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 1

OVERVIEW OF GEOLOGIC STORAGE OF CO_2

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ABSTRACT

This paper presents an overview of geologic storage of CO_2. Topics addressed include the nature and extent of formations that could be used for geologic storage, the physical and chemical processes responsible for geologic storage, risks of geologic storage, and demonstration projects underway today. In addition, this chapter introduces the topics that are covered in this book.

INTRODUCTION

Over the past several hundred years, atmospheric CO_2 concentrations have steadily increased and have now risen to over 370 ppm from the pre-industrial level of 280 ppm. Increases in CO_2 concentrations are mainly attributed to burning of coal, oil, and natural gas for electrical generation, transportation, industrial and domestic uses. Today, globally, over 20 billion tons of CO_2 are emitted into the atmosphere. There is a growing consensus that increases in CO_2 concentrations will disrupt the earth's climate, cause sea level to rise enough to flood many low-lying coastal regions and damage sensitive ecosystems. Experts believe that to avoid significant disruption of the climate system and ecosystems, CO_2 concentrations must be stabilized within the next several decades. At today's emission rates, atmospheric CO_2 concentrations will continue to grow rapidly and, within 50 years, may exceed the levels needed to protect sensitive ecosystems and avoid flooding in low-lying coastal areas. This situation is even more urgent when we consider that over the next 50 years CO_2 emissions are expected to double as the developing world's economies grow and the standard of living increases. To address this challenge, we need a multi-pronged approach for decreasing CO_2 emissions—more efficient production and use of energy, solar power, wind energy, biomass, switching to fuel sources with lower or negligible CO_2 emissions, and CO_2 capture and storage (CCS), the subject of this book.

CCS is a four-step process where: first, a pure or nearly pure stream of CO_2 is separated and captured from flue gas or other process stream; next it is compressed to about 100 atm; it is then transported to the injection site; and finally, it is injected deep underground into a geological formation such as an oil and gas reservoir where it can be safely stored for thousands of years or longer (see Figure 1). Volume I of this two-part book provides detailed discussion of recent innovations in capture and compression technology. This volume (Volume II) focuses on transportation and storage-related issues.

That CO_2 could be separated from flue gases and stored from the atmosphere emerged in the open literature in the late 1970s [1,2]. However, it was not until the early 1990s that R&D in CO_2 storage began in earnest. Since that time, however, progress has been accelerating through a combination of industrial, academic, and public-sector efforts. A number of factors contribute to the rapid progress in this area, specifically:

- industrial experience in the oil, gas, and gas-storage industry can provide the expertise and technology needed for CO_2 transportation, injection, performance assessment, and monitoring;
- several collateral economic benefits are possible, including CO_2-enhanced oil and gas recovery and enhanced coalbed methane recovery;
- suitable geologic formations, including oil, gas, saline, and coal formations are located near many CO_2 sources; and

- geologic analogs such as natural CO_2 reservoirs demonstrate that geologic structures can store CO_2 over very long times.

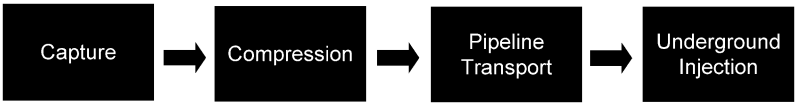

Figure 1: Schematic showing the major steps in the CO_2 capture and storage process.

Over the past decade, CCS has emerged as one of the most promising options for deep reductions in CO_2 emissions, so much so that, in fact, today 1 million tons of CO_2 is being stored annually at the Sleipner Project beneath the North Sea. Several more commercial projects are underway or in the advanced stage of planning: the In Salah project in Algeria, the Gorgon Project in Australia, and the Snohvit Project in the continental shelf offshore of Norway. In addition to these, more are under development.

STORAGE FORMATIONS AND PROCESSES

Sedimentary basins, created by the gradual deposition and compaction of sediments eroded from mountain ranges, are the mostly likely location for storing CO_2. Deposits, as thick as many thousands of meters, have accumulated in sedimentary basins around the world. Typically, sedimentary basins consist of alternating layers of coarse (sandstone) and fine-textured sediments (clay, shale, or evaporites). The sandstone layers, which provide the storage reservoir, have high permeability, allowing the CO_2 to be injected into the storage reservoir. The shale or evaporite layers have very low permeability and act as seals to prevent CO_2 from returning to the surface. Naturally occurring CO_2 reservoirs exist in North America, Australia, China, and Europe, demonstrating that CO_2 can be stored underground for millions of years or longer. In addition, many oil and gas reservoirs also contain large quantities of CO_2 confirming that oil and gas reservoirs can also store CO_2 over geologic time scales.

The conceptual framework and opportunity for storage of CO_2 in saline formations and depleted oil and gas formations were presented in early papers by Koide et al. [3–5], Winter and Bergman [6], Van der Meer [7, 8], Gunter et al. [9], Hendriks and Blok [10,11], Holloway and Savage [12], Holt et al. [13], Bachu et al. [14], Bergman and Winter [15], Omerod [16], and Weir et al. [17]. In 1996, Gunter et al. [18] described a process by which coalbed methane production could be enhanced while simultaneously storing CO_2. Studies by Byrer and Guthrie [19,20,34] and Stevens et al. [21,22] suggest that worldwide CO_2 coalbed methane recovery may also significantly add to the capacity for geologic storage of CO_2. Today, four principle types of geologic formations are widespread and are considered to have significant potential for storing large amounts of CO_2:

- active and depleted oil reservoirs;
- active and depleted gas reservoirs;
- saline formations; and
- deep coal seams and coalbed methane formations.

Other geologic formations such as marine and arctic hydrates, CO_2 reservoirs, mined cavities in salt domes and oil shale may increase storage capacity or provide niche opportunities but are likely to be developed only after the storage formations listed above are utilized.

CO_2 can be stored in these geologic formations by four principal processes [23,24].

- CO_2 can be trapped as a gas or supercritical fluid under a low-permeability cap rock, similar to the way the natural gas is trapped in gas reservoirs or the gas is stored in aquifer gas storage. Immediately after CO_2 is injected, this is likely to be the most important storage mechanism.

- CO_2 can dissolve into the fluid phase. This mechanism is referred to as solubility trapping. The relative importance of solubility trapping depends on a large number of factors, such as the sweep efficiency of CO_2 injection, formation of fingers, and the effects of formation heterogeneity.
- CO_2 can become trapped as a residual, non-wetting phase in the pore spaces of the rock. This mechanism is referred to as residual gas trapping. Once the saturation of CO_2 drops below the residual "gas" saturation, it is no longer mobile and consequently will remain trapped. The importance of this trapping mechanism has only been recognized recently and is expected to contribute significantly to the security of geologic storage [24].
- CO_2 can react, either directly or indirectly, with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix. Formation of carbonate minerals such as calcite, siderite, or alumino-carbonates such as dawsonite and adsorption onto coal are examples of mineral trapping. Mineral trapping will create stable forms of carbon that are unlikely to return to the biosphere and will increase storage security by eliminating the risk of unexpected leakage of CO_2 to the surface.

Over time, the contribution of each of these processes to provide secure long-term storage will change as illustrated in Figure 2. Initially, physical trapping will be the dominant mechanism for keeping CO_2 in the storage formation. As CO_2 migrates away from the injection well it will displace some fraction of the in situ fluids. Simultaneously, CO_2 will dissolve in the pore fluids that are left behind. Over time, as the CO_2 plume grows, larger amount of CO_2 can dissolve, thus increasing the extent of solubility trapping. Over very long periods, small-scale convection cells created by density differences between the CO_2 saturated brine and the in situ fluids will dissolve even more CO_2 [25]. The extent and evolution of CO_2 trapped as a residual phase will depend on the petrophysical properties of the storage formation. Recent studies have shown that the residual saturation may be as high as 20–30% of the pore space. In this case, the CO_2 plume tends to be compact and remains trapped near the injection well. If the residual saturation is much lower, in the range of 5–10%, residual gas trapping will increase over time as the plume migrates over a greater volume. Mineral tapping is expected to be slow but, over long time scales, may trap a significant fraction of the CO_2—the extent of which will depend on the mineralogy of the formation. Storage formations composed of a large fraction of feldspar minerals will have a higher degree of mineral trapping.

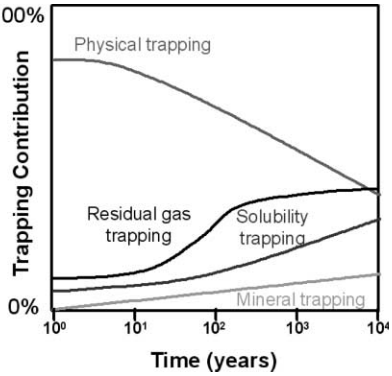

Figure 2: Schematic illustrating that residual gas trapping, solubility trapping and mineral trapping increase storage security over time.

STORAGE CAPACITY

Several worldwide and national assessments demonstrate the significant potential for geologic storage of CO_2 in saline formations, coal formations, and depleted oil and gas reservoirs [16]. Subsequent studies have focused on assessing important aspects of regional geologic formations that may be suitable for storage [18, 26–33]. Global storage capacity estimates are summarized in Table 1. While the range of estimates is large, there is a consensus that the largest potential capacity is in deep saline formations in large sedimentary basins. It is estimated that saline formations have the capacity to accommodate hundreds of years at the current CO_2 emission rates. However, these capacity estimates have not yet been validated by regional or site-specific field experiments.

TABLE 1
SUMMARY OF WORLDWIDE STORAGE CAPACITY ESTIMATES

Formation type	Capacity estimate ($Gt\ CO_2$)	Source
Depleted oil and gas reservoirs	~450	Stevens et al., 2001: GHGT 6, pp. 278–283
Coalbed methane reservoirs	60–150	Stevens et al., 1999: GHGT 5, pp. 175–180
Salt-water filled formations	300–10,000	IEA Greenhouse Gas R&D Programme, 1994 [16]

EXISTING AND PLANNED CO_2 STORAGE PROJECTS

Today there are four active geologic storage projects and at least two more are planned (see Table 2). These demonstrate the range of current experience with CCS. In all but two of these projects, the source of the CO_2 is natural gas. CO_2 is separated from the natural gas because some natural gas reservoirs contain too much CO_2 to sell on the open market unless the CO_2 is removed first. In addition to these projects, which were developed for the specific purpose of CCS, about 20 million tons per year of CO_2 is injected annually to recover oil from over 50 oil fields, primarily from carbonate formations in West Texas.

All the CO_2 storage projects listed in Table 2 are being used to one degree or another as demonstration projects. International teams of scientists, funded by private and government sources, are deploying monitoring technologies, computer simulation models, and risk assessment methods to assess the safety of these projects, improve our understanding of geologic storage, and develop advanced technologies for

TABLE 2
SUMMARY OF CURRENT AND PLANNED CCS PROJECTS

Project (operator)	Application	Mass of CO_2 (million tons/year)	Demonstration activities	Storage formation
Sleipner, North Sea (Statoil)	Storage of CO_2 stripped from natural gas	1 (since 1996)	Monitoring, modeling, best practices	Offshore salt-water sand formation
Weyburn, Canada (Encana)	EOR and CO_2 storage from coal gasification	1.7 (since 2000)	Monitoring, risk assessment, performance assessment	On-shore oil reservoir in carbonate rock
In Salah, Algeria (BP)	Storage of CO_2 stripped from natural gas	1 (since 2004)	Monitoring, risk assessment	On-shore gas reservoir in sandstone
Gorgon, Australia (ChevronTexaco)	Storage of CO_2 stripped from natural gas	4 (planned for 2006)	To be determined	Island salt-water sandstone formation
Snohvit, Offshore Norway (Statoil)	Storage of CO_2 stripped from natural gas	0.7 (planned for 2006)	To be determined	Offshore salt-water sandstone formation
San Juan Basin, New Mexico (Burlington)	Enhanced coalbed methane production		Performance assessment, risk assessment	On-shore coalbed

monitoring CO_2 storage projects. None of these existing projects is as large as would be required to capture and store the 8 million tons per year of CO_2 from a typical 1000 MW coal-fired power plant. However, the scale-up of individual projects ranging from 1–4 million tons per year to 8 million tons per year should be achievable and these projects provide substantial experience on which future projects can build.

RESEARCH AND DEVELOPMENT NEEDED TO ADVANCE GEOLOGIC STORAGE

While rapid progress has been made in the development of geologic storage of CO_2 since its inception in the 1990s, additional knowledge is needed in a number of areas to support widespread implementation of this technology. This book addresses many of these topics, which can be broadly grouped under the following topics.

Storage security and integrity. Additional knowledge is needed about the processes that contribute to long-term storage of CO_2. These include physical trapping beneath low-permeability cap rocks, trapping as an immobile residual phase in the pore spaces of the storage reservoir, and geochemical trapping in fluids or rocks. Information about and strategies to preserve the long-term integrity of well construction materials are needed to assure that the wells penetrating the storage reservoir do not fail and provide a short circuit for CO_2 back to the atmosphere. Geomechanical stresses on the cap rock that could compromise the integrity of the rock by reactivating faults or fractures need to be better understood. The influence of other gases such as H_2S, SO_x, and NO_x, which may be stored along with CO_2 need to be understood. This book addresses all these issues, both by evaluating existing analogues for CO_2 storage, such as naturally occurring CO_2 reservoirs, CO_2-enhanced oil recovery and natural gas storage, as well as presenting the results of original research on this topic.

Storage optimization. Geologic storage of CO_2 can be optimized economically by combining it with enhanced oil and gas recovery. Revenues from enhanced oil and gas recovery can be used to offset the cost of storage, and capital investments can be used to help build the infrastructure for CO_2 storage. Optimization can also be achieved by assuring efficient use of the underground storage space and applying best practices learned from related activities such as natural gas storage. This book addresses both these issues, by both evaluating existing analogues for CO_2 storage, such as naturally occurring CO_2 reservoirs, CO_2-enhanced oil recovery and natural gas storage and presenting the results of original research on this topic.

Monitoring and verification. Monitoring has been identified as one of the highest priority needs to provide safe and secure storage of CO_2. Monitoring CO_2 migration in the subsurface plays several diverse and critical roles in the development and acceptance of geologic storage. First, it is essential for accounting purposes. That is, it will be necessary to verify the net quantity of CO_2 that has been stored in the subsurface. Second, it is necessary for monitoring sweep efficiency and determining whether the available storage capacity is being used effectively. Third, it is needed for optimizing EOR and enhanced coalbed methane recovery. Finally, it is necessary to ensure the safety of storage projects by demonstrating that CO_2 is retained in the formation into which it was injected. This book provides information on monitoring technologies that can serve all these purposes, by both drawing from relevant experience across a number of monitoring applications and presenting the results of original research on this topic. Specific topics include: surface monitoring of rates and compositions of injected and produced gases and liquids; atmospheric CO_2 concentration and flux monitoring; ecosystem monitoring; surface (including 3D seismic methods), surface-to-borehole, single-well, and cross-borehole time-lapse seismic methods; electrical methods such as electrical resistance tomography and cross-well electromagnetic methods; reservoir pressure and temperature measurements; and natural and introduced chemical tracers that will provide additional information needed to quantify hydrodynamic, solubility, and mineral trapping rates and processes.

Risk assessment and mitigation. Assessing risks and developing a risk mitigation strategy are an essential part of the process for selecting and obtaining permits for a geologic storage project. The nature of the risks must be understood fully. Scenarios for both secure and leaking CO_2 storage projects must be developed. Reliable and accepted methods for quantitative probabilistic risk assessment are needed. In addition, methods for mitigating risks, including monitoring and remediation must be developed. Over the past several years, significant progress has been made in this area, particularly with regard to the application of the features, events, and processes (FEP) methodology for risk characterization and assessment. This book describes this methodology and provides examples of its application to a number of storage projects. Significant progress has also been made in understanding the consequences of leaking geologic storage projects on ecosystems and humans. Models have been developed to quantify how CO_2 behaves when released into the near surface environment and escapes back to the atmosphere. The potential impact to underground microbial communities has also been assessed. A compilation of potential remediation options, based on analogous experience in natural gas storage and disposal of liquid wastes, has also been developed. Taken together, these studies provide the foundation for risk assessment and mitigation for CO_2 storage projects in deep geologic formations.

CONCLUSIONS

Geologic storage of CO_2 in underground formations has quickly advanced from a mere concept to a reality. Significant progress has been made in the critical areas of storage security and integrity, storage optimization, monitoring and verification, and risk assessment and mitigation. More remains to be accomplished before widespread application of this technology takes place, but the results of research conducted in this project and others continue to demonstrate that this technology can make large contributions to reducing CO_2 concentration in the atmosphere. This book highlights accomplishments in the areas listed above, and in each case, identifies additional research and development needed to further advance this technology.

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