Geologic Storage of Carbon Dioxide
STAYING SAFELY UNDERGROUND
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# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Summary</td>
<td>i</td>
</tr>
<tr>
<td>Why store carbon dioxide underground?</td>
<td>1</td>
</tr>
<tr>
<td>What is CO₂?</td>
<td>4</td>
</tr>
<tr>
<td>Where can the CO₂ be stored?</td>
<td>6</td>
</tr>
<tr>
<td>How will CO₂ storage be conducted?</td>
<td>12</td>
</tr>
<tr>
<td>Will the CO₂ stay underground?</td>
<td>16</td>
</tr>
<tr>
<td>What impacts could storage have?</td>
<td>20</td>
</tr>
<tr>
<td>How will storage be monitored?</td>
<td>22</td>
</tr>
<tr>
<td>How can leaks be fixed?</td>
<td>24</td>
</tr>
<tr>
<td>Questions to ask project developers</td>
<td>27</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

Geologic storage of carbon dioxide (CO₂) is the underground disposal of CO₂ from large industrial sources such as power plants. Carbon Capture and Storage (CCS), also known as Carbon Capture and Sequestration, includes geologic storage as one of its components.

CCS is a powerful tool—along with energy efficiency, fuel switching and renewable energy sources—essential to reducing atmospheric CO₂ levels. Many studies show that the most effective and least-costly way to reduce CO₂ levels to avoid climate change is to use all CO₂ reduction tools, including CCS.

CO₂ is a natural substance in the air that is essential to life. As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO₂. Meanwhile, green plants absorb CO₂ for photosynthesis and emit oxygen back into the atmosphere. CO₂ is also widely used for many purposes such as carbonating drinks and filling fire extinguishers. As a greenhouse gas, its presence in the atmosphere traps heat from the sun. Normally, this keeps the climate warm enough for life to continue. However, the burning of fossil fuels is increasing CO₂ levels in the atmosphere above naturally-occurring levels, contributing to global climate change.

In geologic storage, CO₂ is injected under high pressure into deep, stable rocks in which there are countless, tiny pores that trap natural fluids. Some types of rock formations have securely trapped fluids, including CO₂, for long periods, even millions of years. The CO₂ will be injected into these types of formations.

Several types of rock formations are suitable for CO₂ storage. These include depleted oil and gas reservoirs, deep saline formations and unmineable coal seams. Deep, porous rock formations with trapped natural fluids such as oil, natural gas or highly salty and unusable water are common throughout the world. Geologists have found that these formations have the capacity to securely hold vast amounts of CO₂, potentially equivalent to hundreds of years of man-made emissions.

The same geologic forces that kept the original fluids in place will also secure the CO₂. Once injected, the CO₂ will be trapped initially in tiny pores within the storage rocks. Over time, the CO₂ will dissolve in water already in the rock formation and then may combine chemically with the rocks to trap it even more securely. The CO₂ will be far below the surface, separated from usable groundwater by thick, impermeable barriers of dense rock.

Image Source: CO2CRC
Safe, long-term underground geologic storage (sequestration) of CO₂ must be conducted properly. This means thorough planning and geologic analysis of the storage site, safe operating practices, careful monitoring of the underground CO₂ during injection, and continued monitoring for some time afterward. Reliable geological surveys can prove the presence of impermeable rock barriers and the capability of deep rock formations to hold fluids. Geologic storage uses established techniques and equipment used over many years by industry, although more advanced technologies designed specifically for CO₂ injection are also being developed. Storage sites are monitored so that any undesirable CO₂ movement can be readily detected and fixed.

Geologic storage projects have already successfully stored millions of tons of CO₂, some for many years, without detectable leakage. For example, the IEA GHG Weyburn-Midale CO₂ Storage and Monitoring Project in Canada has injected over 5 million tons of CO₂ into a depleted oil field. Extensive monitoring by an international team of scientists has detected no leakage. Similarly, the Sleipner Project off the coast of Norway has injected over 10 million tons of CO₂ in a deep saline formation with no leakage. Other projects are now underway and many new projects are planned throughout the world in the years to come.

Geologic storage of CO₂ can be a vital part of the solution to the problem of global climate change. Methods and technologies are developing rapidly, as are the legal frameworks to regulate them. Geologic storage projects undertaken over the next ten years will be critical for demonstrating CO₂ storage in diverse geologic settings and will establish the basis for its widespread global application as a means of preventing climate change.
WHY STORE CARBON DIOXIDE UNDERGROUND?

Carbon Capture and Storage (CCS), also known as Carbon Capture and Sequestration, is the separation and capture of carbon dioxide (CO₂) from the atmospheric emissions of industrial processes and the transport and permanent disposal of the CO₂ in deep underground rock formations. By preventing CO₂ from large-scale industrial facilities from entering the atmosphere, CCS is a powerful tool for combating climate change. Geologic storage is the component of CCS in which the CO₂ is disposed of underground. Geologic storage is also sometimes called “geologic sequestration” or “geosequestration.”

CO₂ from industry and other human activities is a major contributor to global climate change. The CO₂ for geologic storage comes from industrial facilities that emit large amounts of CO₂, particularly those that burn coal, oil or natural gas. These facilities include power plants, petroleum refineries, oil and gas production facilities, iron and steel mills, cement plants and various chemical plants. In CCS, CO₂ is not removed from the atmosphere. Rather, CO₂ that would otherwise have been emitted into the atmosphere is captured and disposed of underground.

CCS enables industry to continue with less disruption while minimizing industry’s impact on climate change. Studies show that CCS could make a significant contribution to reducing CO₂ emissions. The greatest emissions reductions are achieved when all options for reducing CO₂ emissions are utilized, including energy efficiency, fuel switching, renewable energy sources and CCS.

Geologic storage is one component of Carbon Capture and Storage (CCS). In CCS, CO₂ is captured before it can be emitted into the atmosphere, transported to the injection site and then disposed of underground in suitable rock formations.

Image Source: CO2CRC
This booklet is a summary of what is currently known about the permanence and safety of geologic storage of CO₂. The information it contains is based on a number of different sources and the input of expert geologists who participated in its development. The most comprehensive source is Chapter 5: *Underground Geological Storage* of the Special Report on Carbon Dioxide Capture and Storage by the Intergovernmental Panel on Climate Change (IPCC). The IPCC Special Report is available to be downloaded on the IPCC website at http://www.ipcc.ch.

This booklet describes:

- The properties of CO₂,
- Where the CO₂ can be stored,
- How geologic storage should be conducted,
- The permanence of underground disposal,
- The potential impacts of leakage, and
- How potential leaks could be detected and fixed.

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Since each geologic storage project is different, this booklet also provides a list of questions to ask project developers about permanence and safety. The answers should help decision makers and the public understand geologic storage.

This booklet makes no claims about specific projects. A thorough and accurate evaluation of specific projects requires substantial expertise in geology and geological engineering as well as detailed information on the proposed storage site.

Geologic storage uses a set of rapidly-evolving technologies and practices. CO₂ has been injected into oil reservoirs to increase recovery of oil for over 30 years. Since the early 1990s, considerable research and development around the world has been devoted to geologic storage for the purpose of reducing CO₂ emissions. It is now employed for that purpose in some commercial projects. Geologic storage needs further development, however, before it can become widely commercial; researchers are learning more virtually every day.
WHAT IS CO₂?

CO₂ is a naturally-occurring substance made up of carbon and oxygen, two of the most common chemical elements on earth.

Under normal atmospheric conditions, CO₂ is a gas. It can be compressed into a liquid, frozen into a solid (dry ice) or dissolved in water (carbonated beverages, beer and sparkling wines). In the atmosphere, CO₂ comprises about 0.04 percent of the air we breathe. It also occurs naturally in both fresh and sea water and in the ground. Carbon dioxide is not flammable, does not explode and is not toxic. In fact, it is used in some fire extinguishers.

CO₂ is necessary for life on earth. People and animals inhale oxygen from the air and exhale CO₂. Meanwhile, green plants absorb CO₂ for photosynthesis and emit oxygen back into the atmosphere. CO₂ is also exchanged between the atmosphere and the oceans and is emitted or absorbed in other natural processes. Working together in a natural system called the carbon cycle, these processes have in the past kept the levels of CO₂ in the atmosphere stable over time.

Nature’s carbon cycle normally keeps CO₂ levels in balance, but human activity, mostly the burning of fossil fuels, produces more CO₂ than nature can absorb. The arrows in this diagram show the annual flows of carbon in billion tonnes (metric tons). The human contribution is relatively small, but enough to throw the cycle off balance. The extra CO₂ stays in the atmosphere, where it causes global warming.

Image courtesy of CO2CRC, with values of carbon fluxes and sinks sourced from NASA Earth Science Enterprise and the International Energy Agency.
**CO₂ is a greenhouse gas.** That is, its presence in the atmosphere traps heat energy from the sun. This keeps the climate warm enough for life to continue. The balance is delicate, however. As atmospheric CO₂ levels increase from natural levels the climate becomes warmer, changing the natural balance in most parts of the world. This has a wide range of major disruptive impacts on the environment, natural resources and human communities throughout the world. Both the temperature and the impacts increase with rising CO₂ levels.

Living things consist largely of water and molecules containing carbon. When fuels derived from living things such as wood or fossil fuels (oil, coal or natural gas) are burned, the carbon combines with oxygen to form CO₂ that is released into the atmosphere. People have thrown the natural carbon cycle out of balance by burning fossil fuels. More CO₂ is now entering the atmosphere than can be naturally absorbed, contributing to global warming. Geologic storage returns carbon back into the ground where it was captured eons ago when the remains of prehistoric plants and animals decomposed into coal, oil and natural gas.

**CO₂ also has many practical uses.** For example, it is used in industries as varied as chemicals, metals, food and beverages, healthcare, pulp and paper, electronics and waste treatment. It is used to make fertilizer; it adds fizz to carbonated beverages; it is used in commercial freezing and refrigeration in its frozen form, dry ice. The amount of CO₂ needed for all these uses, however, is miniscule compared to the amount emitted into the atmosphere by burning fossil fuels.
WHERE CAN THE CO$_2$ BE STORED?

In geologic storage, CO$_2$ is injected under high pressure into very deep underground rock formations. In many areas, these rocks already securely hold fluids such as oil, natural gas or water that is too salty to use. Several natural trapping mechanisms keep these natural fluids in place, often for millions of years. These trapping mechanisms can do the same for CO$_2$.

CO$_2$ itself has been securely trapped in rock formations in many places around the world. Geologists searching for CO$_2$ storage sites look for rock formations that already securely hold fluids and therefore have proven to have these trapping mechanisms.

Injection of CO$_2$ as a Supercritical Fluid

In geologic storage, CO$_2$ is injected under pressure into suitable subterranean geologic formations, taking advantage of natural trapping mechanisms in those formations. In fact, the CO$_2$ is injected at sufficiently high pressures and temperatures that it becomes what scientists call a *supercritical fluid*. Supercritical fluids are like gases in that they can diffuse readily through the pore spaces of solids but, like liquids, they take up much less space than gases. Supercritical CO$_2$ is sometimes used as a non-toxic method for decaffeinating coffee and dry cleaning clothes. Supercritical CO$_2$ compresses further as the depth increases, increasing the amount that can be stored in the same volume of rock. High pressure at sufficient depths (i.e., greater than 800 meters or 2600 feet) maintains the supercritical fluid state. Various trapping mechanisms can keep it at these depths.

![Image of CO$_2$ injection and density changes](Image Source: CO2CRC)

$CO_2$ will be injected at depths below 0.8 km (2600 feet). CO$_2$ increases in density with depth and becomes a supercritical fluid below 0.8 km. Supercritical fluids take up much less space, as shown in this figure, and diffuse better than either gases or ordinary liquids through the tiny pore spaces in storage rocks. The blue numbers in this figure show the volume of CO$_2$ at each depth compared to a volume of 100 at the surface.

*Image Source: CO2CRC*
Trapping Mechanisms

A trap is a configuration of rocks suitable for containing fluids and sealed by a relatively impermeable formation through which fluids will not migrate. CO₂ is held in place in a storage reservoir through one or more of five basic trapping mechanisms: stratigraphic, structural, residual, solubility, and mineral. Trapping mechanisms depend on the local geology and work together when more than one is present.

Generally, the initial dominant trapping mechanisms are stratigraphic trapping or structural trapping, or a combination of the two. Cap rock is a dense layer of impermeable rock that overlays the rocks holding the CO₂ and forms a continuous primary seal. In stratigraphic trapping, cap rock, sometimes coupled with impermeable rocks elsewhere within the same layer as the CO₂, forms a closed container to trap the CO₂. In structural trapping, impermeable rocks shifted by a fault or fold in the geologic strata hold the CO₂ in place. In addition, CO₂ storage rocks are generally separated from the surface by other thick layers of impermeable rock, called secondary seals.

In stratigraphic trapping (left), CO₂ is trapped by an overlying layer of cap rock coupled with impermeable rock within a narrowing of the storage formation. In structural trapping, CO₂ is trapped by a fold in the rock formations (middle) or by impermeable rock layers shifted along a sealing fault (right) to contain the CO₂. These are just three of several possible ways that stratigraphic and structural trapping could contain CO₂.

Image Source: CO2CRC

Over time, other even more secure trapping mechanisms take over. In residual trapping, which usually begins after injection stops, the CO₂ is trapped in the tiny pores in rocks by the capillary pressure of water. After injection stops, water from the surrounding rocks begins to move back into the pore spaces containing the CO₂. As this happens, the CO₂ becomes immobilized by the pressure of the added water.

As more CO₂ is injected, the CO₂ moves further from the injection site and, since it is lighter than the highly saline water or oil, the CO₂ may also initially rise toward the top of the porous storage rocks, where stratigraphic and structural trapping keep it in place. Injection pressures must be high enough to force the liquid CO₂ into the porous rock, but not so high as to break the cap rock forming the primary seal immediately above the storage formation.
Much of the injected CO$_2$ will eventually dissolve in the saline water or in the oil that remains in the rock, somewhat like sugar dissolves in water to make sweetened beverages. This process, which further traps the CO$_2$, is solubility (or dissolution) trapping. Solubility trapping forms a denser fluid which may then sink to the bottom of the storage formation. Depending on the rock formation, the dissolved CO$_2$ may react chemically with the surrounding rocks to form stable minerals. Known as mineral trapping, this provides the most secure form of storage for the CO$_2$ but it is a slow process and may take place over thousands of years. Currently, research is underway to evaluate how mineral trapping works and the long-term impact of CO$_2$ on fluids and rocks in a variety of geologic settings.

![Image of storage rock with blue spaces showing CO$_2$ trapped supercritical fluid](image-source:CO2CRC)

**CO$_2$ will be trapped as a supercritical fluid in tiny pore spaces within the storage rock, as is shown by the blue spaces in this photograph of a microscopic section of storage sandstone. The white grains are mostly quartz.**

*Image Source: CO2CRC*

**Evaluation of the properties of rocks that may be used for storage or seals can be complex.** Two important attributes of the rocks are visible in the above picture. Porosity is a measure of the space in the rock for storing fluids. Permeability is a measure of the ability of the rock to allow fluid flow. Permeability is strongly affected by the shape, size and connectedness of the spaces in the rock.

Rocks suitable for storage typically (but with some exceptions) have high porosity to provide space for the CO$_2$ and high permeability for the CO$_2$ to move into that space. By contrast, the seals covering the storage formation typically have low porosity and permeability to trap the fluids stored below. Another property of the potential storage site called injectivity is also important. Injectivity is the rate at which the CO$_2$ can be injected into a storage reservoir formation. Typically, the CO$_2$ must be injected at much the same rate as it is captured from the sources. The trade-offs between the injectivity required, the reservoir storage capacity, and the quality of the seal can be intricate and require careful evaluation by geologists and geological engineers.
These trapping processes take place over many years at different rates. Generally, the longer CO\(_2\) stays underground, the more secure its storage becomes. With the passage of time, more-secure trapping mechanisms are increasingly likely to have significant effect. Which trapping mechanisms apply and the rates at which they work can vary widely with the geology. Scientists are now developing the tools to accurately predict how these mechanisms will work over time in a diverse set of specific geological settings.

As time goes on, increasingly secure trapping mechanisms come into play and the overall security of storage increases.

Types of Underground Storage Sites for CO\(_2\)

Candidate sites for geologic storage include depleted oil and gas fields, deep saline formations and deep unmineable coal seams. Both depleted oil and gas fields and deep saline formations use the five trapping mechanisms described above. Such geological formations have cap rocks on top of the porous sedimentary rocks that could contain CO\(_2\). Deep unmineable coal seams are also potential candidates for geologic storage, but use a somewhat different trapping mechanism involving the CO\(_2\) fixing on or in the coal particles. Much of the vital work on geologic storage over the next 10 years will involve demonstrating storage in diverse geological settings so that it can be deployed afterward on a widespread global basis.

In depleted oil and gas fields, CO\(_2\) fills the pores in the rock that were once filled with oil or natural gas. Depleted oil and gas fields are likely to be used early for CO\(_2\) storage because, in some cases, the injected CO\(_2\) could lead to greater production of oil or natural gas. This practice is known as Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR). EOR with injected CO\(_2\) is a common practice today in some oil fields, having been used for over 30 years. Increased production of oil or gas could offset the costs of capture and storage. In other cases, the CO\(_2\) may be injected into the pores of rocks where the oil or gas has already been produced, resulting in no further oil or gas production.
Natural trapping mechanisms in oil and gas reservoirs have successfully contained oil, gas and water for millions of years. The geology of most oil and gas fields has been thoroughly studied. In addition, the oil and gas industry widely uses accurate computer models of the underground behavior of these fluids. Such models are being adapted to CO₂. One concern in some oil and gas fields is the impact of any abandoned oil and gas production wells since improperly sealed wells may provide an escape route for CO₂. Addressing this concern requires analyzing prior drilling activity in the area and ensuring that closed wells are properly sealed.

Deep saline formations are very deep, porous rocks containing water that is unusable because of its high salt or mineral content. Such formations are widely dispersed throughout the world, including in areas with no appreciable oil and gas production. These formations meet all the necessary criteria to provide long-term storage. Injected CO₂ adds to fluid already trapped in the rocks, eventually dissolves in the saline water, and may combine chemically with the surrounding rocks. Deep saline formations contain most of the global geologic storage capacity for CO₂ and are likely to become the most widely used type of geologic storage site.

Deep, unmineable coal seams are also possible storage sites. CO₂ can enter into very small spaces, called micropores, within the coal. Generally, CO₂ that enters coal in that way is held so tightly that it will remain in place even without cap rocks. Coal often contains methane. In these micropores, CO₂ can, in some cases, displace the methane which can be recovered and used as a fuel. This type of methane production is called Enhanced Coal Bed Methane. It is experimental at this time as greater knowledge is needed on the fundamental processes of CO₂ uptake and methane release from coal.

Basalt and oil shale formations are also possibilities, but their potential for storing CO₂ is currently theoretical.
Disposal of Other Substances with the CO₂

In most cases, small amounts of other substances accompanying CO₂ will also be disposed of underground. Although emissions controls and CO₂ separation can be highly efficient, they are not 100 percent effective and some other substances may be present in the captured CO₂ stream. The types and amounts of those substances will depend on the process from which the CO₂ is captured.

The other injected substances may include gases from the air such as nitrogen and oxygen, small amounts of pollutants not removed by any emissions controls such as sulfur oxides, nitrogen oxides and particulate matter, or hydrocarbons or other gases such as hydrogen sulfide. Re-injecting a mixture of CO₂ and hydrogen sulfide byproducts of oil and gas production (known as “acid gas”) into depleted oil reservoirs, for example, has long been an accepted means of pollution control since the 1990s in Alberta, Canada and is now being planned for Enhanced Oil Recovery. To the extent that the other injected substances are air or water pollutants, underground disposal further reduces those forms of pollution. The impact of the other substances on CO₂ storage capacity, however, needs to be understood prior to disposal.

Capacity for CO₂ Storage

It is now clear that rock formations appropriate for geologic storage exist throughout the world and that they have a vast capacity compared to the need. Geologists only recently began estimating capacity for geologic storage and new discoveries are still being made. In its Special Report on Carbon Dioxide Capture and Storage, the Intergovernmental Panel on Climate Change estimated total global CO₂ storage capacity to be in a range that is hundreds of times annual CO₂ emissions from large industrial sources. That report also noted that, since CO₂ storage is so new, current methods for estimating storage capacity require more development and many gaps exist in capacity estimates at the global, regional and local levels. This means that global storage capacity may be even greater than estimated in that report.
HOW WILL CO\textsubscript{2} STORAGE BE CONDUCTED?

Geologic storage projects are generally conducted in three sequential phases: planning and construction, injection, and post injection. While the specifics of each project differ, similar activities are involved in each phase. The activities in each of these phases can affect the permanence and safety of the underground storage.

Planning and Construction

Planning starts with an industrial facility capable of capturing the CO\textsubscript{2}. The amount of CO\textsubscript{2} that is to be captured is projected and a search begins for a geologic formation to store the projected amount of CO\textsubscript{2}. In the future, large sources of CO\textsubscript{2} such as coal-fired power plants may be purposely located near geologic formations suitable for geologic storage. A suitable storage site must have a number of characteristics. See box below.

![What is a Good Geologic Storage Site?](image)

If the CO\textsubscript{2} injection site is not at the same place as the source, CO\textsubscript{2} must be liquefied and transported by pipeline or ship. Pipeline transportation of CO\textsubscript{2} is a well-established and safe practice. About 3000 miles (4800 km) of CO\textsubscript{2} pipelines exist in the United States alone. In one commercial project, a 200 mile (320 km) pipeline carries CO\textsubscript{2} captured at a coal gasification plant in the U.S. state of North Dakota to a geologic storage site in the Canadian province of Saskatchewan. Ships to transport CO\textsubscript{2} over water are currently being designed.

Two types of analyses are typically conducted during planning:

1. **Site identification and selection** finds possible alternative storage locations and pipeline routes. The most appropriate storage reservoir and the locations for facilities such as pipelines, injection wells and monitoring wells are then selected on the basis of technical, cost and regulatory considerations.
2. Site characterization studies the geology of a prospective storage reservoir and surrounding rock formations. Good site characterization is essential to ensure effective and permanent storage for the anticipated quantities of CO₂.

Site characterization typically starts with descriptions of geological structures, groundwater and rock chemistry. Ultimately, it should address what will happen to the injected CO₂. Most of the analysis focuses on the storage reservoir and the cap rock immediately above the reservoir that will be the primary seal, but rock formations above the cap rocks also need to be understood to determine whether they may be secondary seals. Analyses may include simulations and modeling of the behavior of the injected CO₂ over time and field tests to verify the simulations. Similar simulations and modeling have been used for many years for oil and gas production. The behavior of injected CO₂ is somewhat different and work is currently underway to refine simulation and modeling methods for this application.

The detail and depth of the planning analyses will vary with specific needs. These studies require geologic data that may be collected by seismic surveys and by drilling. Some of this data may be available from prior geologic work such as government surveys or oil and gas exploration. In many other places, new data will have to be collected.

Seismic imaging uses reflected sound waves to create pictures of underground rock formations. Pictures such as this show potential CO₂ reservoirs and seal rocks as well as other geologic features such as faults. After injection begins, these pictures can show the location of the CO₂. This picture also shows where two test wells were drilled to make measurements and take rock samples. Taken together, all this information can provide an accurate and detailed understanding of conditions underground.

Image Source: CO2CRC
Following these studies, detailed plans for the project are developed. These plans typically lay out how the facility will operate under normal conditions and possible contingency responses. Risk assessments will typically also be performed. In the oil and gas industry, risk assessments for similar injection operations are routine and are conducted with a high degree of confidence based on extensive experience. Work is currently underway to develop risk assessment methodologies specifically for geologic storage.

If studies produce acceptable results, the necessary rights, permits and licenses are obtained. Finally, as plans and permits allow, injection wells are drilled and connected with the CO₂ pipeline. In some cases, separate wells for monitoring CO₂ in the storage formation may also be drilled. If the storage site is located offshore, then offshore platforms or subsea installations will be used.

**Injection and Post Injection**

Once operations start, CO₂ is compressed into a supercritical fluid and pumped under high pressure into the storage formation. The equipment and practices for injection are already widely used in the oil and gas industry. Injection equipment is fully commercial, although more advanced technologies for CO₂ injection are also being developed.

Industry practice for the injection of fluids into geologic formations is well established and regulated in many areas. Indeed, CO₂ is safer to handle than the oil and gas routinely handled in similar well operations because it is not flammable, explosive or toxic. Since CO₂ is colorless and odorless, however, instrumentation is required to detect it. Industry already has substantial experience handling it and using such instrumentation. For example, CO₂ is routinely injected into some oil fields to increase the oil production through EOR.

During the period when injection is taking place, Measurement, Monitoring and Verification (MMV) activities are conducted to ensure that the correct amount of CO₂ is injected, that it is injected effectively and safely, and that no unwanted migration occurs. Data is compared to similar information gathered in a baseline survey prior to the beginning of injection. Further computer modeling can also be conducted during this time based on actual measurements to refine the projections of CO₂ behavior made during the planning activities. If any unwanted migration is identified, the leaks can be stopped, as is explained in a later section. Some MMV activities usually will continue for some time after injection has ended to ensure that no later unwanted migration takes place.
CO₂ injection wells are generally small and have little impact on surrounding areas, as shown in this picture of a CO₂ injection well in Canada.

WILL THE CO\textsubscript{2} STAY UNDERGROUND?

Geologic storage sites should be selected for their ability to trap CO\textsubscript{2} underground over a very long time, making leakage very unlikely. Geologic storage builds on an extensive base of experience successfully injecting fluids underground, including CO\textsubscript{2}. In addition, naturally-occurring underground concentrations of gases, including CO\textsubscript{2} and natural gas, have remained underground for millions of years.

Potential for Leakage from Storage

Studies of geologic storage test sites suggest leakage rates of less than 1 percent over thousands of years. Best estimates of leakage rates by geologists are well below levels that would cause any significant increase in atmospheric CO\textsubscript{2} or risk to public safety.

Most geologic storage projects are expected to take advantage of multiple trapping mechanisms. As a result of a combination of stratigraphic, structural, residual, solubility and mineral trapping, any CO\textsubscript{2} movement out of the formations is unlikely. Evidence shows that these kinds of movements are very slow for appropriately selected and designed sites that are operated and monitored properly. Moreover, the CO\textsubscript{2} will typically be stored in rock formations that have proven their ability to retain fluids, some for millions of years. Injected CO\textsubscript{2} would not exist as an underground gas bubble that could rapidly burst forth to the surface.

The greatest risk for escape of CO\textsubscript{2} may come from other wells, typically for oil and gas, which penetrate the storage formation. Such wells need to be properly sealed in order to ensure that they do not provide pathways for the CO\textsubscript{2} to escape into the atmosphere. Research is currently underway to better determine the effect of CO\textsubscript{2} on materials such as cement used to seal such wells. Planning for geologic storage must take such wells into account. This may be an issue in areas with many older abandoned wells that may be poorly documented. Nonetheless, such leaks appear to be very rare in West Texas, which has many of these older, undocumented wells, and where CO\textsubscript{2} has been widely injected for EOR since the 1970s. CO\textsubscript{2} escaping through water wells is much more unlikely since water wells are usually much shallower than the storage formation.

Relevant Industrial Experience

The oil industry has extensive experience successfully injecting CO\textsubscript{2} underground to increase oil production through Enhanced Oil Recovery. Similarly, an experimental project injected CO\textsubscript{2} to displace natural gas and enhance its production from a formation in the Netherlands and this may soon be done elsewhere, as well.

Fluids have been injected without problems into deep geologic formations over many years for natural gas storage and disposal of waste products. Natural gas, acid gas, and various hazardous wastes are routinely injected underground. As a result, there is already significant experience for evaluating fluids injected deep underground. Underground injection has been used for short-term storage of natural gas for nearly 100 years. The majority of such projects, like proposed geologic storage projects, are in depleted oil and gas reservoirs or saline formations. The success of these projects has depended on the same factors needed for a successful CO\textsubscript{2} geologic storage site, for example, capacity, injectivity, and factors that affect storage security such as cap rock integrity, geological structure and composition of the rocks within the site. Acid gas—a mixture of hydrogen sulfide and CO\textsubscript{2}—has been disposed of by injecting it into over 50 sites in western Canada since 1990.
While they may share some technology and practices, the differences between natural gas storage and geologic storage of CO₂ are also significant. Natural gas is flammable and, under certain circumstances, explosive; CO₂ is neither flammable nor explosive. Natural gas is stored underground so that it can be easily re-extracted. By contrast, the CO₂ for a geologic storage project would be injected so that it would be difficult to extract. That is, as described earlier, the CO₂ would be injected as a supercritical fluid into a formation with strong trapping mechanisms, often much deeper than natural gas storage.

Geologic storage projects, while relatively recent, have already successfully stored millions of tons of CO₂ without detectable leakage, some for many years. For example, the Sleipner Project off the coast of Norway has injected over 10 million tons of CO₂ in a deep saline formation with no leakage. Similarly, the IEA GHG Weyburn-Midale CO₂ Storage and Monitoring Project in Canada has injected over 5 million tons of CO₂ into a depleted oil field. Extensive monitoring by an international team of scientists has detected no leakage. Other projects are now underway (see map, page 2) and many new projects are planned throughout the world in the years to come.
Regulatory standards for the safe transportation and injection of CO₂ are vital. Some environmental regulatory agencies have developed standards for siting, operation and abandonment of facilities for injecting CO₂ and others are developing such standards. Existing regulations for injection of other substances can be modified to apply to CO₂ injection. One aspect of these regulations is that equipment such as pipelines, valves and injection equipment must be resistant to the corrosive action of CO₂. In the United States, most underground injection activities are regulated by the U.S. Environmental Protection Agency (EPA), which sets minimum standards and regulatory requirements for underground injection activities. The EPA’s goal is to protect drinking water. Any project that seeks to inject hazardous waste, for example, must submit a petition to the EPA demonstrating that injected fluid will not migrate from the disposal site for 10,000 years or more. EPA is now studying how these regulations could be modified for geologic storage of CO₂. In Canada, most drilling activities are regulated by provincial authorities. The province of Alberta has detailed regulations relating to the construction, operation and abandonment of five different classes of injection wells, including acid gas. In Australia, the government is modifying laws designed to regulated offshore oil and gas production to cover exploration for CO₂ injection and storage.

Natural Underground CO₂ Accumulations

The permanence of CO₂ storage depends on trapping mechanisms to keep the CO₂ in place. CO₂ exists naturally underground in many places throughout the world, either by itself, mixed with natural gas or oil or dissolved in water. Many geological formations have securely contained CO₂ without leakage over tens of millions of years. In other areas CO₂ naturally vents to the surface. Such areas are often the sites of natural spas and the sources of naturally sparkling mineral waters.

Image Source: Copyrighted material, Intergovernmental Panel on Climate Change, Special Report on Carbon Dioxide Capture and Storage, 2005, (used by permission).
Volcanoes and Geologic Storage - Not the Same

In volcanically active areas, underground CO₂ is released naturally when seals are inadequate. Most releases are harmless and difficult even to detect; others can be destructive. Lake Nyos in the African nation of Cameroon, for example, is located in a volcanic crater. Hot magma lies under the lake and vents CO₂ that accumulates in the lake. In 1986, there was a large-scale release of this naturally-occurring CO₂ that resulted in the deaths of some 1700 people. Since then, equipment has been installed in the lake to vent carbon dioxide slowly into the atmosphere and avoid any further accumulations. Similarly, releases of CO₂ from volcanic activity around Mammoth Mountain in California destroyed 40 hectares (99 acres) of pine trees, but did not harm people. In early 2006, however, three people were killed when they fell into a volcanic vent hidden by snowfall that contained CO₂ and other gases. Geologic storage sites will not have such vents.

Volcanic areas are generally well known and geologic storage sites should be chosen to avoid active volcanic areas. Volcanic systems typically vent many gases, including CO₂, and contain natural faults that provide pathways for gases to migrate to the surface at much higher rates than other areas. CO₂ releases in volcanically active areas are not representative of much slower movements through wells or small fractures that might be anticipated for geologic storage.

What about Earthquakes?

Storage sites are selected because they are inherently stable, have effective seals, and are located away from areas of seismic instability. Criteria for considering seismic effects in site selection are being developed.

CCS projects will likely be sited away from earthquake faults, but even earthquakes appear unlikely to cause leaks. Seals in a properly-designed project are very effective and most of the energy of earthquakes tends to spread at depths much shallower than where CO₂ would be stored. In October 2004, a major earthquake measuring 6.8 on the Richter scale occurred 20 kilometers from the injection site of a CO₂ geologic storage site at Nagaoka, Japan. This project stored CO₂ in a saline formation 1100 meters deep. Injection activities were halted immediately after the earthquake, but were resumed shortly thereafter. The storage formation was monitored before, during and after the earthquake and no leakage has ever been detected. Further evidence that earthquakes would not cause leaks is that a large number of producing oil and gas fields in California are near seismically active faults. They have much the same trapping mechanisms as CCS and earthquakes over many years have not caused them to leak.

Another consideration, known as induced seismicity, must be addressed in planning for CO₂ storage. Fluid injection in some geologic formations can cause fracturing and movement along faults. This may induce low levels of seismic activity, generally termed microseismic events. This was first noticed in the early 1960s in underground natural gas storage facilities. Since then, most natural gas storage facilities have been sited away from potentially active faults. This precaution nearly eliminated microseismic events. Seismic surveys can readily detect faults before a site is selected. Similar precautions can be used for CO₂ storage. Even where faults do exist, controlling injection pressures generally prevents induced seismicity. Most importantly, the well-established and long-standing practice of injecting CO₂ for EOR has not caused any significant seismic events.
WHAT IMPACTS COULD STORAGE HAVE?

CO₂ should be stored securely at depths far below the surface and usable groundwater. Significant impacts on the climate, to plants and animals or to groundwater are highly unlikely.

Will Leakage Affect the Climate?

The purpose of geological storage is to keep CO₂ out of the atmosphere where it affects the climate. The major impact of geologic storage will be a reduction in the CO₂ emissions that cause climate change. It is possible over time, however, that some CO₂ injected into geologic formations could escape into the atmosphere. In order for geologic storage to be effective for its intended purpose, the rate at which CO₂ escapes does not have to be zero, but it does have to be small enough to have no appreciable effect on atmospheric CO₂ concentrations.

The IPCC Special Report on Carbon Dioxide Capture and Storage estimated that it is likely that 99 percent or more of the CO₂ injected in appropriately selected and managed geological reservoirs would remain in the intended storage formation for at least 1000 years. The amount of CO₂ likely to enter the atmosphere is thus well below any level that would significantly impact the climate. Even if a few projects were to leak, the leaks are likely to be minimal and their total impact would be very small. The IPCC Special Report reached these conclusions based on substantial evidence from current CO₂ injection projects, other types of gas injection projects, and similar natural occurrences of CO₂ and natural gas in underground formations. As further experience is gained with geologic storage of CO₂, it will become possible to make more precise estimates of the probability and magnitude of leakages across a large number of storage sites.

Will Plants and Animals be Affected?

In normal atmospheric concentrations, CO₂ is harmless, but at much higher concentrations, it could affect plants and animals. CO₂ is odorless and is heavier than air, so it may tend to accumulate in low-lying areas. Plants could be affected by increased concentrations of CO₂ in the soil. Normally, CO₂ comprises 0.2 to 4.0 percent of the gases naturally found in soil. Concentrations of CO₂ above 5 percent of soil gas can be harmful to plant growth; extreme concentrations in the soil above 20 percent may kill plants.

Healthy adults would have to be exposed to twelve times the normal atmospheric levels of CO₂ over several hours to feel any effect. Such exposure could cause headaches, drowsiness and lost concentration. Exposure to extremely high concentrations of CO₂—at least 150 times the level of CO₂ present in normal air—could lead to unconsciousness and ultimately asphyxiation, but this could be preceded by the obvious symptoms listed above.

Any CO₂ that is released from geologic storage is very unlikely to even approach minimally harmful levels. Moreover, technologies are available to monitor CO₂ levels and provide timely warning if CO₂ ever begins to be released. The closest monitoring, in some cases, may need to be where existing oil and gas wells penetrate the storage formation.

Will CO₂ Affect The Water Supply?

CO₂ injection will usually be much deeper (generally below 800 meters or 2600 feet) than usable sources of groundwater and will generally be separated by one or more layers of thick, impermeable cap rock. CO₂ injection is proposed for deep saline formations containing water, but this water is unusable because of its high salt and mineral content.
Given proper site selection and operation, the risks to usable water supplies would be extremely small. In the unlikely event that CO₂ would migrate upward toward shallower groundwater, seismic monitoring, groundwater analysis, and chemical tracers can detect any CO₂ that migrates upward into groundwater reservoirs and evaluate its effect on water quality.

Rock formations for geologic storage, such as deep saline formations, would be much deeper than any usable groundwater and separated from that groundwater by thick barriers of impervious rock. These formations generally already proved their effectiveness by keeping highly-salty saline water separate from usable groundwater for millions of years.

Image Source: CO2CRC

If CO₂ leaks into shallow groundwater, it could be removed, if necessary, by aerating the water and either using the water or re-injecting the CO₂ back into the storage formation. Aeration could also remedy any leakage into surface water supplies.

The combination of CO₂ dissolved in water is mildly acidic. In some cases, acidified water may very slowly dissolve metals and other minerals in adjoining rocks. Core samples from test wells can be examined to identify this possibility prior to injection. If it happens, several methods are available to correct the situation:

- The water may be pumped out and treated to remove the contaminants,
- Injection and extraction wells can be drilled to create a hydraulic barrier, and
- Passive methods utilizing natural biological processes can be employed.

Another potential risk to groundwater would arise if highly saline water (brine) were displaced into shallow drinking water aquifers. Ensuring that brine displacement does not occur is an important part of site characterization. For storage projects using a small fraction of the pore volume of the storage reservoir, brine displacement is not likely to be a serious concern.
HOW WILL STORAGE BE MONITORED?

Storage projects should be carefully tracked through Measurement, Monitoring and Verification (MM&V) procedures both during and after the period when CO₂ is being injected. These procedures address the effectiveness and safety of storage activities and the behavior of the injected CO₂ underground.

The objectives of MM&V will be to:

✓ Verify quantities of CO₂ injected and stored,
✓ Ensure the integrity of the injection well against leakage,
✓ Assure that the CO₂ remains in the intended subterranean geological formation,
✓ Detect leakages early enough for remediation to be effective,
✓ Monitor the effectiveness of any necessary remediation, and
✓ Make certain that abandoned wells are not leaking.

More MM&V activities are likely to be undertaken in research and development projects.

Types of Measurements

MM&V is used to measure the amount of CO₂ stored at a specific geologic storage site, to monitor the site for leaks or other deterioration of storage integrity over time, and to verify for accounting purposes that the CO₂ is stored and that it poses no harm to the host ecosystem. MM&V ensures safe permanent storage and can help satisfy regulators and government officials who must permit geologic storage projects. MM&V will also provide valuable feedback for continual refinement of injection and management practices.

Techniques for MM&V will, for the most part, be new applications of existing technologies. These technologies now monitor oil and gas fields and waste storage sites. They measure injection rates and pressures, subsurface distributions of CO₂, injection well integrity, and local environmental impacts.

Injection rates and pressure measurements are used to verify the amount of CO₂ injected and whether it is in a supercritical or gaseous state. Present technology can provide information on the state of the CO₂ (supercritical, liquid or gas) as well as an accurate measure of the amount of CO₂ injected.

Subsurface distributions of CO₂ are measured to determine how the CO₂ is spreading through the reservoir and whether it is staying within the intended reservoir. A number of direct and indirect techniques exist for monitoring the subsurface distribution of CO₂. Direct techniques include the use of tracer gases to track the movements of the CO₂, measurements of water composition and subsurface pressure, the use of probes inserted in the well, and active seismic techniques. Indirect techniques include passive seismic monitoring, gravity and electrical measurements to detect the movements of CO₂, measurements of land surface changes and satellite imaging.

Underground water quality can be monitored for any changes due to CO₂ using specially-designed devices.

Image Source: Lawrence Berkeley National Laboratory and CO₂CRC

22
Injection well integrity is evaluated to ensure that the operation does not result in leaks. Established techniques currently in use in the oil and gas industry can be used to monitor the integrity of CCS injection wells. Logging techniques, utilizing probes in the well, can be used to assess the bond and continuity of cement around the well casing. Similar probes to measure temperature and noises in the well are routinely used to detect well failures in natural gas storage projects and can be readily adapted for CCS projects.

Local environmental impacts are monitored to ensure that there is no effect on groundwater, air quality and/or plant and animal life. Methods are available to detect the effects of CO₂ migration by analyzing groundwater, air quality and ecosystems. Methods to detect CO₂ migration into groundwater include ongoing chemical analyses of water samples, and use of tracers in the injected CO₂. Migration of CO₂ into the atmosphere from geologic storage, if it occurs, is likely to be slow and, hence, unlikely to raise levels significantly above natural atmospheric levels. CO₂ levels in the air can be monitored by various types of chemical instrumentation. Effects of CO₂ on ecosystems can be determined by examining the productivity and diversity of plant and animal life. Other methods of evaluating possible CO₂ leaks include remote sensing, soil analyses and measurement of water quality.

Post-injection Monitoring

Once CO₂ injection has stopped and the injection well sealed, some monitoring may continue to detect any CO₂ migration that might occur afterward. Although all the techniques previously discussed can be utilized for long-term monitoring, project developers will prefer those that are easily deployed and most cost effective. Since more secure storage mechanisms tend to have more effect over time, the need for monitoring will most likely decrease over time.

Current Status of Monitoring Technology

Although geologic storage monitoring is relatively new, most of the technologies needed are already in existence, having been developed for other purposes. Improvements for this application and new types of equipment are being rapidly developed. Work is currently being done on the design of overall monitoring networks. Further work is also being conducted to assess the need for long-term monitoring of injection sites after they have been closed.
HOW CAN LEAKS BE FIXED?

Geologic storage sites should be chosen and projects operated to avoid leaks. Leaks can usually be prevented by thorough analysis of adequate geological information prior to injection, careful management of pressures during injection, good sealing during closure and effective MM&V during and after injection. In the unlikely event of a leak, however, methods are generally available to fix the problem. Responsibilities for such activities are set out in legal frameworks which are being developed in many jurisdictions.

CO$_2$ that is trapped by residual trapping, solubility/dissolution trapping, mineral trapping or inside the micropores of deep, unfractured coal seams is so tightly held that it not likely to move out of the storage formation. CO$_2$ that is kept in place primarily by stratigraphic or structural trapping, however, has the potential to move out of the storage formation if there are:

- Fractures in the cap rocks that may occur if the CO$_2$ is stored at too high pressure,
- Previously undetected pathways such as fractures or faults in the cap rock, or
- Poorly designed wells or badly sealed abandoned wells.

In deep coal seams, CO$_2$ has the potential to move out of storage through fractures in the coal seam that reach its top.

Methods to Fix Leaks

Should movement of CO$_2$ from the storage reservoir occur during or after injection, methods are generally available to fix the leak. Most of these methods have long been used to fix leaks from other types of wells. A substantial base of experience has been gained over many years rectifying leakage from natural gas storage projects, subterranean liquid waste disposal projects, and groundwater and soil contamination from other sources. These techniques can also be used for CO$_2$, with the advantage that, unlike those other materials, CO$_2$ is not explosive or flammable, nor is it toxic at the concentration levels likely from a leak. It is reasonable to expect that these techniques would work for CO$_2$. They have not yet been used for this purpose, however, primarily because it has not been necessary to fix leaks at existing geologic storage projects.

Leaks can generally be expected to be eliminated by reducing injection or storage reservoir pressures or by adjusting pressures in different parts of the reservoir. Leaks may also be eliminated by stopping injection at the current site and resuming it at a more suitable site.
Leaks into the soil, atmosphere or groundwater can be safely dissipated or the CO₂ can be collected and re-injected. Although dissipation into the atmosphere reduces the effectiveness of CCS, the expectation is that the need to take such an action will be very rare. In any event, the leak will not likely pose any danger to humans or the environment because, other than possibly through improperly sealed wells, the leaks will probably be very slow and the resulting concentrations well below harmful levels. Particular care, however, needs to be taken in low-lying or enclosed areas where CO₂, which is heavier than air, may tend to accumulate.

Leaks from abandoned wells may present the most significant vulnerability in some areas. These can usually be sealed with heavy mud or cement. If the abandoned well to be sealed, however, is not accessible on the surface, another well can be drilled nearby to intercept the leaking well and seal it by pumping mud down the injection well. If the injection well itself leaks, it can be repaired by replacing parts of the well or injecting cement to seal the leaks. If necessary, the well can be properly sealed and abandoned. These are standard and long-established techniques for sealing leaking wells. Many countries have established procedures for abandonment of oil, natural gas and other mineral extraction wells that can be applied to CO₂ injection.

Due to the trapping mechanisms utilized by geologic storage and the dispersion of the injected CO₂, any movements from the storage formation are likely to be slow, allowing time to make repairs before any damage is done. Appropriate monitoring techniques are needed to ensure that any migration is caught early.

Who is Responsible?

In a geologic storage project, some party or parties must be responsible for effective planning, safe and secure operation, detecting and fixing any migrations that occur and repairing any adverse impacts, however unlikely. Who those parties are depends on the project operator and the applicable legal system, which varies by jurisdiction.

**CCS is a new type of activity and legal frameworks for it are evolving.** In countries where extensive oil and gas production activities take place (in particular, EOR or acid gas injection), the legal framework may be relatively well advanced due to the similarity of CCS to those activities. In other jurisdictions, less of the legal framework may be in place.

Storage in geologic formations under the ocean is governed by various international treaties, most notably the London Convention, which covers every ocean in the world. In addition, other treaties govern specific ocean regions. The London Convention and its 1996 Protocol, (known as the London Protocol) in particular, govern marine pollution and ocean dumping. The governments that are parties to the London Protocol agreed in 2006 to allow injection of CO₂ in sub-seabed geologic formations.

The project operator will usually have the primary responsibility to effectively plan the project, obtain the necessary permits, operate the injection facilities safely and close the facilities properly when the injection period is over. Monitoring and remediation responsibilities may vary, especially post-injection. Parties with post-injection responsibility may include the operator, governments, a third party brought in under contract, or some combination, all subject to the prevailing legal framework. This may also change over time.
Government organizations—which vary by jurisdiction—may have oversight for various aspects of the CCS project, including the procedures used, health and safety, liability, protection of water supplies and monitoring. The responsibilities and obligations are still evolving in some jurisdictions. According to the IPCC Special Report on Carbon Dioxide Capture and Storage, the following legal and regulatory issues need to be considered:

- The role of pilot and demonstration projects in developing regulations;
- Approaches for verification of CO₂ storage for accounting purposes;
- Approaches for regulatory oversight of selecting, operating and monitoring CO₂ storage sites, both in the short and long term;
- Clarity on the need for and approaches to long-term stewardship; and
- Requirements for decommissioning of a storage project.
 QUESTIONS TO ASK PROJECT DEVELOPERS

The best assurance of safe and secure geologic storage is a project that is well designed and carried out. The answers to the following questions, taken together, can provide some of the basic information to determine whether that is being done. This booklet provides a relatively non-technical perspective on the issues these questions address. A thorough and accurate evaluation, however, requires substantial expertise in geology and geological engineering as well as detailed information on the proposed storage sites.

1. How much CO₂ will be injected, at what rate, and over what period?  
   – How might this vary? 
   – What impurities, if any, will the CO₂ stream contain? 
   – What safety precautions will be undertaken on the surface at the injection site?

2. Into what geologic formation will the CO₂ be injected?  
   – What is the type of rock, thickness and extent of the geologic formation? 
   – Where will the CO₂ be injected? 
   – How deep is the storage formation where it will be injected?

3. What alternative sites were considered for CO₂ storage and injection?  
   – Why were this storage reservoir and injection site(s) selected?

4. What studies were conducted of the storage reservoir and the alternatives?  
   – What measurements were taken and analyses performed using these results? 
   – Does the reservoir have enough storage capacity to meet foreseeable needs? 
   – What level of confidence do the results provide?

5. How will the CO₂ be trapped in this formation and what evidence do you have that the trapping will be effective?  
   – What trapping mechanisms exist within the storage formation? 
   – What is the primary seal and its thickness? 
   – Are there any secondary seals and what are their thicknesses? 
   – Do any faults or fracture zones intersect the primary or secondary seals? 
   – Is the injection pressure below what would affect the cap rock primary seal? 
   – Do any active or abandoned wells penetrate the primary or secondary seals?

6. What seals exist between the storage formation and any usable groundwater?  
   – What is the condition of those seals (e.g., faults, fractures, penetrations)?

7. What monitoring activities during and after injection will be conducted and by whom will those be performed?

8. Who will be liable for leaks and what will be done by whom to fix any detected leaks both during and after injection?

9. What precautions will be taken at project closure to ensure continued safe storage?

10. What aspects of the project are regulated and under what regulatory authority?  
    – What are the specific laws and regulations that govern geologic storage? 
    – Have all necessary legal and regulatory approvals been obtained?