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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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

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Chapter 25

LESSONS LEARNED FROM INDUSTRIAL AND NATURAL ANALOGS FOR HEALTH, SAFETY AND ENVIRONMENTAL RISK ASSESSMENT FOR GEOLOGIC STORAGE OF CARBON DIOXIDE

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ABSTRACT

This literature survey was conducted to gather and interpret information regarding potential approaches for assessing, managing and mitigating risks associated with the deep geologic storage of CO_2. Information was gathered from three principle sources: (1) industrial analogs such as natural gas storage, deep injection of hazardous wastes and nuclear waste storage and (2) natural analogs, especially those with CO_2 leaks at the surface and (3) industrial uses of CO_2 for a variety of applications. A set of lessons learned from these analogs was compiled and forms the basis for recommendations in the areas of risk assessment framework and methodology, risk management approaches and risk mitigation and remediation methods. Lessons learned include:

1. There is an abundant base of experience to draw on that is relevant and suggests that CO_2 can be stored safely if geologic storage sites are carefully selected and monitored.
2. The human health effects of exposure to elevated concentrations of CO_2 have been extensively studied and occupational safety regulations are in place for safe use. Ecosystem impacts from elevated soil gas concentrations are less well characterized and may require additional research.
3. The hazard created by CO_2 releases depends more on the nature of the release rather than the size of the release. In particular, since CO_2 is denser than air, hazardous situations arise when large amounts of CO_2 accumulate in low-lying, confined or poorly ventilated spaces. Releases, even large ones, do not pose a hazard if they are quickly dissipated in the atmosphere, such as from tall industrial stacks or explosive volcanic events.
4. Many of the risks of CO_2 storage are well understood based on experience from natural gas storage and deep injection of hazardous waste. Experience from these analogs suggest that the biggest risks from CO_2 storage will be due to: leakage through poor quality or aging injection well completions; leakage up abandoned wells; leakage due to inadequate cap rock characterization; and inconsistent or inadequate monitoring of injection wells, groundwater in overlying formations and leakage from abandoned wells.
5. Regulatory paradigms and approaches for the industrial analogs vary and none address all the issues that are important for CO_2 storage.

This chapter reviews the lessons learned and also provides recommendations for additional research to address gaps in knowledge and risk management approaches.

INTRODUCTION

Three operations are currently underway in the US that provide useful insights for geologic storage of CO_2, namely: (1) deep well injection of industrial wastes; (2) natural gas storage; and (3) industrial use of CO_2 for a variety of applications. An assessment of these activities and the lessons they provide was performed to assist the CO_2 Capture Project in selecting a portfolio of R&D projects that could improve health, safety and environmental (HSE) risk assessment for geologic storage of CO_2. In particular, the following were reviewed:

- history, status and scope of the activity;
- risk assessment framework and methods, including key issues, performance specifications and performance assessment methods;
- risk management approaches, including regulatory oversight and permitting, site characterization methods, monitoring and performance confirmation;
- risk mitigation and remediation methods employed or planned in the event that performance specifications are not met or other unintended consequences arise; and
- case studies documenting responses to historical accidents.

HSE risk assessment for geologic storage will be driven by the hazards associated with exposure to elevated concentrations of CO_2; therefore, in addition to reviewing the history and status of these activities, we also reviewed information about human and ecological health risks from exposure to elevated levels of CO_2, information from natural analogs for CO_2 storage, industrial uses of CO_2 and monitoring technology for CO_2 detection. A complete version of the extended literature review is available in Benson et al. [1].

REVIEW OF INDUSTRIAL ANALOGS RELEVANT TO CO_2 STORAGE

Natural Gas Storage

Underground natural gas storage projects have been operated successfully in the US for almost 90 years and today, 450 projects store approximately 139 million metric tonnes (MMT) of natural gas in 30 states (see also Perry [2]). The majority of storage facilities are in depleted oil and gas reservoirs, but 51 are in brine-filled aquifers and 40 in salt caverns. Experience has shown that there are a number of factors critical to the success of these projects:

- first, it is important to have a site that is adequately characterized (i.e. permeability, thickness and extent of storage reservoir, cap rock integrity, geologic structure, lithology, etc.);
- second, the storage formation should be deep enough to allow sufficiently high gas pressures for the economic success of the operation;
- third, injection/withdrawal wells must be properly designed, constructed, monitored and maintained;
- fourth, overpressuring the storage reservoir should be avoided;
- finally, abandoned wells in and near the project must be located and plugged.

While underground natural gas storage has been used safely and effectively, there have been a number of documented cases where leakage has occurred [1,2]. In over one-half of these cases, leakage was caused by defective wells (poorly constructed or improperly plugged abandoned wells). Over time, as engineering practices have improved and regulatory oversight has grown more stringent, fewer accidents have occurred, and modern procedures have made underground natural gas storage a safe and effective operation.

One of USEPA’s primary regulatory responsibilities is to protect drinking water aquifers from detrimental effects caused by underground gas storage. The USEPA has delegated authority to most of the states, which have effective regulations for permitting, operating and monitoring underground gas storage fields [3]. Regulations differ from state to state and are tailored to local concerns, such as in Pennsylvania where extra measures are taken to avoid leakage of gas into underground coalmines. In several states with abundant oil, gas, coal and/or mineral resources, a protection (or buffer) zone is established to avoid or reduce the risk of accidents caused by human intrusion.

Monitoring is an important part of the regulatory oversight of these projects [1–3]. While regulations on monitoring and reporting vary among states, almost all monitoring requirements focus on assuring that the wells are not leaking (e.g. pressure measurements and down hole logs such as temperature, pressure, noise/sonic and casing inspection logs). Observation wells installed and monitored for the purpose of verifying that gas has not leaked into shallower strata are rarely required; however, a few storage projects have over 100 wells for this purpose. Geophysical techniques to monitor the operation are not required.

Depleted oil and gas reservoirs are easier to develop than aquifer storage projects because the geologic structure and cap rock are usually well characterized from existing wells. Moreover, since the structure is known to have trapped and stored hydrocarbons over geologic time periods, it is likely to be effective for natural gas storage. Standard natural gas reservoir engineering practices are used during the permitting process and storage operations. For aquifer gas storage projects, extensive site characterization is required and well testing methods specifically for evaluating the permeability and continuity of the cap rock have been developed.

In the event that leakage occurs, remediation is possible by producing or venting the gas accumulated in shallower layers and/or reducing reservoir pressure [2,4]. In most cases, leakage is caused by the presence of leaking or abandoned wells, which should be identified and plugged as soon as possible. Some projects, such as the Herscher storage project in Illinois, continue to operate even though leakage continues. Here shallow extraction wells are used to capture the gas that leaked from the storage interval.

When a natural gas storage site is shut down, as much of the gas as is practical is removed from the formation. The injection wells are then plugged and abandoned using prescribed procedures. No long-term monitoring is required after a project has been shut down.

Deep Injection of Liquid and Hazardous Waste

The USEPA's Underground Injection Control Program recognizes five classes of injection wells, including [3,5]:

- *Class I*: wells used to inject hazardous, industrial or municipal waste beneath the lowermost formation containing an underground source of drinking water;
- *Class II*: wells used to inject fluids related to the production of oil or natural gas;
- *Class III*: wells used to inject for the extraction of minerals such as sulfur, salt, potash, or metals such as uranium by solution mining;
- *Class IV*: wells used to dispose off hazardous or radioactive waste into or above a formation that contains a USDW or an exempted aquifer. These wells are now effectively prohibited;
- *Class V*: injection wells not included in Classes I, II, III or IV.

Class I and Class II wells are most relevant to geologic storage of CO_2, particularly with regard to the potential for contaminating drinking water aquifers. However, it is important to recognize that regulations regarding the HSE effects of surface facilities and leakage of CO_2 back into the atmosphere are likely to be regulated through other programs. Confusion and inefficiencies from overlapping jurisdictions and requirements may create a regulatory morass. Early attention to this issue may prevent decades of frustration with an overly complicated and inefficient set of regulations.

Industrial liquid waste disposal by deep-well injection was initiated in 1939. Since that time the practice has expanded so that now, 9 billion gallons per year of hazardous, industrial and municipal wastes are injected into 485 Class I wells. In 1987, the cost of liquid hazardous waste disposal ranged from $49 to $207/ton. Early performance was mixed, with many examples of well failures and contamination of drinking water aquifers. Failures were attributed to: (1) poor characterization of the confining units; (2) improper well completion techniques; (3) use of well construction materials that were incompatible with the waste streams and, consequently, corroded; (4) inconsistent or inadequate monitoring; and (5) leakage through abandoned wells. Because of these problems and the inconsistent approach to oversight, progressively more stringent regulations were put in place to make the practice of industrial waste disposal by liquid injection safer. By 1988, the current set of regulations was put in place and since that time there have been no incidents where drinking water contamination has been reported.

EPA has adopted the approach of stringent regulation of deep-well-injection operations, with the goal of ensuring that contamination does not occur in the first place [5]. To obtain a permit for hazardous waste disposal by deep-well injection, the operator must demonstrate that "No Migration" of the waste will occur outside the formation into which it is injected. The formation must contain over 10,000 ppm of dissolved solids, be overlain by a suitable cap rock and be separated from a drinking water aquifer by at least one other impermeable formation.

The regulations mandate stringent controls for the siting, operation, reporting and abandoning of injection wells. Experience has shown that leaks from injection and abandoned wells were the most frequent short-term failure mechanisms. Consequently, much of the current regulatory approach focuses on minimizing the possibility of such failures. Current well completion and rehabilitation techniques appear to be adequate to prevent leakage, although finding abandoned wells remains a significant challenge. As for contamination of drinking water aquifers distant from the wellbore, some efforts to detect transmissive faults between the injection zone and overlying aquifers are mandated, and if monitoring wells are already in place in overlying protective aquifers, EPA also requires that these must be monitored for contamination. The permitting process for hazardous waste injection wells is extensive, time consuming and expensive. According to USEPA [5], factoring in the costs for geologic testing and modeling, a "No Migration" petition can cost in excess of $2,000,000.

When a facility is shut down, the EPA is particularly concerned that deep injection wells, especially those that have injected hazardous waste, are properly plugged and abandoned. Upon closure, a Class I hazardous waste well must be plugged with cement in a manner that will not allow the movement of fluids into or between drinking water aquifers. Class I hazardous waste well operators must also prepare and comply with a plan for post-closure care. The plan must include the predicted position of the waste front at closure, the status of any cleanups required and the estimated cost of proposed post-closure care. In addition, the owner or operator must continue to conduct any required groundwater monitoring until pressure in the injection zone decays to the point that the well's cone of influence no longer intersects the base of the lowermost drinking water aquifer. The owner or operator must demonstrate and maintain financial responsibility for post-closure care. This obligation survives the termination of a permit or the cessation of injection and is enforceable regardless of whether the requirement is a condition of the permit.

For deep-well injection of liquid wastes, the density of the injected fluid is usually within ±5% of the surrounding formation fluids [6]. In this case, the injected wastes tend to migrate away from the injection well with little buoyant force driving it up or down. For CO_2 storage in oil or water-filled geological formations, this will not be the case. Buoyancy forces will tend to drive CO_2 upward. A case study of municipal waste disposal in Florida demonstrates that under these conditions, containment can be more difficult and there is evidence that the less dense effluent is migrating in the opposite direction than originally anticipated based on regional hydrologic gradients. This is an important lesson for geologic storage of CO_2 and highlights the unique requirements for characterizing sites where the injected fluid will migrate under the action of gravity and not necessarily follow the migration path of or move at the same rate as regional groundwater [6].

Industrial Use of CO_2 and Human Health Effects from CO_2 Exposure

Carbon dioxide is generally regarded as a safe and non-toxic, inert gas. It is an essential part of the fundamental biological processes of all living things. It does not cause cancer, affect development or suppress the immune system in humans. Carbon dioxide is a physiologically active gas that is integral to both respiration and acid–base balance in all life. Exposure to elevated concentrations of CO_2 can lead to adverse consequences, including death. The effects of elevated CO_2 depend on the concentration and duration of exposure.

Ambient atmospheric concentrations of CO_2 are currently about 370 ppm. Humans can tolerate increased concentrations with no physiological effects for exposures up to 1% CO_2 (10,000 ppm) [7]. For concentrations of up to 3%, physiological adaptation occurs without adverse consequences. A significant effect on respiratory rate and some discomfort occurs at concentrations between 3 and 5%. Above 5%, physical and mental ability is impaired and loss of consciousness can occur. Severe symptoms, including rapid loss of consciousness, possible coma or death, result from prolonged exposure above 10%. Experiments conducted on a group exposed to up to 3% CO_2 for many weeks and short-term exposures to even higher concentrations have shown that all effects are reversible except for prolonged coma, the consequences of prolonged hypoxia (lack of oxygen) and death. These experiments, however, have been conducted on healthy adults and these conclusions may not be applicable to other more sensitive populations. Loss of consciousness occurs within several breaths and death is imminent at concentrations above 25–30%. Deaths from catastrophic releases of CO_2 are known from industrial accidents and natural disasters.

Carbon dioxide is used in a wide variety of industries: from chemical manufacture to beverage carbonation and brewing, from enhanced oil recovery to refrigeration and from fire suppression to inert-atmosphere food preservation [7]. Sources of CO_2 include natural reservoirs, separation from crude oil and natural gas and as a waste product of industrial processes (chemical manufacture), combustion processes (energy production) and biological respiration (brewing). Because of its extensive use and production, the hazards of CO_2 are well known and routinely managed. Engineering and procedural controls are well established for dealing with the hazards of compressed and cryogenic CO_2. Nevertheless, the hazards of CO_2 are significant as fatalities from fire-suppression system malfunctions and confined-space accidents attest.

Carbon dioxide is regulated by Federal and State authorities for many different purposes, including occupational safety and health, ventilation and indoor air quality, confined-space hazard and fire suppression, as a respiratory gas and food additive, for animal anesthesia and the humane slaughter of livestock, transportation and most recently as a greenhouse gas (UNFCCC). Federal occupational safety and health regulations set three limits:

- 0.5% or 5000 ppm for an average 8 h day or 40 h week;
- 3% or 30,000 ppm for an average short-term 15 min exposure limit;
- 4% or 40,000 ppm for the maximum instantaneous exposure limit above which is considered immediately dangerous to life and health.

Most industrial and safety regulations for CO_2 focus on engineering controls and specifications for transportation, storage containers and pipelines.

Monitoring is a routine part of industrial use and production of CO_2. Both real-time monitors and air sampling are used to ensure that levels remain within the regulatory guidelines. In addition, CO_2 concentrations are routinely measured and used as a proxy for air quality in buildings.

LESSONS LEARNED FROM NATURAL AND INDUSTRIAL ANALOGS

A large amount of valuable information was obtained from investigating natural and industrial analogs for geologic storage of carbon dioxide. What follows here is a synthesis of this information into five lessons that can be used to identify issues that must be addressed, identify best practices that could be adopted for geologic storage, find technologies that may be applicable for risk management or mitigation, and avoid the pitfalls encountered in the industrial analogs.

Lesson 1. There is an abundant base of experience to draw on that is relevant and suggests that CO_2 can be stored safely if geologic storage sites are carefully selected and monitored.

This includes relevant experience from the following.

- Natural gas storage projects, depleted oil and gas reservoirs, as well as aquifers have been successfully used for the purpose of providing local storage to meet fluctuating daily and seasonal demand for natural gas. Today, in the US 139 MMT of natural gas is stored annually in over 450 projects in 35 states. Over 90 years of relevant experience is available that buoyant fluids such as CO_2 can be safely stored.
- Deep injection of liquid and hazardous wastes—deep geologic formations, far below the depth of the deepest drinking water aquifer, are used to dispose off hazardous and other liquid wastes. Today, approximately 9 billion gallons of hazardous waste are disposed off this way and nearly 300 billion gallons of oil field brines are also injected into deep geologic formations. Deep injection of liquid and hazardous waste has been implemented safely since an adequate set of regulations and rigorous enforcement have been established.
- CO_2 enhanced oil recovery—59 projects are currently underway in the US that uses CO_2 to enhance oil recovery from depleted reservoirs. Most of these projects use CO_2 produced from natural reservoirs, specifically, the McElmo and Bravo Domes on the Colorado Plateau. Extensive experience with production, injection and transportation of CO_2 in long pipelines has been obtained from these projects. In addition, natural CO_2 reservoirs demonstrate that CO_2 can be stored underground for geologic time

periods (thousands to millions of years) and can be used to help understand the chemical interactions that take place between the stored CO_2 and the rock formations.

- Food preservation, beverage carbonation, and fire suppression—CO_2 is safely used in a wide range of industrial applications, from food preservation to fire suppression. This experience and the regulations for safe work practices provide further evidence that CO_2 can be managed safely and the risks are well understood.

Lesson 2. The human health effects of exposure to elevated concentrations of CO_2 have been extensively studied and occupational safety regulations are in place for safe use. Ecosystem impacts from elevated soil gas concentrations are less well characterized and may require additional research.

Lesson 3. The hazard created by CO_2 releases depends more on the nature of the release rather than the size of the release. In particular, since CO_2 is denser than air, hazardous situations arise when large amounts of CO_2 accumulate in low-lying, confined or poorly ventilated spaces. Releases, even large ones, do not pose a hazard if they are quickly dissipated in the atmosphere, such as from tall industrial stacks or explosive volcanic events. This conclusion is based on the lack of correlation between the size and consequences of releases from examples such as large volcanic eruptions, natural ecosystem fluxes, refinery emissions, small but fatal confined space releases (fire suppression) and the hazardous limnic releases that recently occurred in Cameroon (e.g. Lakes Nyos and Manoon in Cameroon).

Lesson 4. Many of the risks of CO_2 storage are well understood based on experience from natural gas storage and deep injection of hazardous waste. Experience from these analogs suggest that the biggest risks from CO_2 storage will be due to: leakage through poor quality or aging injection well completions; leakage up abandoned wells; leakage due to inadequate cap rock characterization; and inconsistent or inadequate monitoring of injection wells, groundwater in overlying formations and leakage from abandoned wells.

Lesson 5. Regulatory paradigms and approaches for the industrial analogs vary and none address all the issues that are important for CO2 storage. For example, (1) some regulations rely on performance-based requirements while others use practice-based requirements, (2) some activities are regulated by the states while others have federal regulatory oversight, and (3) there is not a consistent approach or requirement for requirements for short and long-term monitoring. Perhaps more important than these differences, none of the regulations fully address several issues that are important for CO_2 storage in geologic formations.

- Storage is needed over a comparatively long time frame to ensure that geologic storage is an effective method for decreasing greenhouse gas concentrations in the atmosphere (hundreds to thousands of years), therefore, performance requirements, regulations and liability issues over this extended time period need to be addressed [8–10].
- Additional storage security is provided by dissolution of CO_2 in pore fluids, residual gas trapping and mineral trapping; consequently, a regulatory framework that includes the storage benefits of these geochemical trapping processes is needed [6,11].
- Migration is strongly controlled by the density contrast between CO_2 and native pore fluids, leading to buoyancy-driven flow and subsequent trapping beneath low permeability and capillary barriers. Regulations specific to CO_2 should be considered that fully account for migration driven by buoyancy forces [6].
- The fact is that CO_2, unlike most other substances that are regulated for environment, health and safety purposes, is not only non-hazardous at low concentrations but also an essential part of all living systems. Alternatives to regulatory approaches used to protect groundwater quality, which are based on avoiding exposure to very low concentrations of contaminants, may be needed.

RECOMMENDATIONS FOR FUTURE RESEARCH AND EVALUATION

From the lessons learned that are described above and an evaluation of the gaps between future needs and the current knowledge, we have identified a number of recommendations for future research and evaluation. These recommendations are divided into three categories, namely, those related to: (1) risk assessment methodology; (2) risk management approaches; and (3) risk mitigation and remediation. These recommendations are summarized in Table 1. As described in this volume, many of these issues are being addressed through research and development projects sponsored by the CCP.

TABLE 1
SUMMARY OF RECOMMENDATIONS FOR RISK ASSESSMENT, RISK MANAGEMENT, AND REMEDIATION OF GEOLOGIC STORAGE PROJECTS

Topic	Recommendations
Risk assessment methodology, including key issues, performance specifications and performance assessment methods	(1) Develop a common health, safety and environmental (HSE) risk assessment framework, including treatment of uncertainty, for geological sequestration f CO_2 (2) Develop performance requirements for each of the critical components of the sequestration system, namely, at a minimum, specifications for: – Injection well completion and monitoring; – Acceptable leakage rates from the primary containment structure; and – Surface concentrations of CO_2 that could effect human health or ecosystems (3) Identify and quantify risks to ecosystems and natural resources in the vicinity of surface leaks (4) Develop and test coupled atmosphere, land-surface and subsurface models that predict atmospheric dispersion of CO_2 from leaks (5) Adapt the *F*eatures–*E*vents–*P*rocesses (FEP) procedure used in nuclear waste storage for identifying and ranking importance of critical performance parameters for geologic storage of CO_2
Risk management approaches, including regulatory oversight and permitting, site characterization methods, monitoring and performance confirmation	(1) Develop a single, consistent regulatory approach that addresses HSE issues, especially those issues dealing with surface leakage – Local safety concerns – Effectiveness for greenhouse gas control (2) Identify and investigate the effectiveness of multi-containment concepts (e.g. solubility and mineral trapping) (3) Develop well completion methods, well abandonment procedures and methods for sealing abandoned wells that are compatible with long-term containment of CO_2 (4) Develop a risk management strategy that couples monitoring requirements to performance confirmation

(*continued*)

TABLE 1
CONTINUED

Topic	Recommendations
Risk mitigation and remediation methods employed or planned in the event that performance specifications are not met or other unintended consequences arise	Methods for mitigating and remediating risks caused by leakage of CO_2 from the primary storage reservoir should be developed. Examples of potential mitigation methods include (1) controlling the pressure within the storage reservoir to prevent leakage or damage to the cap rock, (2) in the event that leakage has occurred, gas that has accumulated in shallow traps can be pumped out to prevent further migration and surface releases, (3) injection well monitoring to detect damage or leakage and (4) repair of leaking injection, production or abandoned wells

In addition, other general recommendations that will expedite development of safe and effective methods for CO_2 storage in deep geologic formations include: (1) considering the implications of others gases on HSE risk assessment (H_2S, SO_x, NO_x, hydrocarbons); (2) investigating natural analogs for HSE risks from surface leakage; (3) supporting the development and systematic evaluation of computational models that include the full set of physical, geochemical and geomechanical processes that influences the safety and effectiveness of geologic storage; and (4) supporting pilot tests in a number of geologic setting. This last recommendation is particularly important as experience has shown that most knowledge is gained from real-world experience and invariably surprises arise that were not anticipated during planning studies.

CONCLUSIONS

In conclusion, the key poorly understood HSE concerns surrounding geologic storage of CO_2 relate to the potential for unanticipated leakage. Such releases could be associated with surface facilities, injection wells or natural geological “containers” and may range from small-scale diffuse leaks to large catastrophic incidents. Extensive industrial experience with CO_2 and gases in general shows that the risks from industrial storage facilities are manageable using standard engineering controls and procedures. Serious accidents have occurred, but the incidents were preventable and experience teaches us how to operate these facilities even more safely. On the other hand, our understanding of and ability to predict CO_2 releases and their characteristics in any given geologic and geographic setting is far more challenging. Certainly there are many sites, such as oil and gas reservoirs where the probability of leakage is very low. However, brine formations, which generally are not well characterized and do not have cap rocks or seals that have stood the test of time, will require significant effort to evaluate potential risks, and these risks must be taken seriously.

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