

# CARBON DIOXIDE CAPTURE AND STORAGE

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## Assessment of Risks from Storage of Carbon Dioxide in Deep Underground Geological Formations

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# Introduction and Results

*“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO<sub>2</sub> releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas” (IPCC, 2006).*

## Purpose of this Report

The purpose of this report is to summarize what is known about the health, safety and environmental risks associated with the storage of CO<sub>2</sub> in deep underground geological formations. Because this is a relatively new technology, we draw not only on the actual experience, but in addition, on similar activities such as natural gas storage, acid gas disposal and CO<sub>2</sub>-enhanced oil recovery. While qualitative in nature, this report provides a framework that, with further quantitative analysis, could be used as the basis for a quantitative risk assessment for geological storage of CO<sub>2</sub>.

## Approach

This report draws on published studies regarding the risks of geological storage of CO<sub>2</sub>, analogous industrial practices and natural releases of CO<sub>2</sub>. These studies include assessments of the three existing geological storage projects – the Sleipner Project<sup>2</sup> offshore of Norway, the Weyburn Project<sup>3</sup> in Canada, and the In Salah Project in Algeria – research papers on storage processes, “lessons-learned” reviews

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<sup>1</sup> Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change (IPCC), 2006, Cambridge University Press, Cambridge, U.K.

<sup>2</sup> Best Practices Manual, Saline Aquifer CO<sub>2</sub> Project, Statoil Research Center, N-7005, Trondheim, Norway, 40 pp.

<sup>3</sup> IEA GHG Weyburn CO<sub>2</sub> Monitoring & Storage Project Summary Report 2000-2004. PTRC, M. Wilson and M. Monea, eds (2005), PTRC, Canada, 273 pp.

from similar industrial activities<sup>4</sup>, and assessments such as those recently completed by the Intergovernmental Panel on Climate Change.

The report begins with a brief review of the concepts behind geological storage of CO<sub>2</sub> and a description of the multiple lines of evidence that lead scientists and engineers to conclude that this technology can be safe and effective. The remainder of the report addresses questions regarding the nature and likelihood of health, safety and environmental (HSE) risks associated with CO<sub>2</sub> storage. As described above, at this time, this analysis is largely qualitative. However, by comparison to the ongoing activities such as natural gas storage and CO<sub>2</sub>-EOR, which are carried out safely today, one can infer the level of risks associated with CO<sub>2</sub> storage. Analysis of HSE statistics from these related activities could be used to improve quantification of the risks associated with CO<sub>2</sub> storage.

## Results

On a project-by-project basis, the risks of geological storage of CO<sub>2</sub> are expected to be no greater than the risks associated with analogous industrial activities that are under way today. Oil and gas production operations, natural gas storage, and disposal of liquid and hazardous waste have provided experience with underground injection of fluids and gases on a massive scale. The injection volume of an individual storage project will be comparable to the larger scale CO<sub>2</sub>-EOR projects taking place in the U.S. today. Because the technology for characterizing potential CO<sub>2</sub> storage sites, drilling injection wells, safely operating injection facilities, and monitoring will be adapted and fine-tuned from these mature industrial practices taking place today, it is reasonable to infer that the level of risk will be similar.

Regulatory permitting and ongoing oversight is also an important component of assuring an acceptable level of risk associated with injection operations. All of the existing injection operations fall under some kind of state and/or federal regulatory regime, depending on the nature of the injection operations. These regulations are designed to protect the health of workers, the public, and the environment. For existing injection operations, regulations exist for ensuring that the injection site and depth are sufficient to protect drinking water resources, that injection pressures are low enough not to damage the caprock of the storage formation, and that injection wells are properly monitored and maintained. For CO<sub>2</sub> storage, additional monitoring to track migration of the injected CO<sub>2</sub> may also reduce risks from unanticipated leakage. At the end of the active injection period, ongoing monitoring

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<sup>4</sup> Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results from the CO<sub>2</sub> Capture Project, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification, S.M. Benson, ed. (2005), Elsevier Publishing, UK. 654 pp.

for some period after injection would provide additional confirmation that the injected CO<sub>2</sub> remains in the injection formation.

A recent assessment of CO<sub>2</sub> capture and storage authored by 32 authors from around the world concluded that, based on multiple lines of evidence regarding the short and long-term security of geological storage, for large-scale CO<sub>2</sub> storage projects (assuming that sites are well selected, designed, operated and appropriately monitored) it is likely the fraction of stored CO<sub>2</sub> retained is more than 99% over the first 1,000 years. The expected long retention times, combined with a wealth of related experience with large-scale injection, lead these authors to conclude (IPCC, 2006):

*“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO<sub>2</sub> releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas”*

The results of this assessment, taken together with actual operating experience from three CO<sub>2</sub> storage projects with a collective operating experience spanning 17 years, suggests that CO<sub>2</sub> storage in deep geological formations can be carried out safely and reliably.

# Carbon Dioxide Capture and Storage Overview

*CO<sub>2</sub> capture and storage technology can eliminate most of the CO<sub>2</sub> emissions from the use of fossil fuels at stationary sources such as power plants by capturing and injecting them into deep geological formations for long-term or permanent storage. Three CO<sub>2</sub> capture and storage projects exist today, and more are under development. This is a tremendously important new climate change mitigation technology that can significantly reduce CO<sub>2</sub> emissions while continuing to use fossil fuels, such as coal, for power generation.*

Today, 22 billion tonnes of CO<sub>2</sub> are emitted each year into the atmosphere from manmade sources. Worldwide, approximately one-third of emissions are from electricity production, one-third from transportation, and the rest are from heating buildings and other industrial uses. Oil, coal and natural gas are the source of these emissions, and these fossil fuels provide for over 85% of the world's energy needs. Over the next hundred years, demand for energy is expected to more than double. Growth will be particularly critical in developing nations where industrialization and improved quality of life will increase demand for energy. Scenarios designed to predict future emissions estimate that, unless action is taken to limit emissions, by 2100, annual emissions of CO<sub>2</sub> from fossil fuels will range from 16 to 110 billion tonnes per year. Most of these scenarios indicate a doubling of CO<sub>2</sub> emissions by the middle of this century.

Reducing or offsetting CO<sub>2</sub> emissions from fossil fuel use is the primary purpose of the new suite of technologies called Carbon Capture and Storage. Two basic approaches are available. For the first approach, CO<sub>2</sub> is captured directly from the industrial source, concentrated into a nearly pure form and then stored in geological formations far below the ground surface. This approach is commonly referred to as *Carbon Dioxide Capture and Storage (CCS)*. CCS is expected to be most useful for large, stationary sources of CO<sub>2</sub> such as from power plants, petroleum refineries, gas processing facilities and cement factories. The second approach to CCS enhances natural biological processes that take CO<sub>2</sub> out of the atmosphere and sequester it in plants, soils and marine sediments. This approach is often referred to as *Carbon Sequestration* and since it removes CO<sub>2</sub> from the atmosphere, it is particularly useful for offsetting emissions that are difficult to capture directly at the source (e.g. CO<sub>2</sub> emitted from mobile sources like cars and trucks). Carbon dioxide

capture, from sources such as electricity generating plants, and storage in deep geological formations is the focus of this report.

Carbon dioxide capture and storage is a four-step process. First, the CO<sub>2</sub> is separated from power plant “flue gas” and concentrated into a nearly pure form. For today’s natural gas and coal-fired power plants, from 4 to 14% of the flue gas is CO<sub>2</sub>; the rest being is primarily nitrogen and oxygen. After the CO<sub>2</sub> is separated from the flue gas, it is compressed to about 100 bars, where it is in a liquid phase. Next, it is put into a pipeline and transported to the location where it is to be stored. Pipelines transporting CO<sub>2</sub> for hundreds of kilometers exist today. The last step is to inject the CO<sub>2</sub> into a deep geological formation for long term storage.

The technology used for storing CO<sub>2</sub> in deep underground formations is adapted from oil and gas exploration and production technology. For example, technologies to drill and monitor wells that can safely inject CO<sub>2</sub> into the storage formation are available from CO<sub>2</sub>-EOR. Methods to characterize a site are fairly well developed, based on oil and gas exploration and characterization of natural gas storage sites, particularly aquifer storage sites. Models are available to predict where the CO<sub>2</sub> moves when it is injected underground, although more work is needed to further develop and test these models, particularly over the long time frames and large spatial scales envisioned for CO<sub>2</sub> storage. Monitoring of the subsurface movement of CO<sub>2</sub> is currently being successfully conducted at several sites, although again, more work is needed to refine and test monitoring methods.

## **What kind of geological formations are suitable for CO<sub>2</sub> storage?**

*Oil and gas reservoirs, deep saline formations with suitable caprocks and deep unmineable coal formations can be used for CO<sub>2</sub> storage. Most suitable formations will be ½ mile or deeper below the ground surface.*

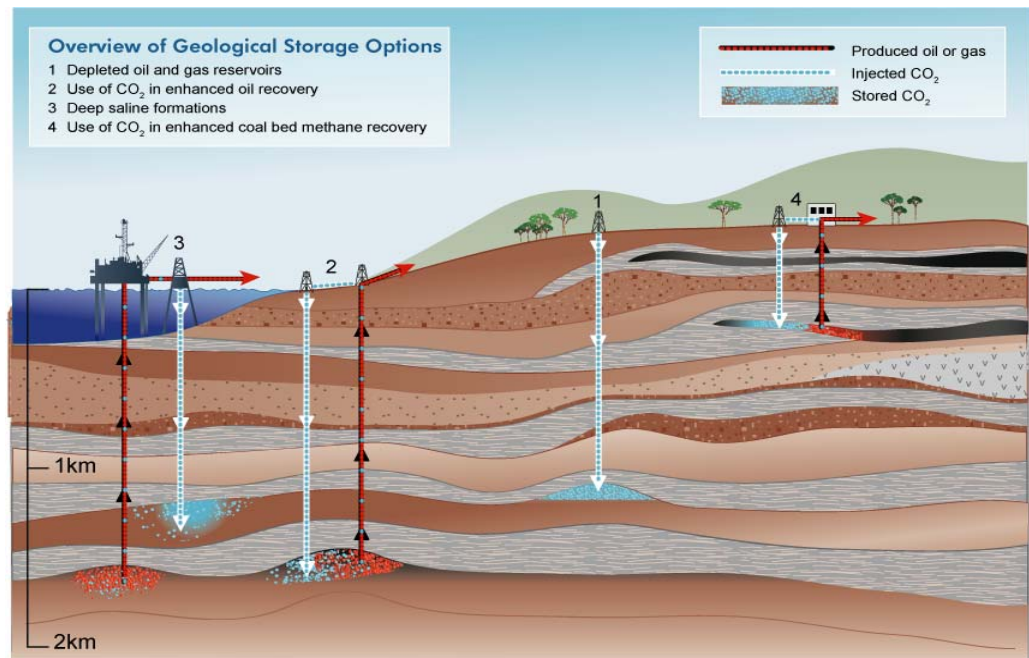
Geological formations suitable for storage of CO<sub>2</sub> occur in sedimentary basins — where thick accumulations of sediments have been deposited over geological time periods of millions of years. Rocks in sedimentary basins are composed of transported and deposited rock grains, organic material, and minerals that form after the rocks are deposited. The pore space between grains or minerals is occupied by fluid (mostly water, with occasional occurrences of oil and gas). The same kinds of geological setting where oil and gas deposits are found are suitable for geological storage. These settings are distinguished by the presence of alternating layers of rocks with different textures. Some of the layers consist of very-fine-textured materials such as clay, silt and salts (evaporites). These form impermeable barriers, or seals, that trap oil and gas underground—and are also essential for trapping CO<sub>2</sub> underground. Alternating with these low-permeability layers are coarser textured layers, consisting typically of sand or carbonate rocks (mainly limestone and

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dolomite), that form the reservoir in which the oil and gas reside. These coarse-textured sand and carbonate layers can also be used for underground storage of CO<sub>2</sub>.

As shown in Figure 1, CO<sub>2</sub> can be stored in oil reservoirs, gas reservoirs and saline formations (rocks filled with salty water that is not suitable for drinking water, agricultural or industrial use). In addition, deep unminable coal beds may also be suitable for CO<sub>2</sub> storage, although this technology is not as well developed as the other options.

In general, CO<sub>2</sub> will be stored at depths ½ a mile or more below the ground surface. At these depths, CO<sub>2</sub> is more like a liquid than a gas, resulting in efficient use of the underground storage space. In addition, the security of underground containment is enhanced by number of factors, including smaller density differences between the CO<sub>2</sub> and *in situ* fluids, increased probability of multiple geological barriers between the storage formation and the ground surface, and the smaller number of old abandoned wells that penetrate the caprock of the storage formation.



**Figure 1.** Illustration showing several options for storage of CO<sub>2</sub> in deep geological formations (IPCC, 2006).

## How many CO<sub>2</sub> storage projects exist today and are more planned?

There are three CO<sub>2</sub> storage projects in operation today: the Sleipner Project offshore of Norway; the Weyburn Project in Saskatchewan, Canada; and the In Salah Project in Algeria.

- The Sleipner Project, which began in 1996, pumps about 1 million tonnes per year of CO<sub>2</sub> into a saline formation located offshore of Norway. Carbon dioxide is captured from a natural gas processing plant and pumped into the Utsira Formation, a highly permeable sandstone at depth of 800 m beneath the sea-bottom.
- The Weyburn Project combines CO<sub>2</sub>-EOR with CO<sub>2</sub> storage. Since it began in 2000, between 1 and 2 million tonnes per year have been pumped into an oil reservoir.
- The In Salah Project, which began in 2004, pumps about 1 million tonnes per year of CO<sub>2</sub> into the water-filled part of a producing gas reservoir.

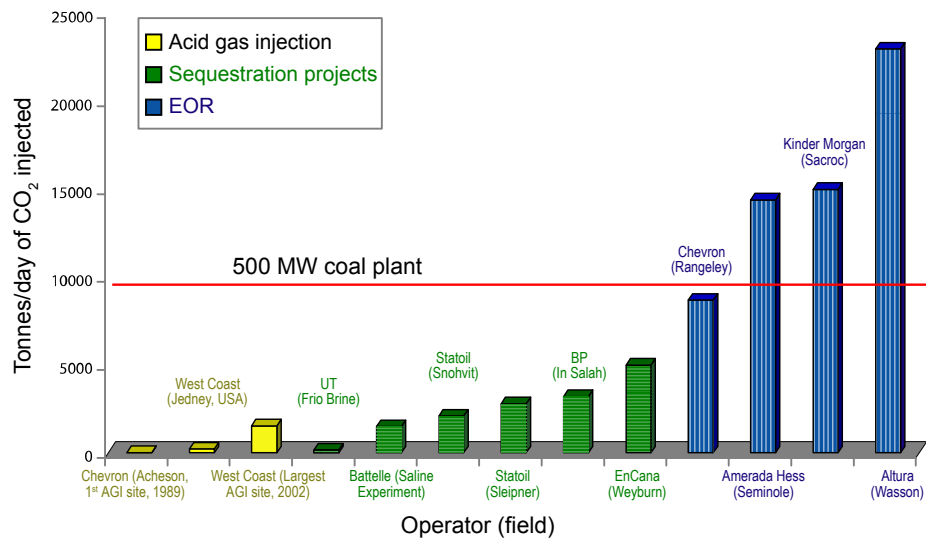
All of these projects include extensive monitoring by international research teams—monitoring which has demonstrated safe and effective storage at each of these sites. Within the next several years, several more industrial-scale projects will become operational. In addition, over 20 pilot projects are under way, including those sponsored by the Department of Energy through the Regional Sequestration Partnership Program.

Recently, plans for two industrial scale CCS projects have been announced in the United States. The FutureGen Alliance will build a 275 MW coal-fired power plant with CO<sub>2</sub> capture and storage. The site for this project will be selected in 2006. The second project, announced in February 2006 by BP and EMG, will build a 500 MW pet-coke fired power plant in California. The CO<sub>2</sub> will be stored in an oilfield in conjunction with CO<sub>2</sub>-EOR as described below.

In addition to these CO<sub>2</sub> storage projects, CO<sub>2</sub>-enhanced oil recovery has been under way for more than 30 years. To enhance recovery of oil, CO<sub>2</sub> is pumped into deep oil reservoirs and used to displace oil that would be difficult to remove by conventional methods. Although not designed for CO<sub>2</sub> storage, the technology for CO<sub>2</sub>-EOR is essentially the same. In the United States, 73 CO<sub>2</sub>-EOR operations inject up to 30 MtCO<sub>2</sub> each year.

### How do existing CO<sub>2</sub> injection operations compare to large scale CCS projects?

Figure 2 shows that storage of CO<sub>2</sub> emissions from a 500 MW coal-fired power plant would be from 2 to 3 times larger than the existing storage projects, but only about ½ the size of the largest CO<sub>2</sub>-EOR projects. The similar size of these projects suggests that much about the risks on CO<sub>2</sub> storage can be learned from existing CO<sub>2</sub> injection operations.



**Figure 2.** Comparison of the magnitude of CO<sub>2</sub> injection activities, illustrating that the storage operations from a typical 500 MW coal plant will be the same order of magnitude as existing CO<sub>2</sub> injection operations (IPCC, 2006).

## How secure is geological storage of CO<sub>2</sub>?

*For large-scale operational CO<sub>2</sub> storage projects, assuming that sites are well selected, designed, operated, and appropriately monitored, the balance of available evidence suggests the following:*

- *It is very likely that the fraction of stored CO<sub>2</sub> retained is more than 99% over the first 100 years.*
- *It is likely that the fraction of stored CO<sub>2</sub> retained is more than 99% over the first 1000 years (IPCC, 2006).*

There are multiple lines of evidence regarding the security of geological storage of CO<sub>2</sub>. Evidence from naturally occurring hydrocarbon accumulations, CO<sub>2</sub>-EOR, natural gas storage, fundamental scientific studies, model predictions and actual CO<sub>2</sub> storage projects provide evidence for short- and long-term storage security.

- Naturally occurring oil, gas and CO<sub>2</sub> reservoirs demonstrate that buoyant fluids such as CO<sub>2</sub> can be trapped underground for millions of years.
- Industrial analogues such as natural gas storage, CO<sub>2</sub>-EOR, acid gas injection, and liquid-waste-disposal operations have developed methods for injecting and storing fluids without compromising the integrity of the caprock or the storage formation.
- Fundamental principles of multiphase flow of CO<sub>2</sub> in the subsurface indicate that several mechanisms contribute to long-term storage security, including physical trapping beneath low-permeability rocks such as silts, clays and evaporates; dissolution of CO<sub>2</sub> in brine; capillary trapping of CO<sub>2</sub>; adsorption on coal, and mineral trapping. The relative importance of these mechanisms will vary from site to site, depending primarily on the geological structure and mineralogical makeup of the rocks. Together these trapping mechanisms increase the security of storage over time, thus further diminishing the possibility of potential leakage and surface release.
- Computer simulation models, although in need of additional enhancements and validation, predict that carefully chosen sites will not leak unless specific features intended to induce leakage are included in the models.
- Finally, early experiences at the Sleipner Project in the North Sea (9 years of operation), the Weyburn Project in Saskatchewan (six years of operation), Canada and the In Salah Project in Algeria (2 years of

experience) have been successful, with no evidence of leakage or safety problems. Today we have the benefit of over 17 years of cumulative experience from which we can draw conclusions regarding the risks of CO<sub>2</sub> storage projects.

Taken together, available lines of evidence suggest that for large-scale CO<sub>2</sub> storage projects, assuming that sites are well selected, designed, operated, and appropriately monitored, retention rates will be high. The IPCC Special report on CO<sub>2</sub> Capture and Storage (2006) concluded that the fraction of stored CO<sub>2</sub> retained will likely be more than 99% over the first 1000 years. The report also concludes that storage security will continue to increase over time as a result of processes that immobilize the CO<sub>2</sub>, such as by the formation of carbonate minerals.

## **What is involved in a typical CO<sub>2</sub> storage project?**

*Phases of a CO<sub>2</sub> storage project include site characterization and selection, obtaining permits from regulatory agencies, injection operations and monitoring, and eventually site closure. Each of these steps is designed to assess, manage and reduce the risks associated with CO<sub>2</sub> injection and storage.*

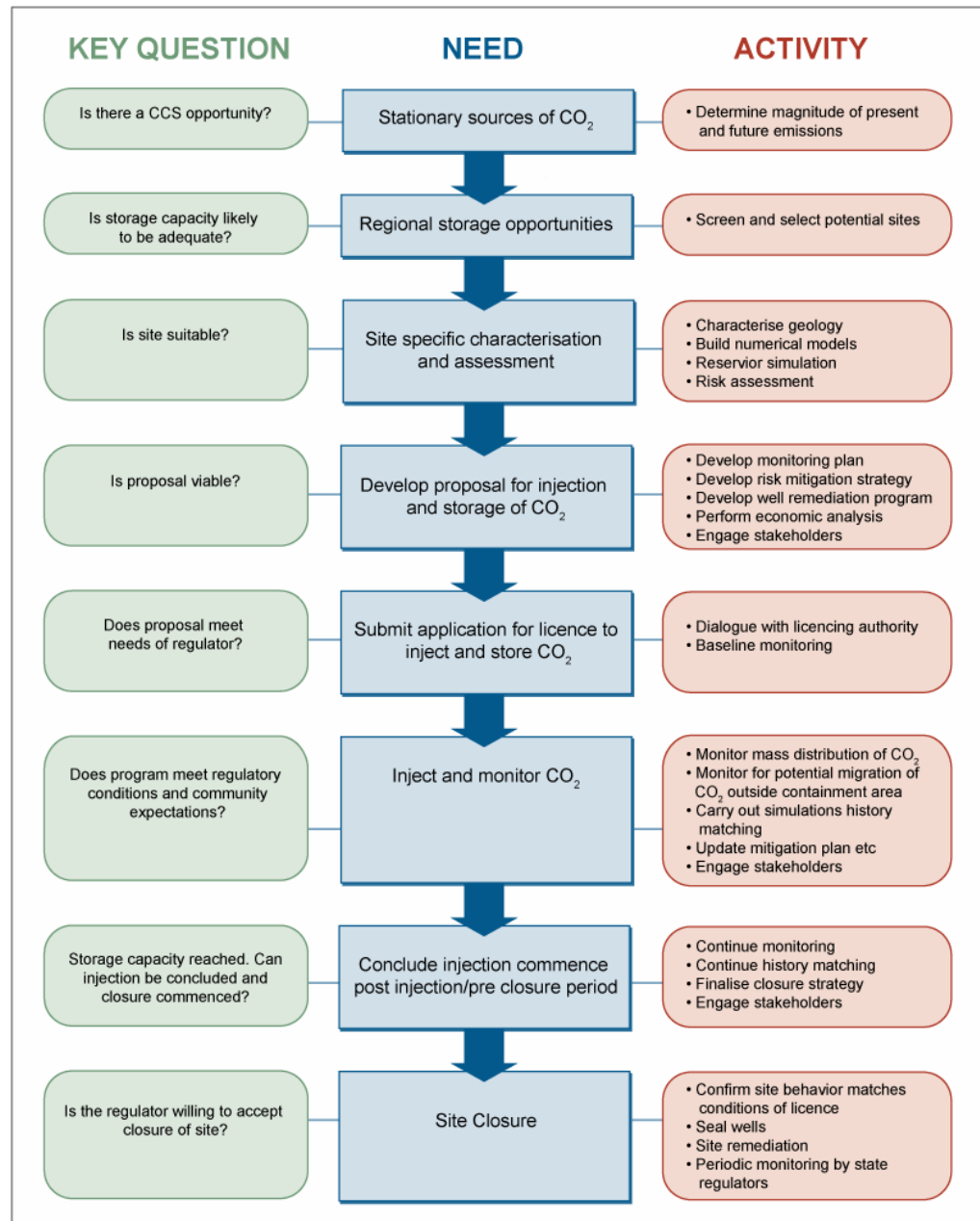
The life-cycle of a typical storage project is shown in Figure 3. Each of these steps is designed to assess, manage and reduce the risks associated with CO<sub>2</sub> injection and storage. Initially, site characterization and selection will assess the quality of the caprock, storage capacity, and injectivity. For storage in oil and gas reservoirs, much of this information is likely to be available in advance of the project. For storage in saline formations, this requires a significant effort, including drilling and testing wells. Sophisticated computer models are used to predict where the injected CO<sub>2</sub> will migrate underground and how efficiently the storage volume will be filled. Computer models will also be used to predict the very long term storage performance. Careful site characterization and selection is the most important element of assessing and managing risks. It is expected that this may take from one to five years to complete, depending on the amount and quality of information that is available at the onset of the project. Before injection of CO<sub>2</sub> can begin, permits are required from regulatory agencies to start operations. Permits also include performance prediction modeling, monitoring and verification, and reporting requirements.

During the operational phase of a project, ongoing monitoring will be used to ensure that workers, the public and the environment are protected. During the early phases of the storage project, monitoring is especially important for confirming that the site is suitable and behaving as predicted. Comparisons between the actual performance and predictions are important for confirming that the site will have

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acceptable storage performance. These same computer models and approaches are used in the oil and gas industry to manage and optimize oil and gas recovery.

Over the assumed 30 to 50-year lifetime of a “typical” large-scale storage project, from 150 to 250 million tonnes of CO<sub>2</sub> will be injected underground. After the injection phase is completed, the surface facilities will be removed and the injection wells will be sealed in accordance with regulatory requirements. During this phase of the project, monitoring will continue to observe the post-injection pressure decline and to monitor continued movement, if any, of the injected CO<sub>2</sub>. Eventually, when it is confirmed that the CO<sub>2</sub> is securely trapped underground, monitoring will decrease or stop. The time frame over which this occurs could be as short as a few years in a depleted gas reservoir or may be much longer in a saline formation where a combination of capillary trapping and solubility trapping will eventually immobilize the CO<sub>2</sub>.



**Figure 3.** Life-cycle of a CO<sub>2</sub> storage project illustrating how risks are assessed, managed and reduced over the 30-to-50 year duration of a typical project (IPCC, 2006).

# Methods for Assessing the HSE Risks

*Storage of CO<sub>2</sub> in deep underground geological formations uses many of the same technologies that have been developed by the oil and gas industry. Experience in oil and gas production, CO<sub>2</sub>-enhanced oil recovery, natural gas storage, acid gas disposal and underground disposal of liquid wastes provides experience from which the risks of geological storage can be assessed. In addition, the industrial use of CO<sub>2</sub> in a variety of applications provides guidelines for the safe handling of CO<sub>2</sub>.*

Assessing the risks of CO<sub>2</sub> capture and storage draws from an extensive body of knowledge developed over the past century, from basic physiological studies of the effects of CO<sub>2</sub> on humans, occupational safety for handling CO<sub>2</sub> in a variety of industrial applications, studies of natural CO<sub>2</sub> releases in volcanic settings, to related oil-field experience with injection of CO<sub>2</sub> or other fluids in deep geologic formations. In addition, three CO<sub>2</sub> storage projects are beginning to develop a track record of experience from which quantitative performance metrics can be established. Probabilistic methods specifically for assessing the risk of CO<sub>2</sub> storage projects are also under development.

## Is CO<sub>2</sub> hazardous to humans and the environment?

*CO<sub>2</sub> is a familiar and integral part of our everyday lives that is generally regarded as safe. However, concentrated CO<sub>2</sub> in confined spaces poses a significant but well-known hazard that falls within standard industry practice, engineering controls, and safety procedures.*

To begin a risk assessment of geologic storage of CO<sub>2</sub>, we must first understand both the context for evaluating CO<sub>2</sub> exposures and the human health and environmental impacts of exposure to elevated concentrations of CO<sub>2</sub>. Fortunately, there is a large amount of information to draw on in this regard. Carbon dioxide was one of the first gases identified, and it remains widely used in industry. Regulations are well developed for using CO<sub>2</sub> in occupational and industrial settings and for storing and transporting it.

Carbon dioxide is ubiquitous in the natural world. It undergoes an endless cycle of exchange among the atmosphere, living systems, soil, rocks, and water. Volcanic eruptions, the breathing of living things from humans to microbes, mineral weathering, and the combustion or decomposition of organic materials all release CO<sub>2</sub> into the atmosphere. Atmospheric CO<sub>2</sub> is then cycled back into plants, the oceans, and minerals through photosynthesis, dissolution, precipitation, and other chemical processes. Biotic and abiotic processes of the carbon cycle on land, in the atmosphere, and in the sea are connected through the atmospheric reservoir of CO<sub>2</sub>.

Carbon dioxide is a commodity that 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. Because of its extensive use and production, the hazards of CO<sub>2</sub> are well known and routinely managed. Engineering and procedural controls are well established for dealing with the hazards of compressed and cryogenic CO<sub>2</sub>.

Ambient atmospheric concentrations of CO<sub>2</sub> are currently about 380 ppm. Humans can tolerate increased concentrations with virtually no physiological effects for exposures that are up to 1% CO<sub>2</sub> (10,000 ppm). 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%. Loss of consciousness occurs within several breaths and death is imminent at concentrations above 25 to 30%.

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, and transportation. Federal occupational safety and health regulations set three limits:

- 0.5% or 5,000 ppm for an average 8-hour day or 40-hour week.
- 3% or 30,000 ppm for an average short-term 15-minute exposure limit.
- 4% or 40,000 ppm for the maximum instantaneous exposure limit above which is considered immediately dangerous to life and health.

Ecosystem impacts from exposure to elevated concentrations of CO<sub>2</sub> are less well understood. Plants in general are even more tolerant than invertebrates to elevated CO<sub>2</sub>, so any small-scale, short-term gas leaks would have minimal impacts. Because CO<sub>2</sub> could accumulate in soils, persistent leaks, in contrast, could suppress respiration in the root zone or result in soil acidification, which would be harmful to plants. While unlikely to occur, catastrophic releases could certainly kill vegetation as well as animals. Moderate increases in CO<sub>2</sub> concentrations stimulate plant

growth, while decreasing the loss of water through transpiration. At the other end of the scale, tree kills associated with soil gas concentrations in the range of 20 to 30% CO<sub>2</sub> have been observed at Mammoth Mountain, California, where volcanic outgassing of CO<sub>2</sub> has been occurring since at least 1990.

## **Why is the existing experience with CO<sub>2</sub>-EOR and natural gas storage relevant?**

*The cumulative experience from CO<sub>2</sub>-EOR and natural gas storage provides the foundation for qualitatively and quantitatively assessing the risks of CO<sub>2</sub> storage.*

Carbon dioxide is stored in deep geological formations by injecting it through a well into a porous formation that is sealed on top by a low permeability cap. Essential elements of this technology include site characterization, performance prediction models, injection well drilling and construction, pumping, and monitoring. All of the technologies have been developed over the past century and are widely used for injection of fluids, particularly for oil-field operations, including CO<sub>2</sub>-EOR, and natural gas storage. The majority of natural gas storage projects are in depleted oil and gas reservoirs and saline formations, although caverns in salt have also been used extensively. Underground natural gas storage projects have operated successfully for almost 100 years and in many parts of the world. In the U.S., over 470 underground natural gas storage facilities are an integral part of our gas supply infrastructure. These projects provide for peak loads and balance seasonal fluctuations in gas supply and demand.

For appropriately selected, managed and operated geological storage projects, on a project-by-project basis, there are no unique risks that are not present in these industrial analogues. In fact, the risks of CO<sub>2</sub> storage are likely to be lower, since unlike natural gas, CO<sub>2</sub> is not flammable. The cumulative experience from these practices provides the foundation for qualitatively and quantitatively assessing the risks of CO<sub>2</sub> storage.

Statistics regarding the number and nature of health, safety and environmental incidents from these industries are collected by State and Federal Authorities, including permitting agencies and OSHA. These data can provide a basis for quantifying the risks from geological storage of CO<sub>2</sub>. This effort has not yet been undertaken.

## **What do natural accumulations and releases tell us about the risks of CO<sub>2</sub> storage?**

*Natural analogues can be important sources of information about two aspects related to health, safety and environmental risk assessment. First, they provide evidence for the feasibility of geologic containment over the long term. Second,*

*looking at surface releases elucidates potential consequences, hazards, and worst-case scenarios in the event that leakage occurs.*

Naturally occurring accumulations of CO<sub>2</sub> are found in natural gas, oil and CO<sub>2</sub> reservoirs throughout the world. Effective containment of CO<sub>2</sub> occurs in the same types of geologic settings that trap hydrocarbons, mostly in sedimentary rocks overlain by low-permeability strata. There is no evidence that CO<sub>2</sub> is stored underground any less effectively than other gases. Moreover, CO<sub>2</sub> accumulates underground as a gas, mixture of gases, supercritical fluid, and/or solute dissolved in oil or aqueous phase, thus providing confidence that storage will be possible for the range of conditions expected for intentional man-made geologic storage.

Examples of settings where CO<sub>2</sub> releases occur span the full range, from the ubiquitous benign examples of diffuse off-gassing from springs, to catastrophic examples from volcanic provenances. Most of the CO<sub>2</sub> releases in these environments are harmless, with people living safely nearby for centuries. However, large natural releases have led to catastrophic consequences. The size of the release, the topography in which the release occurs, and the meteorological conditions of the release all distinguish whether or not a release will be hazardous. Those rare combinations of circumstances that lead to sustained accumulation of high concentrations of CO<sub>2</sub> are those that are most harmful. Most detectable leaks that lead to elevated CO<sub>2</sub> concentrations, and virtually all hazardous leaks, occur in volcanic areas that are highly fractured and therefore unsuitable for CO<sub>2</sub> storage.

## **What other methods are used for quantifying risks?**

*Computer simulation models are available to predict the performance and risks of geological storage projects. Probabilistic methods for assessing uncertainty are under development. With time, these models will improve as a greater degree of site-specific and collective experience with CO<sub>2</sub> storage is gained.*

Computer simulation models play a key role in assessing the risks of a geological storage project. These models include the most important processes that effect what happens when CO<sub>2</sub> is injected underground including:

- Migration of CO<sub>2</sub> through the pore spaces of the rock
- The displacement of water, oil or gas by CO<sub>2</sub>
- The buildup of pressure in the storage formation caused by injecting CO<sub>2</sub>
- Geochemical reactions between CO<sub>2</sub> and the formation, which largely act to transform CO<sub>2</sub> into immobile forms by dissolving it in water or converting it to minerals

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- Deformation of the formation and overlying rocks caused by the pressure buildup in the formation
- Changes in the state of stress on faults and fractures which may alter their sealing characteristics and induce seismicity
- Potential leakage up the injection well, nearby wells or abandoned wells that have not been sealed properly

During site selection, these models are used by the project developers to demonstrate that the site will provide sufficient storage security and pose no unacceptable risks. If during this stage of the project a site is shown to be inadequate, it would be abandoned in favor of a more suitable site.

Over the life-cycle of a storage project, the model continues to be refined as new performance data are available. By the end of the 30-to-50 year project, there will be a high degree of confidence in the long-term predictions in the post-injection period.

It is also possible to incorporate uncertainty into these models, such that the probability of a successful project can be assessed. Uncertainty or variability in models, parameters and scenarios can be included through the use of Monte-Carlo methods (i.e. systematic consideration and quantification of uncertainties using models). Alternative approaches to probabilistic risk assessment include expert elicitation, use of experience-based statistics, and methods such as fault-tree analysis (quantitative evaluation of risk based on a combination of models, expert elicitation and experience-based statistics). All of these approaches are under development at this time. With time and experience, confidence in the predictions from these models will increase.

# Assessment of Risks from Geological Storage of Carbon Dioxide

*“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO<sub>2</sub> releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas” (IPCC, 2006).*

Risk assessment involves determining both the consequences and likelihood of an event. The industrial analogues, CO<sub>2</sub>-EOR and natural gas storage discussed in the previous chapter, provide the basis for assessing the likelihood, and in part, the consequences of these events.

Scientific assessments and predictions from computer simulation models also contribute in assessing both the consequences and likelihood of an event.

## What are the risks from geological storage of CO<sub>2</sub>?

Risks from geological storage of CO<sub>2</sub> primarily result from the consequences of unintended leakage of CO<sub>2</sub> from the storage formation. There are two principal unintended leakage scenarios that must be considered. First, and the most likely, is that CO<sub>2</sub> leaks up a well — either the injection well itself, or a nearby well that is improperly sealed. In this case, releases at the surface are likely to be confined to a small area, have a comparatively high flux, and pose a risk only to those in the close vicinity of the leaking well. The second unintended leakage scenario arises from leakage up a fault or fracture that was not identified or properly characterized during site selection. In this case, the surface release may take place over a broader area, but is likely to have a lower flux and (depending on the release rate) may or may not create a significant risk to people or the environment. Combinations of these two scenarios are also possible, where leakage by one or another of these scenarios converts to the other as the CO<sub>2</sub> moves towards the land surface.

If leakage up a well were detected, methods are available to seal the well, thus preventing further leakage. Sealing wells can be accomplished shortly after the problem is identified. For leakage up faults or fractures, stopping the leakage may be more difficult, taking some time to first locate the source of the leak and then, if possible to stop it. A better approach is to monitor the underground movement of CO<sub>2</sub> and detect leakage long before it reaches the ground surface. Early warning that leakage is occurring can be used to either stop the project or implement methods, such as lowering the injection pressure, to stop leakage.

These are the same risks associated with unintended leakage of fluids or gases from CO<sub>2</sub>-EOR and natural gas storage projects, both of which take place in geological settings similar to that in which CO<sub>2</sub> storage is likely to take place. Experience has shown that in the U.S., the largest risks are associated with improperly sealed abandoned wells that are located in oil and gas exploration provinces.

### **What is the likelihood of unintended leakage from geological storage of CO<sub>2</sub>?**

Whether or not unintended leakage occurs will depend heavily on the quality of the site characterization and selection, effectiveness of regulatory oversight, operation of the facility within the known safety envelope, use of appropriate monitoring approaches and implementation of remedial measures should leakage be detected. With these caveats, it is reasonable to conclude that the risk of unintended leakage is low—based on the following:

- No unintended leakage has resulted from the three existing CO<sub>2</sub> storage projects, now representing collective experience of over 17 years.
- Experts conclude based on number of lines of evidence that retention rates will be greater than 99% over 1000 years, suggesting a low probability of unintended leakage (IPCC, 2006).
- Natural gas storage projects (which generally operate at shallower depths than CO<sub>2</sub> storage projects) operate with low rates of unintended leakage, and where it occurs, remedies have been in place to stop the leakage or control it at acceptable levels.
- In general, CO<sub>2</sub>-EOR projects do not experience significant health, safety or environmental problems, such as widespread groundwater impacts, unacceptable occupational safety problems, or uncontrolled releases of CO<sub>2</sub>.

## **Will groundwater become contaminated because of geological storage of CO<sub>2</sub>?**

No known contamination of groundwater has occurred from injection of CO<sub>2</sub>. However, unintended leakage of CO<sub>2</sub>, either from wells or along faults and fractures, could impact groundwater quality. Increases in dissolved CO<sub>2</sub> concentration that might occur if CO<sub>2</sub> migrates from a storage reservoir to the surface would alter groundwater chemistry, potentially affecting shallow groundwater used for potable water and industrial and agricultural needs. Dissolved CO<sub>2</sub> forms carbonic acid, altering the pH of the solution and potentially causing indirect effects, including mobilization of metals, sulphate, or chloride; and possibly giving the water an odd odor, color, or taste. In the worst case, by-products of CO<sub>2</sub> migration into groundwater resources might reach dangerous levels, excluding the use of groundwater for drinking or irrigation.

Another potential consequence of geological storage of CO<sub>2</sub> arises from displacing salty brines from the storage formation into adjacent fresh water aquifer. This could degrade the quality of the aquifer, potentially limiting beneficial uses. The likelihood of this occurring is site specific, depending on the size of the storage formation, what fraction of the storage formation will be occupied by CO<sub>2</sub>, and the regional hydrology. Addressing the likelihood of brine displacement should be addressed on a site-specific basis in the site selection process. However, for many large regional-scale storage formations, only a few percent of the potential storage volume will be occupied by CO<sub>2</sub>. In this case, the likelihood of brine displacement is low, because the volume of brine displaced by CO<sub>2</sub> can be accommodated by a small pressure increase over the extent of the storage formation.

## **Will faults and fractures in the subsurface allow CO<sub>2</sub> to leak from the storage formation?**

Faults and fractures are present in many areas. The role they play in controlling fluid movement varies from place to place, and must be assessed on a site specific basis. In some cases, faults and fractures create seals that trap oil and gas. These seals have contained oil and gas over millions of years, showing how effective they can be for trapping fluids, including CO<sub>2</sub>. In other cases, faults and fractures provide conduits for fluids to move from great depths to shallower depths. This is particularly true in volcanic terrains, where (for example) most geothermal energy systems are created when fractures are allowed to transport hot water from great depth to near surface accumulations.

The role of faults and fractures in controlling fluid movement is assessed by studying the regional geology, hydrology and geochemistry. Together, this information can be used to ascertain whether these features will act as conduits or barriers to fluid flow. Well testing, where fluid is withdrawn from the formation

while pressures are measured can be used to confirm the results from other fault characterization methods.

If a fault is present in the vicinity of a storage project, the potential for it to allow leakage will be assessed during the site characterization and selection phase of a project. This will include assessment of the effects of CO<sub>2</sub> injection on the sealing properties of the fault. Should the fault be found to have the potential to leak, an alternative site will be found—or the injection rates and pressures will be limited to those that retain the sealing properties of the fault.

### **Will CO<sub>2</sub> storage cause earthquakes?**

During the 1950s it was discovered that injection of fluids at high pressures could cause small-to-medium-sized earthquakes. Subsequent scientific studies identified “hydrofracturing”, slippage along pre-existing fractures, and fault activation as the causes for these earthquakes. Based on understanding local and regional stresses in the earth’s crust, guidelines have been developed to prevent injection-induced microseismicity. Now, regulatory agencies limit injection rates and pressures to avoid unintentional hydrofracturing. Microseismic monitoring is often done early in a project to establish operational parameters for injection.

Carbon dioxide storage projects would operate under similar guidelines, thus eliminating concerns about causing earthquakes. In addition, CO<sub>2</sub>-EOR and natural gas storage projects operate without generating significant seismic events.

### **Could a situation like Lake Nyos occur?**

In 1987, about 0.25 million tonnes of CO<sub>2</sub> was released from a Lake Nyos in Cameroon over a short period. The release resulted from the overturn of a “stably stratified” lake that had accumulated large quantities of CO<sub>2</sub>. Over 1,700 people and more than 3,000 livestock were killed during this tragic event. The question is often asked, could such a fatal release occur from a geological storage site?

There are a number of reasons for concluding that such a large and unexpected release is unlikely to result from seepage through wells or fractures from underground geological storage sites. First, the mechanism for the release, overturn of a lake, is completely different than the release from an underground storage site, where the CO<sub>2</sub> would seep through small pores or fractures in the rocks, significantly limiting the rate at which CO<sub>2</sub> is released. Second, the CO<sub>2</sub> at Lake Nyos had accumulated in the lake over many years — and then was quickly and unexpectedly released over a short time. It is highly unlikely that such a large release from a porous formation at depth could take place over such a short time. Finally, if CO<sub>2</sub> leaked from a storage reservoir and subsequently accumulated in a shallow formation, an accumulation of this size would easily be detected by

monitoring. Thus, measures to prevent its rapid and unexpected release could be put in place.

### **Are the risks of CO<sub>2</sub> storage acceptable?**

After an extensive assessment of the literature regarding geological storage and related activities, a group of 32 scientists and engineers from around the world concluded –

“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO<sub>2</sub> releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas” (IPCC, 2006)

These activities are carried out safely today, and good work practices continue to even further reduce risks and their environmental footprint. Many oil and gas companies are industry leaders in occupational safety practices. Such a track record indicates that with diligent application of sound safety and environmental practices, geological storage of CO<sub>2</sub> can be carried out safely and effectively.

### **How long will monitoring be needed?**

Monitoring will play an important role during the 30 to 50 year injection phase of a storage project, both for the purpose of assuring worker and public safety and confirming that the storage project is performing as expected. If the seal of a storage formation or the plug in an abandoned well is going to fail, mostly likely this will occur during the injection phase when the pressure in the storage formation is highest. After injection stops, monitoring is also likely to continue for observing the post-injection pressure decline and to monitor continued movement, if any, of the injected CO<sub>2</sub>. The frequency and intensity of monitoring will decrease over time as greater assurance of long term storage integrity is obtained. If repeated measurements indicate that the CO<sub>2</sub> is not moving and remains trapped in the storage formation, there may come a time when monitoring is no longer needed, nor the costs for ongoing monitoring justified. The time frame over which this occurs could be as short as a few years in a depleted gas reservoir with a well defined geological trap. For storage in a saline formation without a closed trap, more time may be needed before a combination of capillary trapping and solubility trapping [dissolution of CO<sub>2</sub> in the salt water] eventually immobilize the CO<sub>2</sub>. Model studies indicate that this can take anywhere from decades to centuries, or longer, before the CO<sub>2</sub> is immobilized. Information from model studies and ongoing monitoring would be used to assess how much longer monitoring should continue. For storage in oil fields, which like gas reservoirs have time-tested geological seals, the duration

of post-injection monitoring is likely to be shorter than for saline formations, perhaps requiring up to several decades after injection stops to provide assurance that the CO<sub>2</sub> is securely trapped.

## What more needs to be done?

Rapid progress is being made in the development of CO<sub>2</sub> capture and storage in deep geological formations. However, more remains to be done to support the large scale technology deployment that would be necessary to achieve large reductions in CO<sub>2</sub> emissions from fossil-fuel fired power plants. Critical actions include:

1. Continue to fully support the Regional Sequestration Partnerships and their small scale pilot tests, regional storage capacity assessments, economic assessments and public outreach.
2. Continue to support the FutureGen Project to demonstrate a fully integrated, commercial scale coal-fired power plant with CO<sub>2</sub> capture and storage.
3. Initiate 4 to 6 commercial scale geological storage demonstration projects that would store over 1 million tonnes of CO<sub>2</sub> per year to provide experience in siting, operating, and monitoring – and to obtain cost and performance data in a variety of different geological and geographical settings.
4. Continue to support a core research program to develop new and innovative monitoring methods that would increase spatial and temporal resolution, improve computer models for predicting long term performance and assessing risks, develop strategies and operating procedures to accelerate trapping mechanisms in saline formations, optimize injection well locations and construction, and develop mitigation measures should leakage occur.
5. Adapt existing regulatory approaches to provide all the needed protections to workers, the public and the environment, while facilitating efficient and streamlined permitting of CO<sub>2</sub> storage projects.
6. Seek to learn more from international experience gained from CO<sub>2</sub> storage projects.