (wind) will be the only practical method for diluting the CO_2.
- For recurrent or ongoing leakage in confined spaces (e.g. cellar around a wellhead) fans could be used to keep the rate of air circulation high enough to ensure adequate dilution.

Indoor Environments and Basements with Chronic Low Levels of Leakage

The remediation of indoor air contaminants has been studied extensively for volatile organic compounds and radon. Leaking CO_2, like radon, would enter the building from the subsurface, so the remediation techniques for radon should be directly applicable to elevated CO_2 in the indoor environment. The two major techniques used today are subsurface or subslab pressurization and subslab depressurization with venting. Schematics of these two processes are shown in Figure 4. Subslab pressurization pumps outside air into the basement or area beneath the foundation slab; this flushes fresh air through the near-building soil air and disperses contaminants (VOC, Rn, CO_2) away from the building. Subslab depressurization pumps air from beneath the foundation slab out the top of the building; the decreased pressure beneath the slab pulls atmospheric air through the soil and flushes out contaminants. Both methods induce airflow through the near-building soil gas in order to disperse contaminants [26–28].

Venting Systems to Remove CO_2 from Deep Stably Stratified Lakes

The most catastrophic natural disaster known to be directly caused by CO_2 was the 1986 incident at Lake Nyos in Cameroon. Approximately 1700 people and many thousands of cattle were killed in this event in which an enormous amount of CO_2 dissolved in the bottom waters of a crater lake exsolved, flowed down the narrow drainage, and suffocated almost all animals in its path for many miles. The CO_2 had built up slowly through time and was measurably increasing again in the years following the 1986 disaster. An international coalition of scientists studied the problem and one group of them, headed by Michel Halbwachs, designed, built and tested a system for degassing Nyos and a smaller nearby lake called Monoun with a similar CO_2 build-up. Figure 5 depicts the degassing principle, which relies on a controlled natural gas lift through a small diameter pipe (http://perso.wanadoo.fr/mhalb/nyos/project/annexes/safety.PDF). The process is now underway and expected to make Lake Nyos and Lake Manoun safe within the next several years.

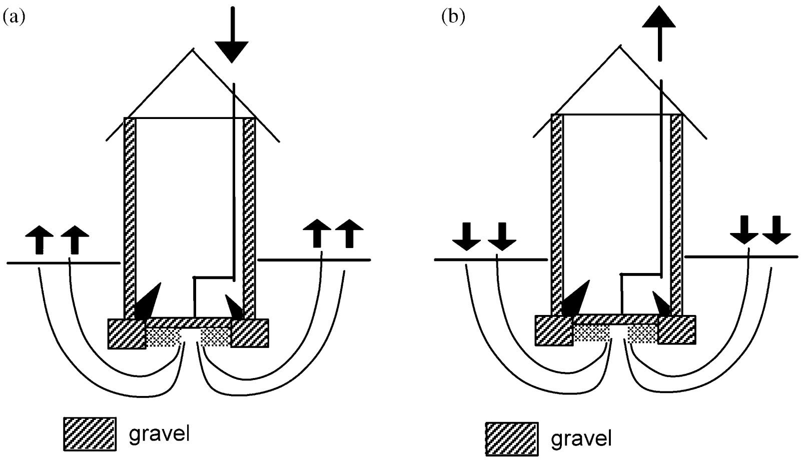

Figure 4: (a) The schematic on the left shows a conceptual representation of a subslab pressurization (ssp) system. (b) The diagram on the right depicts a conceptual representation of a subslab depressurization (ssd) system (after Ref. [26]).

Figure 5: Degassing procedure principle: 1, priming the self-siphon using an electrical pump; 2, autonomous soda fountain (http://perso.wanadoo.fr/mhalb/nyos/).

TABLE 2
OPTIONS FOR REMEDIATION OF LEAKAGE FROM THE STORAGE FORMATION

Scenario	Remediation options
Leakage from the storage reservoir	Lower injection pressure by injecting at a lower rate or through more wells [17] Lower reservoir pressure by removing water or other fluids from the storage structure Intersect the leakage with extraction wells in the vicinity of the leak Create a hydraulic barrier by increasing the reservoir pressure upstream of the leak Lower the reservoir pressure by creating a pathway to access new compartments in the storage reservoir Stop injection to stabilize the project Stop injection, produce the CO_2 from the storage reservoir and reinject it back into a more suitable storage structure
Leakage from active or abandoned wells	Repair leaking injection wells with standard well recompletion techniques such as replacing the injection tubing and packers Repair leaking injection wells by squeezing cement behind the well casing to plug leaks behind the casing Plug and abandon injection wells that cannot be repaired by the methods listed above Stop blowouts from injection or abandoned wells using standard techniques to "kill" a well such as injecting a heavy mud into the well casing. After control of the well is reestablished, the recompletion or abandonment practices described above can be used. If the wellhead is not accessible, a nearby well can be drilled to intercept the casing below the ground surface and "kill" the well by pumping mud down the interception well [18]
Leakage into shallow groundwater	Accumulations of gaseous CO_2 in groundwater can be removed, or at least made immobile, by drilling wells that intersect the accumula tions and extract the CO_2. The extracted CO_2 could be vented to the atmosphere or reinjected back into a suitable storage site Residual CO_2 that is trapped as an immobile gas phase can be removed by dissolving it in water and extracting it as a dissolved phase through groundwater extraction wells CO_2 that has dissolved in the shallow groundwater could be removed, if needed, by pumping to the surface and aerating it to remove the CO_2. The groundwater could then either be used directly, or reinjected back into the groundwater If metals or other trace contaminants have been mobilized by acidification of the groundwater, "pump-and-treat" methods can be used to remove them. Alternatively, hydraulic barriers created to immobilize and contain the contaminants by appropriately placed injection and extraction wells. In addition to these active methods of remediation, passive methods that rely on natural biogeochemical processes may also be used
Leakage into the vadose zone andaccumulation in soil gas [25]	CO_2 can be extracted from the vadose zone and soil gas using standard vapor extraction techniques from horizontal or vertical wells

(*continued*)

TABLE 2
CONTINUED

Scenario	Remediation options
	Fluxes from the vadose zone to the ground surface could be decreased or stopped using caps or gas vapor barriers. Pumping below the cap or vapor barrier could be used to deplete the accumulation of CO_2 in the vadose zone Since CO_2 is a dense gas it could be collected in subsurface trenches. Accumulated gas could be pumped from the trenches and released to the atmosphere or reinjected back underground Passive remediation techniques that rely only on diffusion and “barometric pumping” could be used to slowly deplete one-time releases of CO_2 into the vadose zone. This method will not be effective for managing ongoing releases because it is relatively slow Acidification of the soils from contact with CO_2 could be remediated by irrigation and drainage. Alternatively, agricultural supplements such as lime could also be used to neutralize the soil
Large releases of CO_2 to the atmosphere	For releases inside a building or confined space, large fans could be used to rapidly dilute CO_2 to safe levels For large releases spread out over a large area, dilution from natural atmospheric mixing (wind) will be the only practical method for diluting the CO_2 For ongoing leakage in established areas, risks of exposure to high concentrations of CO_2 in confined spaces (e.g. cellar around a wellhead) or during periods of very low wind, fans could be used to keep the rate of air circulation high enough to ensure adequate dilution
Indoor environments with chronic low level leakage	Slow releases into structures can be eliminated using techniques that have been developed for controlling release of radon and volatile organic compounds into buildings. The two primary methods for managing indoor releases are basement/substructure venting or pressurization. Both would have the effect of diluting the CO_2 before it enters the indoor environment [26]
Accumulation in surface water	Shallow surface water bodies that have significant turnover (shallow lakes) or turbulence (streams) will quickly release dissolved CO_2 back into the atmosphere For deep, stably stratified lakes, active systems for venting gas accumulations have been developed and applied at Lake Nyos and Monoun in Cameroon (http://perso.wanadoo.fr/mhalb/nyos/)

CONCLUSIONS

This study has demonstrated that early detection of CO_2 leakage should be possible and that many remediation options are available that could be applied in the event that leakage occurs, specifically;

- the most probable scenarios for leakage of CO_2 have been identified;
- it has been demonstrated that even small leaks should be detectable if they are confined to limited areas around leaking wellbores, faults or fractures; and
- Remediation options are available that could be used to reduce or stop leakage and control the environmental, health and safety impacts of unintended releases.

While this study has identified many promising options, it must be recognized that remediation of subsurface systems is always expensive, fraught with difficulties and success is not always certain. Additional detailed studies are needed to further assess the feasibility of applying these to geologic storage projects—based on more realistic scenarios, simulations and field studies. In particular, we recommend carrying out controlled release experiments and experiments at sites with natural CO_2 seeps to confirm our ability to detect and remedy leakage.

RECOMMENDATIONS

The study presented here focused largely on identifying existing options for remediating geologic storage projects. While these have been employed with considerable success in analogous situations, particularly for gas storage and cleanup of contaminated soils and groundwater, additional options tailored specifically for geologic storage of CO_2 would be helpful. For example, injecting chemical additives that would increase the dissolution of CO_2 into the in situ fluids or accelerate mineral trapping could be used as a remediation measure. Methods for increasing the extent of residual gas trapping, potentially with surfactant-based foams, could also be useful. Similarly, it may be possible to use foam to block weaknesses in the reservoir seal, at least on a temporary basis. These and other methods should be investigated and tested in real-world situations.

With regard to early detection of leaks, experiments should be conducted to test and improve methods for leak detection. All the techniques for leak detection presented in this book should be employed in concert to determine which of them or combination of them is most effective. Moreover, it is expected that some techniques will be more effective in different geologic settings. Therefore, it is important to repeat these tests in the range of geologic settings where they will be employed.

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