ENVIRONMENTAL ASSESSMENT OF GEOLOGIC STORAGE OF CO_2*

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INTRODUCTION

Efforts to mitigate the effects of climate change have led research and industry groups to explore ways of applying existing technologies and practices to the challenge of reducing CO_2 emissions. The storage of CO_2 in underground geologic reservoirs is one such idea that employs techniques developed for oil and gas production and transmission. For example, CO_2 has been injected into petroleum reservoirs for Enhanced Oil Recovery (EOR) since the 1970's. By 2000, there were a total of 84 operations worldwide (72 in US) involving enhanced oil recovery using CO_2 floods (Kinder Morgan, 2001). CO_2 has also been injected and stored in underground formations for the purpose of acid gas (H_2S, CO_2 and other impurities from gas separation plants) disposal. These experiences, as well as others, have helped to make geologic storage of CO_2 a viable strategy for CO_2 reduction.

In this paper, we explore the environmental and safety risks associated with geologic CO_2 storage. To emphasize some key lessons, we use four analogs: acid gas injection (AGI), enhanced oil recovery (EOR), natural gas storage, and CO_2 transport. These analogs show that 1) CO_2 transport, injection and storage has been occurring for many years, 2) CO_2 injection operations have scaled-up to significant size over time and 3) most of the risks and uncertainties associated with these activities have been managed effectively.

IDENTIFICATION OF ENVIRONMENTAL AND SAFETY CONCERNS

A CO_2 geologic storage system can be broken down into two general subsystems, namely *operational* and *in situ*. The operational subsystem, composed of the more familiar components of CO_2 capture, transportation and injection, has been successfully deployed for many years in EOR and AGI applications. As a result, CO_2 in the operational subsystem is handled and monitored with confidence and safety. But, once the CO_2 exits the injection well and enters the *in situ* subsystem, the fate of the CO_2 is largely out of human control. While there is significant experience and knowledge available to predict the behavior of CO_2 *in situ*, the *in situ* subsystem is characterized by a higher degree of uncertainty.

Operational Subsystem

The most common risks associated with the operational subsystem are a result of well and pipeline failures, which are often attributed to damage caused by unrelated activities such as farming and excavation. Other less likely failures occur as a result of corrosion or mismanagement in the form of over-pressurization and poor engineering practices.

In the event of pipeline failure (e.g. leakage), the amount of CO_2 escaping from a pipeline is limited by the use of automated shutdown valves and other safety technologies. If a rupture in the pipeline were to occur, a pressure sensor would automatically shut an upstream valve, limiting the amount of CO_2 that

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* Presented at the Second National Conference on Carbon Sequestration, Washington, DC, May 5-8 (2003).

would escape from the pipeline. As long as the pipeline is in a well-ventilated area, escaping CO_2 would be diffused in the atmosphere within minutes of a release. Notably, unlike natural gas or oil, CO_2 is neither flammable nor explosive. Years of experience have led to a regulatory regime and operating procedures that make the operational subsystem a safe, reliable and time-tested component of a CO_2 storage system.

***In Situ* Subsystem**

Due to less experience with the *in situ* subsystem, it is characterized by more uncertainty than the operational one. Current research in this field is focusing on ways to minimize the risks of geologic CO_2 storage and better understand the long-term behavior of CO_2 in the reservoir. In the following paragraphs, we review some of the concerns that have been raised about geologic storage of CO_2 and offer some perspective about their implications.

Large Releases to the Surface

Occasionally, large releases of CO_2 to the surface occur from volcanic activities in the earth's crust. Well known examples include Mt. Kilauea in Hawaii (continuously emits about 1.4 million metric tonnes (Mt) per year of CO_2), Mt. St. Helens in Washington State (released 1.8 Mt of CO_2), and Mt. Pinatubo, in the Philippines (emitted 42 Mt of CO_2) (Benson et al., 2002). Fortunately, these CO_2 eruptions are not thought to have caused harm to humans, plants or animals because the CO_2 be dispersed in the atmosphere, which prevented ground-level CO_2 concentrations from reaching harmful levels. Then again, other large CO_2 releases have proven harmful to humans. One of the examples cited most often is the 1986 release from Lake Nyos, a crater lake in the volcanic region of the Cameroons (Holloway, 1997, Stager, 1987). Although unfortunate, the key question is how relevant Lake Nyos, and other natural releases are to the practice of geologic storage of CO_2.

Importantly, the circumstances at Lake Nyos were very different than the circumstances found in geologic storage. At Lake Nyos, the slow continuous accumulation of CO_2 eventually exceeded the lake's finite capacity to hold and contain the gaseous buildup. Eventually, the CO_2 had to be vented, in the same way a balloon must pop if it is continuously filled with air. Due to the mountainous topography, the CO_2 was not able to diffuse to safe levels before it reached populated areas.

It is highly unlikely that such massive releases of CO_2 will occur from geologic storage reservoirs of CO_2. Pressure excursions should occur only near the injection point in which case the CO_2 should diffuse over large areas in the formation. In contrast, Lake Nyos tended to concentrate CO_2, while injection into geologic formations will tend to diffuse the CO_2 as it moves away from the injection point. Proper site selection, monitoring and operation can further reduce the likelihood of a large release from a CO_2 storage reservoir.

Slow Releases to the Surface

Storing CO_2 near populated areas increases the possibility of harmful exposure to concentrated levels of CO_2. Such concentrations may result from the slow release of CO_2 via transmissive faults or fractures, by pathways associated with incomplete plugging of an abandoned well, by penetrating the injection zone, or by migration pathways offered by a poorly sealed injection well. It is possible, though improbable that slow releases from storage reservoirs would pose any direct environmental or safety threat. If fact, slow leaks are likely to go unnoticed as they diffuse in the atmosphere in similar fashion to natural earth degassing, biological respiration, and organic matter decomposition. Nevertheless, certain topographies or confined structures may act to concentrate the CO_2 to dangerous levels.

A combination of variables plays an important role in evaluating the risk of potential CO_2 leakage. Some of these variables include weather, proximity to humans and ecosystems, and topography. Importantly, by employing proper site selection techniques, engineering and design, operational procedures, gas detection and pressure monitoring systems, the risks associated with CO_2 leakage to the surface can be effectively contained and mitigated as has been demonstrated in various operations in the oil and gas industry.

Migration within the Geologic Formation

Fluid movement within the geologic formation is still an uncertain process, even though technological advances have improved our understanding of fluid behavior and formation integrity in the subsurface. Groundwater contamination and the possibility of some type of leaching of toxic metals represent potential risks resulting from CO_2 migration (Bruant et al., 2002). Despite the uncertainty with respect to migration, EOR operations have not experienced significant CO_2 loss in the formations, nor has there been evidence of leaching effects or chemical incompatibility between injected CO_2 and the formation. Although we can gain confidence that migration risks may be low as a result of EOR activity, EOR cannot fully simulate the movement of the CO_2 over the extended time periods necessary for effective CO_2 storage.

Seismic Events

EOR, AGI and natural gas storage operators are not overly concerned with inducing seismic events, primarily due to the low volumes of fluids being injected. However, larger volumes of injected fluid would increase reservoir pressure, displace other fluids and might induce seismic events (Holloway, 1996). Although induced seismic events have been recorded, measures can be taken to significantly reduce the associated risks. Some measures include careful siting, using proper pressure guidelines and design requirements, understanding the geomechanical properties of the storage reservoir, and properly placing wells and pipelines.

Other Risks

Studies conducted over the past two decades have confirmed that biological communities exist deep in the subsurface, including depths where geologic storage of CO_2 is likely to occur. These studies are quite expensive, relatively few in number and have not evaluated the effects of CO_2 on these communities. Nevertheless, the environmental significance of these communities is not likely to be a serious concern as they are unlikely to play an important ecosystem function. Furthermore, the “foot print” of geological storage is going to be small compared to the total amount of subsurface habitat available for these organisms. Even if a particular community is affected, the impact on the total biodiversity and ecosystem of the earth will be negligible.

It has been argued that the adoption of carbon capture and storage technologies will lead to lower CO_2 emissions, but also an increased use of fossil fuels. Although this is not a direct environmental or safety risk, increased fossil use could create a potential risk of enhancing the adverse effects of climate change in the event that these CO_2 storage reservoirs leaked in the future. However, potential risks created by increased fossil fuel use can be managed and mitigated by an appropriate regulatory regime and a systems management approach with proper accounting. Essentially, this problem can be mollified by correctly valuing the benefits of CO_2 storage, even if storage is not permanent (Herzog, Caldeira, and Reilly, 2003).

EXISTING TECHNOLOGIES

A comparison of magnitudes of current CO_2 storage projects compared to CO_2 injection activity in acid gas injection and enhanced oil recovery projects is illustrated in Figure 1. As the market for CO_2 storage develops, combined with advances in storage technologies and/or government incentive programs, these magnitudes will continue to increase in size. At this time, all acid gas injection schemes and current storage projects are smaller than the projected size of future commercial storage applications. However, the largest EOR injection rates far exceed 10,000 tonnes per day, a reasonable metric for commercial-sized storage activities.

We have chosen four analogs – acid gas injection, enhanced oil recovery, natural gas storage and CO_2 transport – to aid our understanding of the critical environmental and safety related uncertainties facing geologic storage. The following paragraphs will present a brief overview of each of the four analogs and attempt to draw out some key lessons concerning their development and operation that are relevant to assessing the environmental and safety risks of geologic CO_2 storage. Although these analogs cannot present a complete picture, they can offer a great deal of insight into how a geologic storage regime might evolve, operate and be managed safely and effectively.

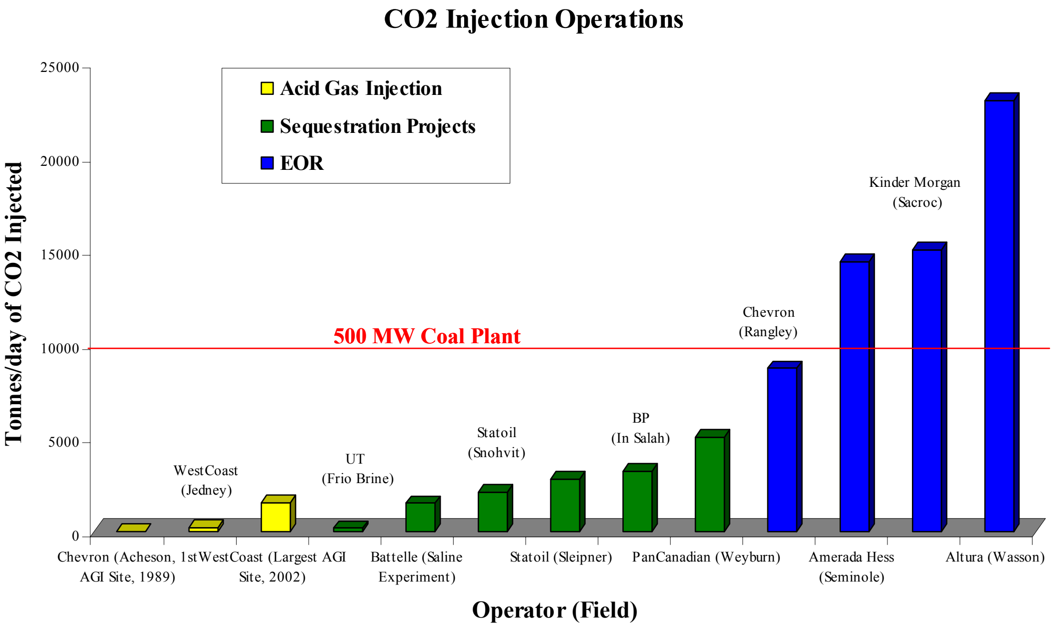

Figure 1: Comparison of CO_2 Injection Activities (Data from Hovorka, 2002; Lock 2002; Maldal, T., and Tappel, I.M., 2002; Roche, 2002; Riddiford, F.A., et. al., 2002; Stevens, et. al., 2000)

Acid Gas Injection

Acid gas injection schemes are designed to remove acid gases (CO_2 and H_2S) from an oil or gas stream produced from a geological formation, compress and transport the gases via pipeline to an injection well, then re-inject the gases into a different geological formation for disposal. Since 1989, when the first AGI operation went on-line injecting acid gas at a rate of 180,000 standard cubic feet (10 tonnes) per day, Canadian oil and gas companies have continued to develop and employ this technology. In fact, in 2001, nearly 6.5 billion cubic feet (over 360,000 tonnes) of acid gas was injected into formations at more than 30 different locations across Alberta and British Columbia (Roche, 2002).

In AGI schemes, the safe removal and storage of H_2S is the primary concern, particularly because of its toxicity; yet, CO_2 often represents the largest component of the acid gas stream. In many cases, CO_2 comprises over 90% of the total volume of gas injected for storage. Thus, many of the acid gas schemes are in fact small-scale CO_2 storage projects.

Most acid gas injection operations inject between 50 thousand and 5 million scf of acid gas per day, compared to Statoil's Sleipner CO_2 storage project, which injects about 50 million standard cubic feet (MMscf) of CO_2 per day. However, the newest AGI project is over half the size of Sleipner. Built by West Coast Energy in the summer 2002, this project injects acid gas at a rate of 28 million scf per day into a nearby depleted gas reservoir in northeastern British Columbia (Roche, 2002).

The presence of H_2S creates many significant environmental and safety risks, which largely overshadow concerns about CO_2. These risks associated with the release of acid gases are effectively reduced by maintaining high system reliability rates, which is achieved through operator training and routine maintenance procedures, automated pressure monitoring and gas detection systems, automated emergency shutdown valves and response systems, effective regulatory enforcement and reporting and years of operating experience. Experience with and knowledge of subsurface conditions and fluid behavior as a result of many years of resource exploration and production is also beneficial and helps to reduce uncertainty.

Engaging the public, which is made easier when the public is familiar with and even benefits from the activity, is key to successful long-term operation. For example, in Alberta, oil and gas production accounts for over 40% of the province's revenues, 60% of its total exports and provides employment for over 183,000 residents. At the Acheson AGI facility, 3 miles outside Edmonton, EnerPro participates in and hosts various joint committees involving the public and nearby residents. They have successfully communicated with the nearby public through regular meetings, hosting open house barbeques, handing out holiday turkeys, promptly responding to complaints, and holding informational/educational sessions (Bezinett, 2002). These activities have facilitated more open communication and credibility with the public and allowed them to be more attuned to public concerns. Thus, oil and gas operators have faced relatively little public opposition even when they have disposed of waste gases underground so close to a major population center.

Enhanced Oil Recovery

Enhanced oil recovery, like AGI, provides considerable experience and insights for safe, reliable injection and storage of CO_2. Since the first EOR operation began in 1972, over 10 states and 5 different oil-producing countries have adopted EOR techniques. In 2000, 84 commercial or research-level CO_2-EOR projects were operational worldwide. (Oil & Gas Journal, 2001).

One of the largest EOR operations can be found near Seminole, Texas. In 1983, Amerada Hess began re-processing waste gas from the production field. Today, flow volume from the production field averages around 175 MMscf per day. The composition of this stream is roughly 85% CO_2, 15% hydrocarbons, and 0.6% H_2S. While essentially all the hydrocarbons are either reused or sold, the majority of CO_2 (145.9 MMscf per day) is recycled and re-injected into the field. Once the recycled CO_2 is combined with the purchased CO_2, this EOR operation injects nearly 260 MMscf of CO_2 per day into the Seminole Unit. These injection rates exceed the volume injected into the Sleipner field by over 5 times.

Environmental and safety risks are mitigated in similar ways to AGI. Not surprisingly, the methods and technologies used for gas detection, pressure monitoring, safety training and public awareness in EOR operations are analogous to those used in acid gas injection. Despite the surface footprints from the facilities and well sites, the environmental issues arising from CO_2 flooding seem to be inconsequential. However, no environmental assessments are required to confirm this general assumption. Operators observe that some CO_2 may be permanently stored in the formation, most probably as a result of fingering or through the oil-water contact zone. EOR operators have estimated that non-recycled CO_2 amounts to anywhere between almost negligible levels to around 5% (Wehner, 2002).

Natural Gas Storage

In addition to providing insight into the operations, risks and management strategies relevant to geologic CO_2 storage, the physical characteristics of natural gas are quite similar to CO_2. Similarities include the gases' tendency to rise within a storage structure, while key differences include the time scales for management, injection and withdrawal rates and the types of reservoirs suitable for storage.

Like AGI and EOR, natural gas storage has increased in scale as well as in geographic scope over the years. The first natural gas injection and storage activity took place in a partially depleted gas reservoir in 1915. Since then, underground natural gas storage has become a relatively safe and increasingly practiced process to help meet seasonal as well as short-term peaks in demand (EIA, 1999).

The most common problems in the business are well leaks resulting from mechanical failure. Fortunately, most of these problems do not create unmanageable environmental or safety risks. Wells can be repaired, reconditioned, or plugged fairly quickly (Benson et al., 2002). Gas leakage and migration within the subsurface had not been a concern until a recent incident in Hutchinson, KS in early 2001. In this case, it was concluded that gas had escaped through a damaged well pipe, migrated 9 miles, re-accumulated and vented through abandoned wells killing two and destroying many downtown businesses ("Report Links," 2002). Poor engineering practices, a lax regulatory regime and mismanagement appeared to be factors. While this is a good example to illustrate the potential for migration and re-accumulation, the catastrophic results described here are not analogous to CO_2 storage since CO_2 is not flammable.

CO_2 Transport

Numerous large natural deposits of CO_2 have existed underground for millions of years and demonstrate that stable long-term storage of CO_2 can be achieved (Holloway et al., 1996). In the last twenty years, many of these natural CO_2 reservoirs have been utilized for EOR operations. To support EOR and other commercial applications, an extensive network of CO_2 pipeline was built up and now stretches nearly 2000 miles, mostly in the United States (Gale, 2001). Although pipeline failure does occur, the technology, operational procedures and risks associated with CO_2 transport are well understood.

LESSONS

In addition to the practical insights gained from the analogs about risk management, technology, operational procedures, etc., broader lessons have emerged. In particular, activities similar to high-volume geologic storage of CO_2 have been managed successfully for decades. Low-volume geologic storage of CO_2 has successfully occurred in the form of enhanced oil recovery for over 30 years and also under the practice of acid gas injection since 1989. Specific knowledge and expertise now exists for effective management of CO_2 storage.

These operations did not develop overnight, rather all four analogs evolved incrementally into substantial injection schemes over time. The first AGI operation injected merely 10 tonnes per day in 1989. Fourteen years later, the largest AGI scheme is injecting nearly 1,400 tonnes per day into a depleted gas field. The development of a geologic CO_2 storage regime will most likely follow the same evolutionary path for scaling up in size and geographic distribution.

Research, experience and public outreach have aided operators and regulators in successfully managing the risks, benefits and public apprehension associated with these activities. It follows that geologic storage of CO_2 can be a promising strategy for climate change mitigation because it can build upon the knowledge and experience gained in the oil and gas industry.

Moving forward, environmental and safety risks should be addressed by industry, government and the research community by focusing on developing a better understanding of the long-term implications and behaviors of CO_2 particularly with respect to the *in situ* subsystem. Existing analogs and newly designed experiments will be important for furthering our knowledge and understanding about the risks involved.

Finally, proponents of geologic CO_2 storage should not underestimate the importance of informing and educating the public about the benefits and uncertainties involved. Educating the public is essential to allow it to make informed judgments about the implications of geologic storage of CO_2.

ACKNOWLEDGEMENTS

The authors wish to thank the Clean Air Task Force for their sponsorship of this project. We also express our gratitude to the following for their comments and contributions to the paper: Sally Benson, Lawrence Berkeley Labs; Peter Cook, Australian Petroleum Cooperative Research Centre; Bill Gunter, Alberta Research Council; Haroon Kheshgi, ExxonMobil Research and Engineering Company; Vello Kuuskraa, Advanced Resources International and Arthur Lee, Chevron Texaco.

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