Risk Assessment and Management for Long-Term Storage of CO_2 in Geologic Formations — United States Department of Energy R&D

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Abstract

Concern about increasing atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHG) and their impact on the earth's climate has grown significantly over the last decade. Many countries, including the United States, wrestle with balancing economic development and meeting critical near-term environmental goals while minimizing long-term environmental risks. One promising solution to the buildup of GHGs in the atmosphere, being pursued by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) and its industrial and academic partners, is carbon sequestration—a process of permanent storage of CO_2 emissions in underground geologic formations, thus avoiding CO_2 release to the atmosphere. This option looks particularly attractive for point source emissions of GHGs, such as fossil fuel fired power plants. CO_2 would be captured, transported to a sequestration site, and injected into an appropriate geologic formation. However, sequestration in geologic formations cannot achieve a significant role in reducing GHG emissions unless it is acceptable to stakeholders, regulators, and the general public, i.e., unless the risks involved are judged to be acceptable.

One tool that can be used to achieve acceptance of geologic sequestration of CO_2 is risk assessment, which is a proven method to objectively manage hazards in facilities such as oil and natural gas fields, pipelines, refineries, and chemical plants. Although probabilistic risk assessment (PRA) has been applied in many areas, its application to geologic CO_2 sequestration is still in its infancy.

The most significant risk from geologic carbon sequestration is leakage of CO_2. Two types of CO_2 releases are possible—atmospheric and subsurface. High concentrations of CO_2 caused by a release to the atmosphere would pose health risks to humans and animals, and any leakage of CO_2 back into the atmosphere negates the effort expended to sequester the CO_2. Subsurface risks, attributable to subsurface releases, arise from the displacement of fluids by the injected CO_2 that could damage nearby hydrocarbon resources or trigger small seismic events. There is also the potential for sequestered CO_2 to leak into non-saline formations, which could cause problems with potable uses of this water. However, overall, risks from CO_2 sequestration are believed to be small.

Implementation of CO_2 sequestration is being approached in phases. The DOE is currently sponsoring a series of pilot tests to generate important data that will elucidate the risks involved in geologic sequestration and lead to the development of risk management protocols. This phased approach should ensure that potential sources of leakage are identified, consequences are quantified, events with the potential to cause harm are analyzed to estimate their frequency and associated risk, and safeguards are put in place to further reduce risks for an operation for which risks already appear to be low.

Keywords
Risk Management, Risk Assessment, Carbon Dioxide Sequestration, and Geologic Sequestration

1. INTRODUCTION

Concern about increasing atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHG) and the potential impact of these increases on the earth's climate has grown significantly over the last decade. Many countries, including the United States, wrestle with balancing economic development and meeting critical near-term environmental goals while minimizing long-term environmental risks. One promising solution being pursued by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory

(NETL) and its industry and academic partners is carbon sequestration—a process of permanent storage of CO_2 emissions in underground geologic formations, thus avoiding CO_2 release into the atmosphere. This option looks particularly attractive for point source emissions of GHGs, such as fossil fuel fired power plants. In this case, CO_2 would be captured, either pre- or post-combustion, compressed to a dense fluid, transported, most likely by pipeline, to a storage site, and sequestered in an appropriate geologic formation, such as a depleted oil or natural gas field, a saline formation, or an unmineable coal seam [1].

The most significant risk from geologic carbon sequestration is leakage of CO_2. Two types of CO_2 releases are possible—atmospheric and subsurface. These may be caused by slow leaks through slightly permeable cap rock or catastrophic releases due to rupture of a pipeline, failure of a field well, or opening of a fault. In general, CO_2 is not classified as a toxic material; however, high concentrations of atmospheric releases pose health risks to humans and animals. Additional risks are attributable to subsurface release of injected CO_2. Although methodologies exist to estimate and report leakage from storage sites, further development is needed.

One tool that can be used to achieve acceptance of CO_2 sequestration is risk assessment, an essential step in risk management. Risk management involves selecting appropriate prevention and control options, policies, and processes to manage risks. Evaluating risk is a proven method to manage hazards objectively in facilities such as oil and natural gas fields, refineries, and chemical and pharmaceutical plants. Although probabilistic risk assessment (PRA) has been applied in these areas, its application to geologic CO_2 sequestration is still in its infancy. A PRA evaluates both the likelihood and the impact of an unplanned event. Use of PRAs allows decisions to be made on the most cost effective risk reduction and management options.

Prudent handling and management of CO_2 are required to offset potential health hazards. Implementation of CO_2 sequestration is being approached in a series of phases. This should ensure that potential sources of leakage are identified, consequences are quantified, events with the potential to cause harm are analyzed to estimate their frequency and associated risk, and safeguards are put in place to reduce risk to an acceptable level.

2. OVERVIEW OF RISK ASSESSMENT

As national policy makers, project developers, and investors begin to evaluate potential investment opportunities and technology options for undertaking emissions reduction activities, evaluation of the cost and overall environmental effectiveness of each technology option is necessary. Moreover, any analysis of applicable technologies must take into account the siting, energy, resource, and policy constraints of the region, state, or city in question. A critical component of this type of evaluation is assessing the risks associated with a particular technology and/or practice. With geologic sequestration, risk assessment will primarily focus on the probability and consequences of CO_2 leakage from a geologic storage site over time and the potentially adverse effects of this leakage on health, safety, the environment, and public policy. This paper addresses these questions.

Risk involves two factors—the probability (frequency) of a specified hazardous event and the severity of the consequences from that event. Risk can be defined as the product of these two factors:

$$\text{Risk} = \text{Frequency x Consequences}$$

Thus, one can have the same level of risk for a frequent event with a low level of damage as for a rare event with a very high level of damage. Therefore, in developing a risk assessment, one must evaluate both frequency and potential damage from an event. Risk assessment can address public safety, employee safety, property damage, revenue loss, and environmental damage. This methodology, called probabilistic risk assessment (PRA), is the industry standard.

PRAs use probability distributions to characterize variability or uncertainty in risk estimates. In a PRA, one or more variables in the risk equation are defined as probability distributions rather than as single values. Similarly, the output of a PRA is a range or probability distribution of risks. Geologic storage of CO_2 is well suited to analysis using PRAs because sequestration is a process-driven problem occurring over a long period of time.

3. RISK ASSESSMENT FRAMEWORK FOR GEOLOGIC SEQUESTRATION

In general, the major risks associated with the operation of an underground CO_2 storage project are related to leakage from the formation. CO_2 leakage from the formation may migrate into potable aquifers or even to the surface, which could result in a significant safety risk. To evaluate this risk requires an improved understanding of formation properties and how the injected CO_2 spreads and interacts with the rock matrix and reservoir fluids. Geologic formations typically consist of layers of rock with different porosities, thicknesses, and chemical compositions. All of these factors affect the suitability of the formation as a site for CO_2 sequestration. Porosity and thickness determine the storage capacity of the formation, and chemical composition determines the interaction of CO_2 with the minerals in place. Also, an impervious cap rock is necessary to prevent the sequestered CO_2 from migrating to the surface. Finally, if the formation consists of a series of aquifers, it is necessary to ensure that CO_2 stored in a saline formation does not migrate to a potable aquifer.

For geologic sequestration to be a viable technical option for climate change mitigation, the risks associated with this activity must be evaluated, including environmental, health and safety, and economic risks. By identifying which aspects of geologic sequestration present potential risks, appropriate actions can be taken prior to the commencement of injection activities to obviate the occurrence of problems.

Environmental Risks

From an environmental point of view, leakage is the most serious potential problem. First, leakage to the atmosphere negates the effort expended in sequestering the CO_2. Leakage serves as a CO_2 source and increases atmospheric CO_2, as well as representing an economic loss. Another potential problem is accumulation of CO_2 in pockets on the surface of the earth. Furthermore, CO_2 could migrate into other strata, with the potential for contaminating fresh water or causing other problems. If the formation into which CO_2 is being injected is below the ocean, leakage of CO_2 into the marine environment could affect ocean chemistry and have potentially serious consequences for marine life. Additional risks arise from potential damage to nearby hydrocarbon resources caused by the displacement of fluids by the injected CO_2, such as saline water production at wells that had been producing oil or gas. Finally, if a project does not operate within prescribed injection rates and pressures, there is some potential for initiating seismic activity.

Injected CO_2 may interact with formation minerals, which may have beneficial or detrimental effects. At this time, mineral interactions are not as well understood as transport processes. The interactions may be beneficial by permanently sequestering the CO_2 or may be harmful by plugging the formation and reducing permeability. There is some evidence that CO_2 injected into coal seams causes the coal to swell, which could affect overlying strata.

Health and Safety Risks

Information on the responses of animals and vegetation to elevated and potentially hazardous levels of CO_2 and low levels of oxygen (O_2) can be found in the literature related to physiology, respiratory physiology, comparative physiology, plant physiology, botany, food preservation, and aerospace. Ecosytem impacts resulting from high CO_2 concentrations are less well known than impacts on humans.

Human exposure to elevated levels of CO_2 can be hazardous in two ways—by a reduction in the oxygen content of the ambient air causing hypoxia or through direct CO_2 toxicity. The National Institute of Occupational Safety and Health (NIOSH) confined-space-hazard classification system defines CO_2 as a nontoxic, inert gas that displaces oxygen [2]. In most cases of hazardous CO_2 exposure, the gas is presumed to act as a simple asphyxiant. However, extensive research indicates that exposure to elevated CO_2 concentrations (>3 percent) has significant effects before oxygen dilution becomes physiologically significant. As O_2 concentration drops below 17 percent, increasingly severe physiological effects occur until below six percent O_2, loss of consciousness is rapid, and death takes place within minutes.

Another safety problem results from the potential for accidents from working around the facilities required to capture, condense, transport, and inject the CO_2. If hydrogen sulfide (H_2S) is sequestered along with CO_2, health risks are significantly increased, as H_2S is highly toxic.

Economic Risks

Regardless of the formation chosen for carbon storage, it is essential that its use be economically feasible. Large-scale application of CO_2 injection for enhanced oil recovery (EOR) is considered a commercially proven process; however, there are still issues that need to be addressed, a key area of concern being the economic risk of implementing geologic sequestration. It is quite expensive to capture and transport anthropogenic CO_2. Retrofitting existing pulverized coal (PC) fired units with currently available CO_2 post-combustion capture and storage technologies could increase the cost of electricity by as much as 65 percent. In the case of integrated gasification combined cycle (IGCC) plants with pre-combustion capture, cost increases are expected to be in the 20-30 percent range (with an ultimate target of only a 10 percent increase).

Aside from the issue of the effect on power costs, there are other economic risks that need to be considered. Economic liability could result if, for example, a pipeline were to rupture and cause injury or death. Such risks are routinely faced by industry and are typically covered by purchasing insurance. Also, a sequestration project might fail to operate as planned. For example, it might be discovered that the site is unsuitable because of the presence of an undetected fault, thus requiring abandoning the project and forfeiting the investment.

There are also risks associated with potential leakage from a storage site. If such leakage were to result in a high enough CO_2 concentration to cause harm, liability could result. CO_2 leakage could result in other types of economic liability. If, for example, a carbon tax were instituted, then CO_2 leakage might be treated as a CO_2 source and the sequestration project operator might have to pay a tax on the CO_2 leakage to the atmosphere. Economic liability could also arise if CO_2 leaked into a potable aquifer and caused problems, or if injected CO_2 caused water to be produced at a hydrocarbon well that had been producing oil or natural gas.

4. MEASUREMENT, MITIGATION, VERIFICATION, AND DETERMINATION OF RISKS FOR CO_2 SEQUESTRATION IN GEOLOGIC FORMATIONS

As indicated above, one of the major risks associated with CO_2 sequestration is the potential for leakage. In order to reduce this risk, technologies are needed for the measurement, mitigation, and verification (MMV) of stored CO_2. MMV is concerned with the capability to measure the amount of CO_2 stored at a specific sequestration site, map its spatial disposition, develop techniques to mitigate potential leakage, and verify that the CO_2 is stored or isolated as intended and will not adversely impact the host ecosystem. MMV for geologic sequestration consists of three areas: modeling and analysis of the geologic structure before injection occurs, subsurface monitoring of the movement of the CO_2 plume, and above-surface measurements that verify that the CO_2 remains sequestered [3].

Modeling and Simulation Prior to Injection

Prior to initiating a CO_2 injection project, the target geologic structure must be thoroughly understood, and the movement of the injected CO_2 must be reasonably well predicted in order to properly site above-ground measurement equipment. A number of models and simulation software packages currently exist to track the movement of underground fluids; however, none are designed for geologically sequestered CO_2 plumes. Modifications to any existing models and simulators to accommodate CO_2 were done for EOR analysis. To effectively model underground CO_2 behavior, three basic types of models are available:

- Standard reservoir simulator
- Geomechanical simulator
- Geochemical simulator

Which one or combination of these are used will depend on the geological attributes of the storage site and the major risks. These simulators can be tailored to meet the unique needs of CO_2 injection and geologic sequestration. Significant understanding of candidate geologic sequestration sites already exists; however, gaps still remain in understanding how CO_2 will behave at these sites. Application of MMV simulators to CO_2 injection will improve the knowledge base and provide greater accuracy of detecting CO_2 movement in underground structures.

Subsurface Measurement of CO_2 Plume Movement

Geophysical tools, such as fluid movement monitoring and seismic studies, will be used to monitor injected CO_2 behavior in targeted structures. These tools will validate and/or calibrate the pre-injection models and simulations and also provide locations of potential above-ground leakage.

Surface Verification That CO_2 Remains Sequestered

Surface verification that the injected CO_2 remains sequestered will take place near or above the surface of the underground formation. These surface MMV methods involve the direct detection and measurement of the CO_2 or, in some cases, of tracer substances moving with the injected CO_2. However, large-scale surface verification detection systems have not been tested to determine if they have sufficient accuracy.

5. GEOLOGIC STORAGE EFFECTIVENESS—PROBABILITY OF CO_2 RELEASE

As discussed previously, potential leakage of CO_2 from geologic storage sites is an important environmental issue that must be studied and will be the final test of the effectiveness of geologic storage. Currently, no studies exist that systematically estimate the probability and magnitude of a CO_2 release across a representative sample of geologic storage systems. Despite the lack of comprehensive studies, rough quantitative estimates of storage effectiveness can be determined by accumulating data from various sources. Five kinds of data are relevant to assessing storage effectiveness:

1. Data from natural systems, including natural gas and oil reservoirs, as well as natural CO_2 reservoirs.
2. Data from engineered systems, including natural gas storage, gas reinjection for pressure support, CO_2 or miscible hydrocarbon EOR, disposal of acid gases, and disposal of other fluids.
3. Fundamental physical, chemical, and mechanical processes regarding the fate and transport of CO_2 in the subsurface.
4. CO_2 transport model results.
5. Current geological storage project results.

Once collected, this data will be used for the development of PRAs for CO_2 sequestration in various types of geologic formations.

6. CASE STUDIES

The chemical and petroleum industries, the nuclear industry, the aviation and space industries, the waste management industry, the military, and some of the food industries are using risk assessment and risk management methodologies as core business tools [4]; and risk assessment and management analysis for CO_2 storage projects is beginning to evolve [5]. The DOE is currently funding several CO_2 injection sequestration projects, including the Regional Carbon Sequestration Partnerships, the Weyburn Field, and several pilot scale projects that are generating data required for CO_2 sequestration risk analysis.

Regional Carbon Sequestration Partnerships Program

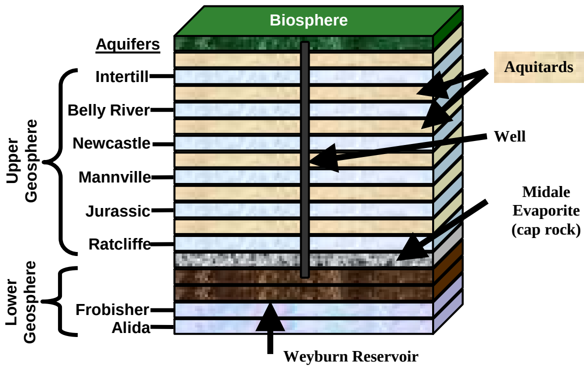
The DOE and NETL have established a network of seven regional partnerships across the U.S. to evaluate the potential for CO_2 sequestration in various regions of the country [6]. These partnerships involve over 240 organizations spanning 40 states, three Indian nations, and four Canadian provinces. In the Initiation Phase of this program, the partnerships identified regional CO_2 point sources and potential geologic sequestration sites, and evaluated CO_2 capture technologies and transportation infrastructure. This information will be used to plan and carry out pilot CO_2 sequestration projects in Validation Phase. Risk assessment will be an integral part of these Verification Phase pilot projects, and the information gathered in the Initiation Phase will be a major part of the input to these assessments. These assessments should ensure that, before CO_2 injection is initiated, potential sources of leakage are identified, consequences are quantified, and events with the potential to cause harm are analyzed to estimate their frequency and associated risk. These assessments will lead to risk management strategies and safeguards to reduce risk to an acceptable level.

Weyburn Field

The DOE and NETL are providing funding to develop and use new formation mapping and predictive tools (surface seismic and tracer injection) to better understand the behavior of CO_2 in a geologic formation. The effort at the Weyburn Field, discovered in 1954 in southwestern Saskatchewan, Canada is being coordinated with Natural Resources Canada and Dakota Gasification Company. Since 2001, several thousand tons of CO_2 per day have been pumped into this reservoir to produce incremental oil. The CO_2 is being transported by a 330 km pipeline from the Great Plains Synfuels Plant in Beulah, North Dakota to Weyburn. It is estimated that approximately 50 percent of the CO_2 remains sequestered with the oil that remains in the ground. The 50 percent that comes to the surface with the produced oil comes out of solution as the pressure drops and is recycled to the injection wells. This work examines the way CO_2 moves through the reservoir rocks, the precise quantity that can be stored in a reservoir, and how long the CO_2 can be expected to remain trapped in the underground formation.

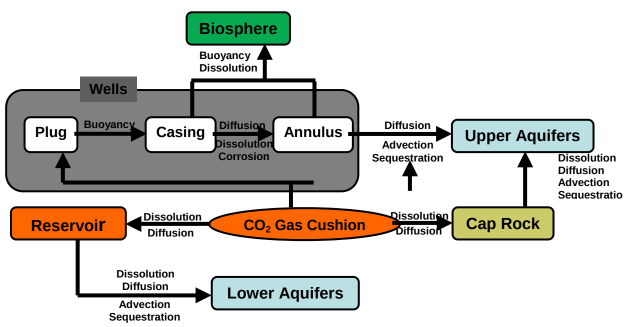
Researchers for the Weyburn CO_2 Monitoring and Storage Project have developed a program called CQUESTRA (CQ-1) and applied it to components of the project [7]. The probabilistic conceptual model (PCM) consists of two components: the model domain, which defines the geologic setting, and the model processes, which include the physical and chemical processes that define CO_2 mass transport and storage. The model domain is divided into four broad areas: (1) the biosphere, in which the interaction of CO_2 with potable aquifers, biota, and human health risks will be assessed; (2) the upper geosphere, which includes all aquifers and aquitards (formations with low permeability for the flow of water) above the reservoir and below the biosphere; (3) the wells, which consist of the wellbore, the annulus (including concrete plugs), and the steel casing; and (4) the lower geosphere, which includes the reservoir and the aquifers and aquitards below the cap rock (Figure 1).

Figure 1. Geology of the Weyburn Project [7]



Local variability in formation porosity, permeability, Darcy flow velocity, etc., is incorporated into probability distribution functions (PDFs) to capture the uncertainty in the PCM's domain features and processes. Once the physical PCM domain is fully described, CQ-1 quantifies the main driving forces pertinent to the storage of CO_2 in a reservoir. A flow diagram showing the interconnectivity of the PCM domain components with the model processes is shown in Figure 2. Input to CQ-1 was provided from a number of sources within the project and included reservoir model and simulation results, hydraulic transport properties for the wells, geosphere and reservoir property data, and geochemical model results.

Figure 2. Flow diagram showing the interconnectivity of PCM domain components with the system processes [7]



CQ-1 was used to model the Weyburn system for a period of 5,000 years after completion of EOR CO_2 injection. This simulation showed that there was considerable migration of CO_2 from the initial formation to the formation below it. There was also some migration of CO_2 into the aquifers above the Weyburn reservoir through the wells, due to corrosive failure of the well casing and leakage through deteriorating concrete plugs. However, because of CO_2 solubility, the leaking CO_2 tended to dissolve in the aquifers above the Weyburn reservoir rather than leaking to the atmosphere. This work shows that PRA models can be valuable tools in the risk assessment of CO_2 sequestration projects.

A Monte Carlo simulation method was used to sample the probability distribution functions for the CQ-1 input parameters. After 5,000 years, the mean release to the biosphere of the mass of CO_2 in place, based on 4,000 simulations, was 0.2 percent. CO_2 flow to the well bore is controlled by the permeability of the Weyburn formation, and varying this parameter had the most effect on CO_2 releases to the biosphere. This simulation showed that between 6 percent and 34 percent of the CO_2 initially in place in the Weyburn formation migrated to upper and lower aquifers. Overall, the model predicted that there is a 95 percent probability that 98.7-99.5 percent of the initial CO_2 in-place will remain stored in the geosphere for 5,000 years. These model runs provide valuable information for developing risk management strategies for EOR operations.

Frio Brine Pilot

The Frio Brine Pilot project is located 30 miles northeast of Houston, Texas in the South Liberty oilfield. This is the first U.S. field test to investigate the ability of brine formations to store GHGs. The project involved injection of 1,600 tons of CO_2 into a mile-deep well drilled into the high porosity Frio sandstone formation. The CO_2 was injected into a brine/rock system contained within a fault-bounded compartment with a top seal of 200 feet of Anahuac shale. The site is representative of a very large volume of the subsurface from coastal Alabama to Mexico and will provide experience useful in planning CO_2 storage in high-permeability sediments worldwide. The project is being extensively monitored to observe the movement of the CO_2. Before injection, baseline aqueous geochemistry, wireline logging, cross-well seismic, cross-well electromagnetic imaging, and vertical seismic profiling, as well as two well hydrologic testing, and surface water and gas monitoring, were all completed. Monitoring was repeated periodically during injection and is continuing. Data gathered during this test will enable researchers to better conceptualize and calibrate models to plan, develop, and effectively monitor larger-scale, longer-timeframe injections and devise risk management strategies for this method of geologic sequestration.

Mountaineer Project

The Mountaineer Project consists of drilling a 9,200 foot well in the Ohio River Valley to determine if the geology of this region is suitable for the injection of CO_2 into saline formations. The site for the project is American Electric Power's (AEP) Mountaineer plant near New Haven, WV. Prior to drilling the well, seismic studies were conducted to characterize the area. The Ohio River Valley is believed to be an ideal candidate for carbon capture and sequestration because of the nature of the geology of the area and because the region is home to many fossil fuel-fired electric generation plants. The data generated by this project are being used for CO_2 sequestration simulations, risk assessments, permit applications, and the design of monitoring facilities for future CO_2 injection projects. Based on the site characterization results, several potential CO_2 injection zones have been identified.

Risk assessment is an important part of this project. This includes site characterization, storage and migration modeling, identification of potential hazards and their risk, and final risk assessment. This information will be evaluated to develop risk management procedures. The conceptual site framework is being used with the reservoir models to simulate injection scenarios for various injection well designs and injection rates. Atmospheric and aqueous dispersion models may be used to evaluate the impact of any CO_2 buildup in shallow water or air and to design monitoring systems. The site information and simulation results are put into a risk assessment framework which includes hazard identification/analysis, dose-response assessment, exposure assessment, and consequence assessment.

Black Warrior Basin

Coal is an important sink for the sequestration of CO_2, and software is being developed to assess the potential risks associated with carbon sequestration in coal. Natural fractures provide important conduits for fluid flow in coal-bearing strata, but these fractures also present the most tangible risks for the leakage of injected CO_2. Discrete fracture network (DFN) models have been successfully used to assess leakage risks associated with hydraulic fracturing and coalbed natural gas production, and these models show promise for assessing risks associated with carbon sequestration in coal. The objectives of this project are to develop a software package, called DFNModeler, for risk assessment and to use this software to assess risks in the Black Warrior basin of Alabama, where coal-bearing strata have high potential for carbon sequestration and enhanced coalbed natural gas recovery [8].

Natural Analogs

Advanced Resources International is evaluating the effect of slow or rapid CO_2 leakage on the environment during initial operations or the subsequent storage period of CO_2 geologic sequestration projects. This study will include a comprehensive and multi-disciplinary assessment of the geologic, engineering, and safety aspects of natural analogs. Five large natural CO_2 fields, which provide a total of 1.5 billion ft^3/day for EOR projects in the U.S., have been selected for evaluation [9]. Based on the results of a geochemical analysis of CO_2 impacts and geomechanical modeling, an evaluation of environmental and safety related factors will be made that can be used in risk assessment and management.

7. CONCLUSIONS

Performance assessments and projects that have been conducted have shown that geologic settings are highly suitable for long-term subsurface storage of CO_2. These studies have highlighted the significant capacity of the geosphere to effectively store CO_2 and prevent its migration to the biosphere. Suitable formations include depleted oil and natural gas formations, unmineable coal seams, and saline formations.

Health effects should be minimal from slow leakage of CO_2, since low levels of CO_2 are nontoxic. The major risk to life would appear to be from a massive leak of CO_2, such as might occur from a pipeline rupture, a well blowout, or the opening of a fault. Years of pipeline operations with natural gas and, to a lesser extent, CO_2 should provide the experience needed for the safe design, operation, and management of CO_2 pipelines. However, there is always the chance that seismic or construction activity could lead to pipeline rupture. The Weyburn risk analysis indicated that the most probable path for transmission of CO_2 from one stratum to another or to the biosphere is along a well bore. Therefore, wells must be carefully drilled and monitored. If CO_2 sequestration is practiced in depleted oil and natural gas fields, then the presence of abandoned wells could cause problems. These wells will need to be effectively plugged and monitored. If H_2S, sulfur oxides (SOx), or nitrogen oxides (NOx) are sequestered along with CO_2, then potential health risks from slow leakage are considerably greater.

The largest uncertainty about leakage may come from sequestration in saline formations, since the presence of an impermeable cap rock is not as certain as in the case of depleted oil and natural gas reservoirs. CO_2 in coal seams should be relatively stable as long as the seam is otherwise undisturbed. The methane in coal seams has been kept in place for perhaps millions of years, and there is no reason that CO_2 cannot be sequestered for at least thousands of years.

In addition to health and environmental risks, there are technical risks. The major technical risk is that the injected CO_2 will affect the strata into which it is being injected in such a way that permeability and/or porosity is decreased, thus limiting the rate or quantity of CO_2 that can be injected. Decreased permeability can be overcome to some extent by increasing injection pressure, but this increases cost, and there is a limit to injection pressure to avoid fracturing the cap rock. These risks will be decreased by employing the data generated by pilot projects, but the risks will need to be included in project risk assessments. Ultimately, the risks associated with geologic sequestration identified in this paper, which are believed to by already low will be further mitigated by effective and comprehensive risk management strategies.

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