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Comparative Assessment of Status and Opportunities for CO_2 Capture and Storage and Radioactive Waste Disposal in North America

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Abstract

Aside from the target storage regions being underground, geologic carbon sequestration and radioactive waste disposal share little in common in North America. The large volume of carbon dioxide (CO_2) needed to be sequestered along with its relatively benign health effects present a sharp contrast to the limited volumes and hazardous nature of high-level radioactive waste. There is well-documented capacity in North America for 100 years or more of sequestration of CO_2 from coal-fired power plants. Aside from economics, the challenges of geologic carbon sequestration include lack of fully established legal and regulatory framework for ownership of injected CO_2, the need for an expanded pipeline infrastructure, and public acceptance of the technology. As for radioactive waste, the U.S. has proposed the unsaturated tuffs of Yucca Mountain, Nevada, as the region's first high-level radioactive waste disposal site. The Canadian radioactive waste program is currently evolving with options that range from geologic disposal to both decentralized and centralized permanent storage in surface facilities. Both the U.S. and Canada have established legal and regulatory frameworks for radioactive waste disposal. The most challenging technical issue for radioactive waste disposal is the need to predict repository performance on extremely long time scales (10^4 – 10^6 years). While attitudes toward nuclear power are rapidly changing as fossil-fuel costs soar and changes in climate occur, public perception remains the most serious challenge to opening radioactive waste repositories. Because of the many significant differences between radioactive waste disposal and geologic carbon sequestration, there is little that can be shared between them from regulatory, legal, transportation, or economic perspectives. As for public perception, there is currently an opportunity to engage the public on the benefits and risks of both geologic carbon sequestration and radioactive waste disposal as they learn more about the urgent

energy-climate crisis created by greenhouse gas emissions from current fossil-fuel combustion practices.

1 Introduction

Accelerating emissions of carbon dioxide (CO_2) from fossil-fuel combustion (Raupach et al., 2007) and associated threats to global climate are motivating an urgent search for low-carbon energy sources. With renewable energy sources such as hydroelectric, solar, and wind projected to supply less than 10 percent of the world's energy needs by 2030 (EIA, 2007), two low-carbon sources of electricity, namely nuclear (fission) power and coal with pre- or post-combustion Carbon Dioxide Capture and Storage (CCS) have been proposed as key components of a multifaceted approach to meeting the global energy-climate challenge (e.g., Pacala and Socolow, 2004). While producing a majority of electricity from nuclear fission and from coal with CCS in the future will drastically reduce atmospheric CO_2 emissions relative to today, nuclear power produces radioactive waste that must be isolated from the environment and the CO_2 from coal combustion must be sequestered. For nuclear power, the waste stream is radioactive, highly toxic, and, depending on the nuclear fuel cycle (i.e., after reprocessing), may present a security risk owing to its capacity for use in producing nuclear weapons (IAEA, 2005). In the case of electricity production using coal, the concern about CO_2 is its role as the main greenhouse gas responsible for climate change.

Research into Radioactive Waste Disposal (RWD) has been going on for decades in North America, and geologic disposal of radioactive wastes is planned in many countries worldwide (e.g., Witherspoon and Bodvarsson, 2006). Of the countries often considered geographically as part of North America, only the U.S. and Canada have substantial amounts of radioactive waste. We therefore restrict our comparisons in this paper to U.S. and Canadian RWD activities. In North

America, as well as elsewhere, the volumes of high-level radioactive waste expected to accumulate over the foreseeable future are typically small enough to allow for geologic disposal in engineered underground facilities, usually excavated horizontal galleries and emplacement tunnels. One centralized repository for the U.S. and one for Canada are likely sufficient to store the expected volumes of domestic high-level radioactive waste over the next several decades. A geologic repository for transuranic radioactive wastes has been operating in the United States since 1999. The so-called WIPP facility (Waste Isolation Pilot Plant), located approximately 42 km (26 mi) east of Carlsbad, New Mexico, stores wastes about 600-700 m underground within a 1,000 m (3,000 ft) thick salt formation.

It has only been in the last 10-20 years that Geologic Carbon Sequestration (GCS), the geologic storage part of CCS, has been considered seriously as an emissions reduction strategy, but because of CO_2's natural abundance and utility in enhancing hydrocarbon recovery, CO_2 injection has been carried out continuously in the U.S. for enhanced oil recovery for approximately 35 years (Bondor, 1992). The experience and knowledge gained from CO_2-enhanced oil recovery has provided a solid foundation for GCS. In the last ten years or so, the pace of investigations into GCS has grown rapidly. For example, studies of capacity (e.g., Bradshaw et al., 2007), cost (Friedmann et al., 2006), effectiveness (Hepple and Benson, 2005), potential impacts (Oldenburg, 2007), regulatory and legal aspects (Wilson et al., 2003), and pilot projects (Litynski et al., 2006) among many others have been published in the last few years.

The purpose of this paper is to compare and contrast GCS and RWD, and evaluate the opportunities and discuss the challenges of implementation in North America, specifically the U.S. and Canada.

Space does not allow us to thoroughly review the science, history, and current activity of RWD, and we refer interested readers to the high-level radioactive waste worldwide review(s) (e.g., Witherspoon and Bodvarsson, 2006) for a comprehensive summary of RWD efforts around the world. Similarly, for GCS the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) provides a comprehensive explanation of the technical basis for GCS that is beyond the scope of this paper. With the ultimate purpose of the collected papers in this volume aimed at comparing options for electricity generation, we focus on sequestration of CO_2 from coal-fired power plants (the largest stationary point sources of CO_2 in North America) rather than on industrial sources (e.g., refineries and cement plants).

2 GCS Status, Opportunities, and Challenges in North America

2.1 Current Status of GCS

Activities involving the injection of large volumes of CO_2 into deep geologic formations in North America are associated with enhanced oil recovery (EOR) (e.g., Bondor, 1992), mostly in West Texas, but also in New Mexico, Oklahoma, Kansas, Arkansas, Louisiana, Mississippi, Wyoming, Colorado, Utah, Montana, Alaska, Pennsylvania, and the Canadian provinces of Alberta and Saskatchewan. The majority of the U.S. CO_2-EOR operations utilize CO_2 produced from natural CO_2 reservoirs, such as those at St Johns-Springerville (Arizona), Bravo Dome (New Mexico), McElmo and Sheep Mountain Domes (Colorado), and Jackson Dome (Mississippi), which are connected by pipelines to the oil fields. Other sources include gas processing plants (e.g., LaBarge (Wyoming)) and an ammonia plant in Oklahoma (Moritis, 2008). Early implementations of CO_2-EOR started in the mid-1970's before there was widespread interest in reducing CO_2 emissions. Notwithstanding the past and ongoing sourcing of CO_2 for EOR from natural CO_2 reservoirs, co-optimization of CO_2-EOR and GCS are areas of current research interest (e.g., Kovscek and Cakici, 2005) anticipating a future in which anthropogenic CO_2 is abundantly available and carbon credits are awarded for CO_2 retained in the formation (sequestered). The most well-known CO_2-EOR projects that use anthropogenic CO_2 are being carried out in Canada (in Saskatchewan) by EnCana at the Weyburn oil field and by Apache at the nearby Midale oil field (White et al., 2004). The source of CO_2 for these projects is a coal gasification plant in Beulah, North Dakota, from which CO_2 is sent by a 330 km- (200 mi-) long pipeline to southern Saskatchewan. In these projects, around one-half of injected CO_2 is produced with oil and recycled, while the other half is sequestered in the reservoir. In Alberta, PennWest has been using CO_2 from a nearby petrochemical plant since 1984 for CO_2-EOR in its Joffre field. Another significant activity in North America involves injecting hydrogen-sulfide and CO_2 that are stripped from produced natural gas (mostly methane) and injected for disposal. Although the injected gas stream is often over 95% CO_2 (Bachu and Gunter, 2004), the primary purpose is to dispose of hydrogen sulfide, hence the name acid-gas injection.

The other major class of GCS activity in North America involves pilot CO_2 injection projects. The first was the Frio Brine Pilot in Dayton, Texas, that began in 2002 with a small 1,700 tonne injection into a brine formation in a mature oil field and finished recently following a second phase of injection (Hovorka et al., 2006). Shortly after the first Frio Pilot injection, the U.S. Department of Energy (DOE) launched its Regional Carbon Sequestration Partnership (RCSP) program (Litynski et al., 2006). In this program, seven RCSP groups representing different regions of the U.S. and Canada embarked in 2003 on a long-term effort to (1) characterize their individual regions in terms of opportunities for GCS, (2) validate the opportunities, and (3) deploy GCS to demonstrate the feasibility of storing hundreds of years' worth of industrial-scale CO_2 emissions. All seven of the

RCSPs have advanced to Phase III to develop sites for the deployment of industrial scale pilot projects involving the injection of at least 10^6 tonnes of CO_2.

2.2 Opportunities for GCS

Opportunities for large-scale GCS in North America are abundant and well-documented. The primary reference for North American GCS opportunity is the NATCARB database, an ongoing development of the U.S. DOE. To allow real-time queries on sources of CO_2, pipeline transport, potential sequestration sites (sinks), and more, NATCARB can be accessed online at http://drysdale.kgs.ku.edu/natcarb/eps/natcarb_alpha_content.cfm. Focusing here on electricity generation which represents approximately 86% of CO_2 point-source emissions in North America (NATCARB, 2006), we present in Figure 1 the locations of large power-plant sources of CO_2 in North America as compiled by NATCARB in its 2006 database. The sources shown emit an estimated 3.3 Gt CO_2/yr (NATCARB, 2006). The locations of CO_2 sources from power generation in the U.S. reflect the distribution of population with most sources concentrated in the more densely populated and industrial eastern part of the country.

Shown in Figure 2 is a map from the NATCARB online database showing deep saline formations (blue) and oil and gas fields (red) that provide North America with enormous potential sequestration capacity for CO_2. For brevity, we have omitted from the maps unmineable coal, organic-rich shale, and basalt formations that, while potentially significant, are thought to be less important to the North American region than saline formations and oil and gas fields. Comparing Figures 1 and 2, we observe that many suitable sedimentary basins with saline formations and oil and gas resources underlie the large stationary sources of CO_2 particularly in the industrial Ohio Valley, Midwest, and

Texas Gulf Coast areas, potentially minimizing the need for long pipelines for CO_2 transport. Because of early industrialization in the U.S., oil and gas fields are mostly mature, meaning production over the last 50-100 years has left them depleted or nearing depletion. These mature reservoirs offer the advantages of demonstrated sealing against upward migration of buoyant fluid, potential to inject CO_2 to make up for net extraction of oil and gas, detailed knowledge of the local subsurface from decades of oil and gas production, and a history of land use similar to that associated with GCS.

GCS capacity for North America has been studied by U.S. and Canadian researchers with data compiled by NATCARB. While not all potential sinks have been evaluated, Table 2 shows the documented capacity as determined by NATCARB using a consistent capacity estimation methodology for the various sequestration targets. Assuming total CO_2 emissions from fossil-fuel power plants in North America amount to 4 Gt CO_2/year, and using the low estimates of capacity, the saline formations would provide capacity for over 200 years of CO_2 injection, depleted oil and gas reservoirs for 20 years, and unmineable coal seams for 40 years. Putting aside the uncertainty in emissions growth, capacity estimates (e.g., Bradshaw et al., 2007), practical and economic barriers to capturing CO_2 from all power plants, CO_2 transportation considerations, etc., research to date strongly suggests that very significant amounts of CO_2 can be sequestered safely and effectively in the deep subsurface in North America.

In addition, GCS represents a business opportunity currently being pursued by a variety of companies and sectors. For example, oil and gas companies are viewing depleted reservoirs and associated brine formations as potential revenue-generating sinks for CO_2. Pipeline companies see the potential need for pipeline infrastructure to transport CO_2 from power plant sources to GCS sites. And oil services companies see a large opportunity for characterization and monitoring of field operations of GCS. These nascent industrial efforts are anticipating widespread implementation of GCS as a revenue-generating enterprise.

2.3 Challenges Associated with GCS

Although opportunities of GCS are many in North America, so are the challenges to implementation. The basic barrier delaying industrial GCS in the region and worldwide is economic; simply put, CCS does not pay at present. Without either a cap and trade policy or carbon tax in place in North America, the economic incentive for CCS is missing. The capture part of CCS in particular is expensive and technologically challenging especially for existing coal-fired power plants. Nevertheless, forward-looking scientific, government, industrial, and power utility leaders are looking beyond today's economics to develop the science, technology, policy, and regulations that will be needed to implement large-scale CCS. Assuming there was today an economic advantage or policy imperative for CCS, implementation of CCS in North America faces secondary challenges such as the lack of (1) transportation infrastructure, (2) established GCS injection regulations, and (3) applicable laws regarding ownership and liability of CO_2 in the subsurface. In addition, there are challenges for GCS surrounding public perception and environmental justice that need to be addressed. Finally, there are technical challenges being addressed by scientists and experts, but these do not appear to present insurmountable barriers to implementation. Below we elaborate on each of these challenges.

As shown by comparison of Figures 1 and 2, many of the region's CO_2 sources are located on top of or in close proximity to large saline formation sinks for GCS. However, the scale of the maps belies the details of the extent of need for new networks of pipelines to transport CO_2 from power plants to permitted CO_2 injection wells. In addition, there are large areas of the region with power-generation sources of CO_2 without local onshore GCS capacity, e.g., the southern Atlantic coast area. Simply put, it will be challenging to establish new pipeline transport corridors through areas of existing and growing populations where there is an ever-increasing concern for the local environment—the so-called NIMBY (Not In My Back Yard) syndrome. Because CO_2 transportation represents another business opportunity for GCS, and pipeline infrastructure is well established in North America for hydrocarbon transport, utilities such as power, water, and sewer, as well as fiber-optic data transmission purposes, building such an infrastructure is not expected to be an insurmountable hurdle.

At the time of this writing, the regulatory environment for GCS is rapidly evolving in North America. The existing framework for deep underground injection in the U.S. is covered by the Environmental Protection Agency's (EPA's) Underground Injection Control (UIC) program, designed to protect underground sources of drinking water (i.e., potable water, defined as water with less than 10,000 mg/L total dissolved solids) (e.g., USEPA, 2001; Benson et al., 2002). This program is currently being extended in the U.S. to cover deep injection of CO_2 through the addition of Class VI injection well (a CO_2 injection well) to augment the existing Class I-V wells. Over half of U.S. states retain primary enforcement responsibility, or primacy, and enforce UIC regulations on their own using regulations that are equivalent or more restrictive than EPA's, while seven states jointly enforce UIC regulations with EPA (e.g., California), and the rest (e.g., Arizona) rely on EPA alone for regulation. In Canada, fluid injection is entirely a matter of provincial rather than federal jurisdiction. The Canadian province of Alberta has a regulatory framework potentially applicable for GCS through its CO_2-EOR and acid gas injection programs (Bachu, 2008). The Interstate Oil and Gas Compact Commission recently published guidelines intended as a reference for states and provinces in their development of GCS regulations (IOGCC, 2007), but this does not carry the same force of law as the EPA Class VI proposed regulation. Layered on top of the ongoing and rapid developments in establishing regulations for widespread implementation of GCS is the prospect of future changes in the definition of potable water as changes in climate, water demand, and desalination technology promote use of waters that are considered today non-potable.

If the regulatory framework for GCS can be said to be developing, a GCS-specific legal framework must be said to be non-existent. In short, mineral rights and surface property rights are kept distinct, a system that has worked in practice for the awarding of royalties for mineral and hydrocarbon extraction for over 100 years. However, when it comes to storing fluids in the pore space of rock below the surface owner's property, there are few laws in place (Wilson et al., 2007). The state of Wyoming decided by statute in 2008 to place pore-space ownership in the hands of the surface owner. While it seems likely that other jurisdictions will follow this same model, other statutes and laws are lacking at the time of this writing. Details and analysis of liability issues associated with GCS and RWD are presented in Wilson and Bergan (this volume). The working hypothesis of leaders in the field is that the long sequestration time frames (several hundred to thousands of years) will necessitate the eventual assumption of liability by a governmental entity that can persist longer than any corporation has been known to exist. However, this desire to hand-off the long-term liability for the injected CO_2 is creating suspicion among skeptics that GCS is risky or unsafe and thereby causing a public perception problem.

Public perception of GCS is a growing challenge, but also an opportunity. In North America, the problem of climate change and its relation to greenhouse gas emissions is fairly well known thanks to Al Gore's popular movie, "An Inconvenient Truth," and widespread and growing media coverage of climate change and future emission projections involving the developing world, primarily China and India. When it comes to tackling the energy–climate problem, renewable energy sources, particularly solar and wind, are familiar to people, while the inclusion of CCS as part of a portfolio of approaches is much less well known. In our personal experience talking about GCS in public meetings and university classes, there is great skepticism of any solution promoted by the same entities (power utilities, coal companies, oil companies, governments) perceived as having caused the greenhouse gas emission problem to start with. However, because many people are aware of the problem of climate change and so few people have heard of GCS, there is the opportunity to carefully present the case for GCS to an audience receptive to technologies that will address climate change. For a comparative analysis of public perception issues see Reiner and Nuttal (this volume).

Summaries of GCS physical and chemical processes, technical challenges, and research areas being addressed by scientists worldwide can be found in the literature (e.g., IPCC, 2005; Wilson et al., 2007; Bachu and McEwen, this volume). None of these technical challenges prevents GCS from being initiated today on a single-source scale as the existing worldwide industrial projects (e.g., Sleipner and Snovhit (Norway), In Salah (Algeria), Weyburn-Midale, Canada)) demonstrate. However, it must be mentioned that while capacity in North America is demonstrably large, so too are national point-source CO_2 emissions. Large-scale implementation of GCS involving multiple power-plant sources with injection into the same saline formations can lead to widespread pressure rise (Nicot, 2008) which raises the risk of induced seismicity and brine displacement into shallower groundwater resources (Birkholzer et al., 2009) that are highly valued especially in the arid parts of North America. The brine displacement hazard arises mainly in areas of North America with depleted hydrocarbon reservoirs where there are many abandoned wells that are considered the most likely conduits for leakage of CO_2 out of GCS sites (Gasda et al., 2004; Nordbotten et al., 2004) and which may also serve as brine migration conduits depending on the conditions of the well. The U.S. EPA Class VI draft rule on CO_2 injection addresses the hazard of abandoned wells by requiring their identification and plugging prior to CO_2 injection. It is interesting that many of the same wells that cause concern for leakage (typically the wells that are very old and also very deep) have been the sources of information for indicating the presence of high-quality seals against upward migration, and favorable injectivity and capacity in the storage interval. Although the identified wells of concern will be properly plugged prior to injection, monitoring of these wells may still be needed along with pressure management to reduce pressure rises arising from large-scale injection.

3 RWD Status, Opportunities, and Challenges in North America

In North America, both the United States and Canada have radioactive waste disposal programs that have been working for decades on providing a permanent and reliable method of isolating high-level radioactive waste from the biosphere. The current status of these two programs is quite different. Because of public acceptance concerns, Canada has been in a phase of re-evaluating storage options that range from geologic disposal in mined underground facilities to both decentralized and centralized permanent storage in surface facilities. In the United States, on the other hand, the Yucca

Mountain site in Nevada has been designated and studied for decades as a geologic disposal site, and, as a major step forward, the license application for this site was submitted to the regulatory authorities on June 3, 2008. We focus below on the United States geologic disposal program, while elaborating in lesser detail on the Canadian program.

3.1 Current Status of RWD in the U.S.

3.1.1 Selection of Yucca Mountain

In 1982, the U.S. Congress passed the Nuclear Waste Policy Act (NWPA), a federal Law that established the U.S. policy for the permanent disposal of high-level radioactive waste. While the site screening and selection process including various alternative sites was still ongoing and before a clear technical ranking had been established (e.g., in volcanic rocks, in basalts, and in bedded and dome salt sites), Congress amended the act in 1987, directing the Department of Energy (DOE) to study only Yucca Mountain, Nevada, as the permanent geologic repository. Though the Yucca Mountain site has many technical advantages over other sites, the congressional decision for Yucca Mountain has since been criticized by some as political and arbitrary. The state of Nevada in particular viewed the decision as singularly unfair, made at the expense of a state with less political clout than other states (Carter et al., 2006; Macfarlane, 2006).

Since then, Yucca Mountain site has been characterized and evaluated in numerous scientific studies to determine its suitability. The site characterization phase ended in 2002, when the Secretary of Energy recommended the Yucca Mountain site as suitable for further development. Following this event, DOE began the process of preparing a license application for authority to construct a geologic repository at Yucca Mountain, which was submitted to the regulating authority on June 3, 2008. The following subsections introduce the Yucca Mountain site, discuss the barriers critical to geologic radioactive waste isolation, and provide some details on the regulatory standards. Much of this discussion is based on the summary description given in Arthur and Voegele (2006).

3.1.2 Yucca Mountain Site Description

The proposed Yucca Mountain site is located on federal land in southern Nevada, approximately 90 miles northwest of Las Vegas. The location is remote, far away from population centers. Yucca Mountain is one of a series of north-south trending ridges, consisting of successive layers of volcanic tuffs, millions of years old. The alternating layers of welded and non-welded volcanic tuffs have differing hydrogeologic properties that significantly influence the manner in which downward percolating water moves through the mountain. The proposed repository horizon will be in the welded tuff, which is highly fractured and thus relatively permeable. However, the climate is arid, infiltration into and percolation through the mountain is very small, and the water table at Yucca Mountain is deep, about 600 m below the mountain crest. The repository horizon is located in this thick unsaturated zone, more than 200 m above the water table, such that the repository tunnels would remain relatively dry, accessible by ramps from outside the mountain, and amenable to monitoring and inspection for centuries (Carter, 2006). This specific repository setting, i.e., waste emplacement in a thick unsaturated zone with small rates of water movement but rather permeable rocks, is fairly unique worldwide. Other proposed disposal concepts typically involve repositories in low-permeability rocks such as sparsely fractured granite, claystone, and/or salt situated below the groundwater table in saturated conditions. While Yucca Mountain offers major advantages over sites beneath the water table for reasons listed above, it was also suggested that the number, complexity, and interaction of relevant processes makes prediction of repository behavior more difficult and possibly more uncertain (Macfarlane, 2006).

Figure 3 shows a schematic of the proposed repository design. An existing U-shaped tunnel, named the Exploratory Studies Facility (ESF), allows access into the mountain from two entry points, the North Portal and the South Portal. The ESF was built in the mid-nineties and has been used as an underground rock laboratory, where processes and properties have been studied in multiple *in situ* experiments (e.g., Bodvarsson et al., 1999). In case construction authorization is granted by the regulating authorities, access to the repository will be possible via an additional ramp as well as via ventilation shafts. The waste, contained in cylindrical canisters made from corrosion-resistant material, will be emplaced into circular drifts of about 5 m diameter. More than 11,000 waste packages may be stored in more than 40 miles of emplacement drifts. Titanium drip shields will be installed to protect packages from dripping water and rock fall. Waste canisters will be transported to the site and into the repository primarily by railroad.

The operational period at Yucca Mountain is anticipated to last for decades, during which waste packages will be received at the site, transported underground, and emplaced. Regulations require that the wastes will be retrievable from the repository beginning at any time up to 50 years after emplacement has begun and before final closure. An ongoing performance confirmation program will ensure that further site characterization activities will be conducted in the to-be-drilled emplacement drifts and that monitoring of the drift and near-field environment will take place, with the objective of creating confidence in performance predictions. Because of the extensive engineered barrier systems for the radioactive wastes, it is very unlikely that radionuclides will be released from the repository during or soon after closure, as discussed in DOE's license application for authorization to construct a repository at Yucca Mountain. Thus, monitoring will confirm the predicted system behavior with respect to various heat-related coupled processes, but will not be able to provide insight into the barrier capability of the natural system to prevent or delay radionuclide transport.

3.1.3 Long-term Safety and Performance Criteria

The long-term safety of the repository depends on the performance of natural and engineered barriers, which together prevent or delay the transport of radionuclides to where the public could eventually be exposed. Three major barriers are relied upon at Yucca Mountain, the upper natural barrier, the engineered barrier system, and the lower natural barrier. The characteristics of these barriers, and their overall barrier capabilities, are described in detail in DOE's license application, and shall only briefly reviewed below.

The upper natural barrier, comprising the topography, surficial soils, bedrock, as well as the unsaturated zone above the repository horizon, prevents or limits water from entering the emplacement drifts. According to DOE's license application, important factors contributing to barrier capability are the small net infiltration into Yucca Mountain, on the order of a few millimeters per year, and the specific hydrogeological conditions in the volcanic tuffs above the repository that function to divert the infiltrating water, dampen episodic pulses of infiltration, and limit seepage of water into the emplacement drifts. Future changes in climate may increase net infiltration at the site and are therefore considered in the performance assessment. However, the assumed climatic changes reflect natural cycles, not the possible impacts from global warming.

The engineered barrier system has two functions: (1) it prevents or limits water contact with the radioactive waste, and (2) it limits the release of radionuclides from the waste into the lower natural barrier. The first function is achieved by corrosion-resistant drip shields and waste packages; both of which prevent seepage water from contacting the waste as long as they remain intact. Over long periods of time, corrosion (generalized corrosion or stress corrosion resulting from mechanical damage) is expected to deteriorate some drip shields and may also create local breaches in waste packages. It is important to note that the unsaturated zone at Yucca Mountain is a naturally oxidizing environment in which metals can corrode if they become wet or damp, as from high humidity or water seepage (Carter, 2006). If breaches occur, the release of radionuclides from waste packages will be limited by the slow rate of waste-form degradation, by sorption on iron corrosion products within the waste package, as well as by sorption onto the granular material on the floor of the drifts.

Radionuclides released from the emplacement drifts will enter the lower natural barrier, which comprises the unsaturated zone and the groundwater zone (saturated zone). Radionuclides will migrate downward with the flow in the unsaturated zone to the water table and will then be transported by groundwater flow towards the accessible environment. Both the unsaturated zone and the saturated zone contribute to barrier capability, delaying the migration of radionculides with slow advective flow. In addition, several processes cause the movement of radionuclides to be retarded compared to the rate of movement of the water. These processes include diffusion of radionculides from the advective fracture flow into the matrix pores, sorption onto mineral surfaces, and colloid filtration.

Radiation protection standards for a Yucca Mountain repository have been developed by the U.S. Environmental Protection Agency (EPA), initially issued in 2001. These standards address all potential pathways of radiation exposure and limit an individual's annual exposure to a maximum value of 15 mrem (0.15 millisievert). For comparison: the radiation exposure for an average person is about 350 mrem/year, most of which comes from natural sources of radiation (i.e., cosmic radiation and terrestrial sources such from soils and rocks), the remainder from exposure to artificial radiation sources, such as medical X-rays. The time period initially defined to evaluate radiation exposure was 10,000 years after closure. However, in 2001, a Federal Court ruled that a 10,000-year performance period is not sufficient. EPA has since then proposed a rule that defines performance standards for a significantly longer period, up to one million years after closure, which includes the expected time of peak dose and is within a defined period of geologic stability at Yucca Mountain. Because predictive uncertainties increase as the time period for which the predictions are made increases, the maximum annual dose for the time period after 10,000 years is 350 mrem.

The U.S. Nuclear Regulatory Commission (NRC) is the independent federal entity assigned with the responsibility of regulating the nation's civilian use of radioactive materials, which includes regulating their safe disposal in a geologic repository. As mentioned above, DOE has recently submitted the license application to the NRC. NRC is in the process of conducting a detailed review in a process that will last a minimum of 3 years. The review will include consideration of conformity to regulations based on the proposed EPA standard. Performance of the repository is measured based on the expected dose received by the so called reasonably maximally exposed individual (RMEI), a person assumed to live 18 km downstream of the Yucca Mountain site drinking 2 liters per day from one or more wells. The regulations comprise specific criteria beyond evaluating maximum radiation exposure, such as the requirement of multiple barriers acting in concert and the requirement to incorporate all significant aspects of uncertainty and variability in a probabilistic assessment of the repository's performance. As guidance to NRC review staff, specific review acceptance criteria are provided in the Yucca Mountain Review Plan (NRC, 2003).

3.2 Current Status of RWD in Canada

3.2.1 Evolving Program

Canada is one of the countries where public reactions to radioactive waste isolation plans have recently led to a change in the program approach. For decades, Atomic Energy of Canada Limited (AECL) had been developing the concept for the emplacement of nuclear fuel wastes in a geologic repository excavated in the plutonic crystalline rock of the Canadian Shield. An underground research laboratory (URL) was established in 1989 near Lac du Bonnet, Manitoba, in a large, previously undisturbed, nearly fracture-free granitic pluton, allowing for a comprehensive research program for developing characterization methods, developing *in situ* stress measurement techniques, demonstrating full-scale canister emplacement, evaluating rock stability, modeling groundwater flow and transport, and conducting grouting and tunnel-sealing experiments (Russell et al., 2001). In 1994, AECL submitted the Environmental Impact Statement on the concept of a repository excavated in the plutonic rock of the Canadian Shield to a federal Environmental Assessment Panel (EAP) for review. Public hearing associated with the review took place during 1996 and 1997. In 1998, the federal government completed its review of the concept and found it to be technically safe, and in compliance with regulatory requirements. However, the review also concluded that there was not sufficient public support at that time to implement a repository siting program (Witherspoon and Bodvarsson, 2006).

The government of Canada responded to the recommendations of the EAP and issued the Nuclear Fuel Waste Act (NFWA), which in 2002 initiated the establishment of a new agency, the Nuclear Waste Management Organization (NWMO), to study different disposal options and develop collaboratively with Canadians an approach for long-term management of used radioactive waste that is technically sound, socially acceptable, environmentally responsible, and economically feasible (Russell and Facella, 2006). Three options were then studied in a comparative evaluation of strengths and limitations, as detailed below.

3.2.2 Three Options for Long-Term Management

The first option would involve geologic disposal in an engineered repository in the stable crystalline rock of the Canadian Shield, a concept similar to the one initially developed by AECL. The underground facility would be constructed at a depth of 500 to 1,000 m (CTECH, 2002), consisting of a network of horizontal access galleries and emplacement rooms or boreholes. Used fuel would be placed into long-lived containers, such as steel-lined copper containers, and surrounded by clay-based sealing materials. Approximately 11,000 containers of used fuel would be emplaced and filled-up rooms would be backfilled with bentonite and then progressively sealed (McMurry et al., 2003). Possible designs include in-room placement, in-floor borehole placement, and horizontal borehole placement. Initial performance assessments demonstrate that the Canadian Shield has favorable geologic and hydrologic features for waste isolation.

The second option involves permanent or indefinite storage at the nuclear reactor sites. Existing interim dry storage facilities would have to be expanded or new long-term dry storage facilities would have to be established. The key disadvantage as expressed by the Canadian authorities is the need for continuing control and operation, including the necessary funding, for the thousands of years that the used radioactive waste remains hazardous (Russell and Facella, 2006). Compared to geologic repositories, surface facilities are also more readily accessible to malevolent intervention. The third option would involve storage of all wastes in a new long-term dry storage facility at one site in Canada. Designs of new central facility have been prepared for both aboveground and shallow belowground storage (in rock caverns excavated to a depth of 50 m in competent rock). Similar to the second option above, the key disadvantage is the need for long-term control and operation of such a facility.

3.2.3 A Fourth Option and Path Forward

In a period of dialogue with the public, many Canadians suggested that an additional option should be considered, an option that would attempt to capitalize on the advantages of the other three approaches. This led NWMO to develop the Adaptive Phased Management approach (APM), and to launch a dialogue with Canadians about its appropriateness. Overall, the majority of those engaged in these discussions considered APM to be a reasonable approach for Canada, and the final report that was submitted by NWMO to the government in November 2005 recommended this path forward (Russell and Facella, 2006). The key attributes of the approach are:

- Centralized containment and isolation of waste in a geologic repository within a suitable rock formation, either in the Canadian Shield or in deep sediments such as the Ordovician Shale
- Flexibility in the pace and manner of implementation through a phased decision-making process, supported by a R&D program
- Provision of an optional step in the implementation process in the form of shallow underground storage at a central site, prior to final placement in a geologic repository
- Continuous monitoring of the spent fuel to support confirmation of the safety and performance of the storage facility or repository
- Potential for retrievability of the waste for an extended time period, until a future society makes a determination on the final closure and the appropriate form and duration of postclosure monitoring

The staged approach in Canada would start with an approximately 30-year phase that focuses on (1) technology development for fuel management, and (2) selection of a site that has rock formations suitable for shallow underground storage, an underground characterization facility, and a geologic repository at greater depth. The second phase, which would take an additional 30 years, would concentrate on central storage implementation. Only the third and last phase, which would start after the two 30-year phases, would involve on implementation of long-term containment in a geologic repository (Russell and Facella, 2006).

3.3 Opportunities for RWD

Both the United States and Canada have established paths forward to providing permanent and reliable methods of isolating radioactive waste in a geologic repository. The legal and regulatory framework for RWD has been defined, state-owned organizations have been commissioned that develop and pursue disposal plans, and regulating authorities have been identified. Canada pursues a staged implementation approach that may include temporary disposal in shallow underground storage prior to long-term containment and isolation in a geologic repository. While no specific site has been selected, Canada has various options with several areas hosting rock formations deemed suitable for RWD, such as the crystalline rock of the Canadian Shield .

In the United States, the Yucca Mountain site in Nevada has been designated for high-level RWD, and the license application for this site was submitted in 2008. While there is some controversy among scientists about the scientific basis for the license application and related uncertainties (e.g., Long and Ewing, 2004; Macfarlane and Ewing, 2006), DOE maintains that the plan for disposing of radioactive waste at Yucca Mountain is technically sound and that the repository safely meets the proposed performance standards set by the EPA. If the regulators share the DOE’s assessment of safe disposal at Yucca Mountain during the three- to four-year review process and finally grant construction authorization, high-level radioactive waste could be emplaced at the site within the next 10 to 20 years.

A solution to the radioactive waste problem becomes particularly important in light of the worldwide renaissance of nuclear power. In the U.S., the further expansion of nuclear power is seen as a promising avenue to meet the substantial demand growth for energy, while addressing national energy security (Lake, 2006) and greenhouse gas emission concerns. This change in attitude towards nuclear power, also evident in many countries worldwide, is fueled by the rising costs of fossil fuels and the increased attention to the environmental threats associated with burning fossil fuels.

While economic challenges are a primary barrier for industrial-scale GCS, the implementation of a national RWD facility is typically not governed by market forces and thus dependent instead on political will and/or a legal framework to guarantee sufficient federal funding. In the U.S., for example, the Nuclear Waste Policy Act requires utilities which generate electricity using nuclear power to pay a fee of one tenth of one cent ($0.001) per kilowatt-hour into the so-called Nuclear Waste Fund. As of December 31, 2008, payments and interest credited to the fund totalled $29.6 billion, out of which approximately $9.5 billion have been spent so far by the RWD program in the U.S. In other words, RWD programs are typically more affected by political/social challenges than by economics. While the radioactive waste disposal program in the U.S. has received substantial financial support over the past decades, it has also experienced significant funding fluctuations, depending on the annual budget negotiations between the president and the U.S. Congress.

While capacity constraints and sink/source matching are important issues for GCS, the amounts of radioactive waste expected to accumulate over the foreseeable future are typically small enough to allow for storage in one national underground storage facility. In other words, once a suitable rock formation has been identified and characterized, a large enough system of tunnels and galleries can usually be built to accommodate the expected waste volumes. In the U.S., the situation is a bit different, as the capacity of Yucca Mountain is currently limited—by law—to 70,000 metric tons of high-level radioactive waste. While this is more than the current waste volume in the U.S. (mostly spent fuel from power plants, but also defense wastes), this capacity may not accommodate the future quantities to be produced from the currently 103 U.S. commercial reactors (Peterson, 2003). The U.S. is engaged in advanced fuel cycle initiatives, with the goal of substantially accelerating efforts to develop new reactor and reprocessing technology. The goals of the program are (1) to guarantee that nuclear materials from the fuel cycle are protected from proliferation and misuse for non-peaceful purposes, (2) to recover the substantial energy value in used nuclear fuel to make sure that sufficient fuel remains available for centuries in the face of depleting fossil fuels, and (3) to significantly reduce the burden related to the geologic disposal of nuclear fuel in terms of waste volume, heat load, and radiotoxicity, thereby avoiding capacity problems.

3.4 Challenges for RWD

Public acceptance is arguably the most serious challenge to RWD. High-level radioactive waste is known to be extremely dangerous, and some members of the public are very skeptical about the usefulness and reliability of long-term performance predictions. Some are also concerned about the irretrievability of the radioactive waste once it is emplaced and the repository has been closed off. If radionuclides were to escape because of unexpected early failure, so goes the argument, there is no simple way of mitigating the consequences. While in many countries the reaction of the public to the development of radioactive waste isolation has resulted in site selection delays, reevaluations of disposal approaches, and the development of new ways of engaging voluntarily local communities (Witherspoon and Bodvarsson, 2006), the radioactive waste disposal program in the U.S. and the site selection of Yucca Mountain has over the years been relatively unaffected by public acceptance problems, at least on a national level. The State of Nevada, however, has been strongly opposed to the Yucca Mountain repository, and will likely continue to challenge the project raising technical issues or using legal and political roadblocks. Indeed, recent developments demonstrate that political challenges can impact nuclear waste programs even as far advanced in the process as those in the United States. The incoming Obama administration had been questioning the suitability of Yucca Mountain and declared in early 2009 that a blue-ribbon commission would be installed to devise a new strategy toward radioactive waste handling and disposal. It may be expected that such a new strategy will include (1) developing alternatives to Yucca Mountain as the nation's permanent repository and (2) starting aggressive R&D programs for reprocessing of spent fuel. All the above would require legislative action to revise the Nuclear Waste Policy Act.

In Canada, the radioactive waste disposal program changed its organization and repository approach completely in response to the insufficient public support for implementing a siting program, despite the fact that the geologic storage concept was found to be technically safe. In both countries, further acceptance problems may be expected from the public perception of risks related to transporting radioactive wastes (e.g., by rail) from various interim storage locations to a permanent central repository site.

A technical challenge most difficult to address is the necessity to consider the evolution of a very complex geologic environment over extremely long time scales ranging anywhere from 10^4 to 10^6 years. As discussed in length in Macfarlane and Ewing (2006) for the Yucca Mountain site, there are many factors that make it difficult to predict repository behavior over geologic times, including climate, fractured rock flow and transport, saturated and unsaturated zone behavior, volcanism, seismicity, thermal processes, and geochemical interactions, all of which contribute to significant uncertainty in natural and engineered barriers. The question of the time scale over which a quantitative performance assessment should be undertaken has been widely debated in the radioactive waste community (Maul et al., 2007), and regulations differ from country to country. Prediction uncertainty increases with time, and thus less reliance should be placed on calculation far into the future. As mentioned earlier, the question about the appropriate performance period for Yucca Mountain was settled eventually by a court decision, ruling for a performance period of up to one million years. This decision is in line with a recent review by NEA (2004) emphasizing the need for such long time scales because (1) good sites with well-performing barriers imply release of contaminants only very far into the future and (2) ethical considerations would expect the same level of environmental protection in the far future as in the short term. The same review points out that even the most stable materials and geologic environments, over long enough time scales, are subject to perturbing events and long-term changes, which makes quantitative predictions more and more uncertain. Several suggestions are made how a performance assessment should take into account the changes and uncertainties associated with long time scales (NEA, 2004).

4 Comparison of GCS to RWD in North America

4.1 General Characteristics

We present in Table 1 a comparison of GCS and RWD processes with emphasis on their general characteristics in North America. Although some of the same fundamental physical and chemical processes apply to both GCS and RWD, and methods of characterizing the subsurface and predicting these fundamental processes with simulation models are often similar (e.g., DOE, 2007), GCS and RWD have little in common with respect to their general characteristics in North America as shown in the table. For a comparative analysis of the physical differences between GCS and RWD see Bachu and McEwen (this volume). Of the many profound differences between GCS and RWD, one difference that stands out is that the amounts of materials (high-level radioactive waste in one case, CO_2 in the other) are orders of magnitude different. The total mass of high-level radioactive waste in the U.S. today intended for disposal at Yucca Mountain is restricted by law to 70,000 tonnes. In contrast, the annual production of CO_2 from a single 1000 MW coal-fired power plant is approximately 9 million tonnes (9 Mt), and the total North American power-generation production of CO_2 is over 3 billion tonnes (3 Gt) per year (NATCARB, 2006). The much larger mass of CO_2 produced (over 40,000 times more CO_2 than radioactive waste) presents a great challenge compared to radioactive waste.

Another significant difference between GCS and RWD is the time scale required for containment. Regulations in the U.S. for radioactive waste originally required performance demonstration for at least 10,000 years, but that was extended up to one million years to make them consistent with recommendations by the National Academy of Sciences (National Research Council, 1995). Clearly, the possibility of major yet infrequent disruptive events (such as volcanism, earthquakes) and the effects of long-term changes in the hydrology or geologic environment need to be accounted for over such time scales. For CO_2 storage, the necessary time period of containment can be related to the purpose of reducing atmospheric emissions, namely the mitigation of climate-change effects. Time scales of a few centuries to a few thousand years are likely sufficient for sequestered CO_2 to remain out of the atmosphere globally to address climate change over the next few hundred years while fossil-fuel resources remain abundant, although to date, no time scale has been established by regulation for CO_2 retention in GCS systems in North America. Differences between GCS and RWD can also be seen in the existence of an acceptable global leakage rate for CO_2 calculated at between 0.01-0.1% per year of sequestered CO_2 (Hepple and Benson, 2005). For RWD, an acceptable rate of radionuclide migration is not defined a priori; it is typically constrained indirectly by regulatory requirements limiting radiation exposure to individuals. Although long by human standards, the time scale for isolation for GCS is short relative to geologic time and permits a large degree of confidence in GCS site performance prediction.

Radioactive waste disposal and GCS differ with respect to the time period when failure of containment is most likely to occur. Radionuclide releases from the waste canisters into the subsurface environment are most likely only very long after repository closure, when the engineered barriers may have (partially) degraded, and performance may then depend mostly on the barrier capabilities of the natural system. In contrast, escape of CO_2 from deep storage is most likely in early operational project stages, when injection-induced pressures are high, thus providing an additional leakage driving force, while trapping mechanisms such as solubility trapping or mineral trapping have not yet fully developed.

Careful site characterization is required in the evaluation of the expected performance of both RWD and GCS sites (Maul et al., 2007). Both GCS and RWD require understanding of the basic geologic system and system behavior on a large scale (i.e., kilometer scale), and use similar characterization methods to achieve such understanding (e.g., borehole data, geophysics). However, the level of effort expected to characterize a radioactive waste repository is arguably not necessary in CO_2 storage projects for which the time scale of containment is shorter and limited leakage is tolerable. The level of effort needed for a RWD site would also not be economically feasible for GCS given the large number of sites required to accommodate the enormous volumes of CO_2 that need to be sequestered to mitigate climate change. RWD requires a detailed understanding of the near field (i.e., the immediate surrounding of the repository tunnels) and how its properties may change with tunnel excavation and waste emplacement. Such understanding has been achieved in the U.S. by constructing the Exploratory Studies Facility (ESF), an underground research laboratory for characterization and *in situ* testing in the geologic units of interest at Yucca Mountain, Nevada. For GCS sites, the existence of mitigation options, the relatively benign nature of CO_2, and the ability to monitor injection operations provide the opportunity to continue to characterize a GCS site and monitor its performance throughout the process of injection (e.g., Doughty et al., 2008).

While GCS and RWD share little in common, the contrast in two aspects, namely (1) the relatively small amount of radioactive waste compared to the large amount of CO_2 that needs to be isolated, and (2) the health hazard (radioactive waste is highly toxic, CO_2 is relatively benign) stand out as the most significant differences between the processes from the perspectives of health, safety, and environmental risk, as well as economic and practical feasibility. These two aspects, volume and consequences of storage failure, are at the root of the challenges facing North America as discussed in the following sections.

4.2 Shared Challenges and Opportunities

Both GCS and RWD are widely believed to be technically feasible in North America. A summary of the main points of comparison between GCS and RWD is presented in Table 3 and elaborated upon here. GCS and RWD require available lands and suitable subsurface geologic characteristics to contain CO_2 and radioactive waste, respectively, for long periods of time. The large area and varied subsurface geology and physical geography of North America, including areas of sparse population, provide excellent potential opportunities for both GCS and RWD over the next 100 years or more. Both GCS and RWD will require transportation infrastructure. In the case of RWD, rail and road transport infrastructure that could be used for transport exists in many parts of North America, but its use for the purpose of conveying radioactive waste is expected to be challenged by some in the communities through which it passes. This could be a challenge in the U.S. because the proposed repository is located in the western U.S. (Nevada) while the bulk of nuclear spent fuel is produced in the eastern part of the country. For GCS, additional pipeline infrastructure for transporting CO_2 from point sources throughout the country to GCS sites needs to be built. GCS has the challenge of very large volumes of CO_2 required to be injected to be effective against climate change.

As for legal, policy, and economic considerations, GCS and RWD differ considerably. First, implementation of GCS currently faces legal complications because the U.S. lacks laws regarding ownership of pore space and its contents. No such ambiguity exists with radioactive waste for which government ownership and control are a given. By current law, RWD has the challenge of long time scales for isolation (10^4 to 10^6 years), making predictions of geologic and hydrologic stability and isolation of waste difficult. Even the somewhat shorter sequestration time scales relevant to GCS create complications for assigning long-term liability, and suggest the need for eventual government ownership and control, the policy and funding for which has yet to be established. On the economic side, GCS is widely viewed as a business opportunity once a carbon trading market is developed or a carbon tax is imposed. The oil industry in particular is positioned well for this opportunity with its experience, resources, and capital to transport, inject, and monitor fluids in the subsurface. RWD is by and large a government-run and operated enterprise from which no significant new industries are expected to arise.

RWD and GCS share the technical challenge of characterizing and interpreting geologic systems using relatively sparse data, making long-term predictions about flow and transport processes in the underground over long time periods, and providing quantitative analysis of the future performance of a site in a regulatory and legal environment. Emplacement of hot radioactive waste as well as injection of large volumes CO_2 will both perturb the natural systems and induce complex hydrologic, mechanical, geochemical, and thermal processes, the similarities and differences of which are laid out in Bachu and McEwen (this volume). These technical issues make it inevitable that performance predictions have uncertainties, some of which may be critically important for evaluating whether a site can be suitable, others may be of little consequence. Of the many possible RWD sites worldwide, the Yucca Mountain in Nevada may possibly involve some of the most daunting technical challenges, because of its unique setting in an unsaturated fractured tuff and the strong heat-induced flow perturbations expected from emplacement of waste. Such technical challenges, while they may have been met by sound science or may not even be relevant for performance, can make a safety case for a site very complex and hard to convey to regulators and the public. A lesson learned from RWD for GCS may thus be to choose sites where performance can be demonstrated without having to rely on features and processes that are very difficult to quantify. As an example: a GCS site with a proven seal for trapping of CO_2 or other gases would likely be viewed very favorably.

Public perception is both a challenge and an opportunity for GCS and RWD. The challenge comes from the public's legitimate concerns about safety and environmental impacts of both technologies. The status of RWD in North America may offer a valuable lesson for the less mature GCS development, in that the screening and selection of any geologic repository site needs to be conducted in an environment of open communication with all stakeholders, focusing on sound technical standards and ideally by comparing possible alternatives. The early phase of the RWD program in the U.S. is a negative example for such a process, where the 1987 congressional decision to stop the ongoing screening of several alternative sites in favor of the Yucca Mountain site was viewed by many as political and arbitrary (Carter et al., 2006). The opportunity comes from the sea-change in perception that we anticipate will accompany the growing concern about greenhouse gas impacts on climate. Once the public and elected officials understand the magnitude of climate-related impacts predicted to occur due to burning fossil fuels as currently carried out, i.e., with emission of CO_2 directly into the atmosphere, there may be a large shift in thinking about benefits and risks associated with transportation and storage of radioactive waste and CO_2 underground.

5 Conclusions about GCS and RWD in North America

GCS and RWD in North America share little in common. Vast differences exist in the volumes of material that need to be stored, the means of transportation and emplacement, the geologic environments suitable for the two processes, the depths of emplacement, and the consequences of leakage, among others. These differences mean the legal and regulatory frameworks in place for RWD are not entirely appropriate for GCS. The general need to predict future performance of geologic systems is one commonality, and already there is cross-over as researchers in the U.S. formerly focused on RWD are applying their expertise in site characterization and performance assessment to GCS. The main technical challenge for GCS is to learn how large-scale CO_2 injection involving many wells will perturb and impact the hydrologic, geochemical, and geomechanical systems that provide secure storage while avoiding significant impacts (e.g., on groundwater quality) arising from CO_2 or brine migration. Given the urgent energy-climate challenge, the best way to achieve this understanding is to begin GCS as soon as possible and to "learn while doing" as early projects are implemented with strong and thorough monitoring and verification programs. As for RWD, the license application submitted in 2008 makes the case for the technical feasibility of Yucca Mountain for safely storing radioactive waste. This represents one important step in the potential expansion of nuclear power as a way to achieve net reductions in greenhouse gas emissions from electricity production. As for public perception, we see an opportunity to engage the public on both GCS and RWD as the public becomes better informed about the urgent need to reduce anthropogenic greenhouse gas emissions to minimize climate change.

Because of the severe potential consequences of anthropogenic climate change to global environments and economies, the increased use of nuclear fission and deployment of CCS for fossil-fuel-derived power are promising options for North America. Both approaches present challenges but also opportunities. To the extent that some of these challenges may not be overcome, or that unforeseen events or circumstances may impair one or the other technology, we suggest that policies be put in place to pursue both approaches, with processes in place to ensure health, safety, and minimal environmental impacts, to help reduce North American CO_2 emissions as soon as possible.

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7 References

Arthur, W.J. and M.D. Voegele, Preparing to submit a license application for Yucca Mountain in the United States, Geological Challenges in Radioactive Waste Isolation: Fourth Worldwide Review, edited by P.A. Witherspoon and G.S. Bodvarsson, Lawrence Berkeley National Laboratory Technical Report, LBNL-59808, 2006.

Bachu, S., Legal and regulatory challenges in the implementation of CO_2 geological storage: An Alberta and Canadian perspective, Int. J. Greenhouse Gas Control, 2, 259-273, 2008.

Bachu, S. and W.D. Gunter, Acid-gas injection in the Alberta basin, Canada: a CO_2-storage experience, Geological Society, London, Special Publication 233: 225-234, 2004.

Bachu and McEwen, this volume.

Benson, S.M., R. Hepple, J. Apps, C.-F. Tsang, and M. Lippmann, Lessons learned from natural and industrial analogues for storage of carbon dioxide in deep geological formations, E.O. Lawrence Berkeley National Laboratory Report LBNL-51170, 2002.

Birkholzer, J.T., Zhou, Q., Tsang, C.F., Large-scale impact of CO2 storage in deep saline aquifers: a sensitivity study on the pressure response in stratified systems. International Journal of Greenhouse Gas Control 3(2), 181–194, 2009.

Bodvarsson, G.S., W. Boyle, R. Patterson, and D. Williams, Overview of Scientific Investigations at Yucca Mountain—the Potential Repository for High-Level Nuclear Waste, Journal of Contaminant Hydrology, 38 (1–3): 3–24, 1999.

Bondor, P.L., Applications of carbon dioxide in enhanced oil recovery, Energy Conversion and Management, 33(5-8), 579-586, 1992.

Bradshaw, J., S. Bachu, D. Bonijoly, R. Burruss, S. Holloway, N.P. Christensen, and O.M. Mathiassen, CO_2 storage capacity estimation: Issues and development of standards, Int. J. of Greenhouse Gas Control, 1, 62-68, 2007.

Carter, L.J., The path to Yucca Mountain and beyond, in Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste, Macfarlane, A., and R.C. Ewing (editors), Cambridge, USA, MIT Press, 2006.

CTECH. Conceptual Design for a Deep Geologic Repository for Used Nuclear Fuel. CTECH Report 1106/MD18085/REP/01, 2002.

DOE (U.S. Department of Energy, Basic Energy Sciences), Basic Research Needs in Geosciences: Facilitating 21st Century Energy Processes, 2007. (http://www.sc.doe.gov/bes/reports/abstracts.html#GEO)

Doughty, C.A., B.M. Freifeld, R.C. Trautz, Site characterization for CO_2 geologic storage and vice versa: the Frio brine pilot, Texas, USA as a case study, Environmental Geology, 54(8), 1635-1656, 2008.

Energy Information Agency (EIA), International Energy Outlook 2007, http://www.eia.doe.gov/oiaf/ieo/index.html (accessed 20 June 2008).

Friedmann, S.J., J.J. Dooley, H. Held, O. Edenhofer, The low cost of geological assessment for underground CO_2 storage: Policy and economic implications, Energy Conversion and Management, 47, 1894-1901, 2006.

Gasda, S.E., S. Bachu, and M.A. Celia, Spatial characterization of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin, Environ. Geology, 46, 707-720, 2004.

Hepple, R.P., Benson, S.M., Geologic storage of carbon dioxide as a climate change mitigation strategy: performance requirements and the implications of surface seepage, Environ. Geol., 47(4), 576—585, 2005.

Hovorka, S.D., S.M. Benson, C. Doughty, B.M. Freifeld, S. Sakurai, T.M. Daley, Y.K. Kharaka, M.H. Holtz, R.C. Trautz, H.S. Nance, L.R. Myer, and K.G. Knauss, Measuring permanence of CO_2 storage in saline formations: the Frio experiment, Environmental Geosciences, 13(2), 105-121, 2006.

IAEA (International Atomic Energy Agency), Non-Proliferation of Nuclear Weapons & Nuclear Security, https://www.iaea.org/Publications/Booklets/nuke.pdf, May 2005

Intergovernmental Program on Climate Change (IPCC) Special Report on carbon dioxide capture and storage, ISBN 92-969-119-4, http://www.ipcc.ch/activity/srccs/index.htm, 2005.

IOGCC (Interstate Oil and Gas Compact Commission), Storage of carbon dioxide in geologic structures, a lega and regulator guide for states and provinces, Sept. 25, 2007 (http://iogcc.myshopify.com/collections/frontpage/products/co2-storage-a-legal-and-regulatory-guide-for-states-2008)

Kovscek, A.R., and M.D. Cakici, Geologic storage of carbon dioxide and enhance oil recovery II. Co-optimization of storage and recovery, Energy Conversion and Management, 46, 1941-1956, 2005.

Lake, J.A., The Renaissance of Nuclear Power, eJournalUSA, International Information Programs, http://usinfo.state.gov/journals/ites/0706/ijee/lake.htm, July 2006.

Litynski, J.T., S.M. Klara, H.G. McIlvried, and R.D. Srivastava, The United States Department of Energy's Regional Carbon Sequestration Partnerships program: A collaborative approach to carbon management, Environment International, 32(1), 128-144, 2006.

Long, C.S., and R.C. Ewing, Yucca Mountain: Earth-Science Issues at a Geologic Repository for High-Level Nuclear Waste, Annual Review of Earth and Planetary Science, 32, 363-4-1, 2004.

Maul, P.R., R. Metcalfe, J. Pearce, D. Savage, J.M. West, Performance Assessments for the Geological Storage of Carbon Dioxide: Learning from the Radioactive Waste Experience. International Journal of Greenhouse Gas Control, Volume I, pp. 444-455, 2007.

Macfarlane, A., Uncertainty, models, and the way forward in nuclear waste disposal, in Uncertainty Underground: Yucca Mountain and the Nation’s High-Level Nuclear Waste, Macfarlane, A., and R.C. Ewing (editors), Cambridge, USA, MIT Press, 2006.

Macfarlane, A., and R.C. Ewing (editors), Uncertainty Underground: Yucca Mountain and the Nation’s High-Level Nuclear Waste, Cambridge, USA, MIT Press, 2006.

McMurry, J, D. Dixon, J. Garroni, B. Ikeda, S. Stroes-Gascoyne, P. Baumgartner and T. Melnyk, Evolution of a Canadian Deep Geologic Repository: Base Scenario. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10127-R00, Toronto, Canada, 2003.

Moritis, G., Special report: More US EOR projects start but EOR production continues decline, Oil&Gas Journal, 106(15), April 21, 2008.

NATCARB, U.S. Department of Energy, Carbon Sequestration Atlas of the United States and Canada, Office of Fossil Energy, National Energy Technology Laboratory, 2006.

National Research Council, Technical Basis for Yucca Mountain Standards, Washington, D.C., National Academy Press, 1995.

NEA (Nuclear Energy Agency), The Handling of Timescale in Assessing Postclosure Safety of Deep Geological Repositories, Nuclear Energy Agency, Organization for Economic Cooperation and Development, NEA Report No. 4435, 2004.

Nicot, J.P., Evaluation of large-scale carbon storage on fresh-water section of aquifers: A Texas study. International Journal of Greenhouse Gas Control 2(4), 582–593, 2008.

Nordbotten, J.M., M.A. Celia and S. Bachu, Analytical solutions for leakage rates through abandoned wells, Water Resources Research, 40, 4204-4213, 2004.

NRC (Nuclear Regulatory Commission), Yucca Mountain Review Plan, In: U.S. Nuclear Regulatory Commission, Report NUREG-1804, Revision 2, 2003.

Oldenburg, C. M., Migration mechanisms and potential impacts of CO_2 leakage and seepage, in Wilson and Gerard, editors, Carbon Capture and Sequestration Integrating Technology, Monitoring, and Regulation, pp 127-146, Blackwell Publishing 2007.

Pacala, S. and R. Socolow, Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, Science 305(5686), 968-972, 13 August 2004.

Peterson, P.F., Will the United States Need a Second Repository?. The Bridge. National Academy of Engineering Publications, Volume 33(3), Fall 2003.

Raupach, M.R., G. Marland, P. Ciais, P., C. Le Quéré, J.G. Canadell, G. Klepper and C.B. Field, Global and regional drivers of accelerating CO_2 emissions, Proceedings of the National Academy of Sciences, 104(24), 10288-10293, 2007.

Reiner and Nuttal, this volume.

Russell, S. and Facella, J., Progress towards Long-Term Management of Used Nuclear Fuel in Canada. In: Geological Challenges in Radioactive Waste Isolation: Third Worldwide Review, edited by P.A. Witherspoon and G.S. Bodvarsson, Lawrence Berkeley National Laboratory Technical Report, LBNL-59808, 2006.

Russell, S., P.J. Gierszewski, M.R. Jensen, and T.F. Kempe, Long-term management of nuclear waste Fuel in Canada: Technical developments in the concept for a deep geologic repository. In: Geological Challenges in Radioactive Waste Isolation: Fourth Worldwide Review, edited by P.A. Witherspoon and G.S. Bodvarsson, Lawrence Berkeley National Laboratory Technical Report, LBNL-49767, 2001.

USEPA (United States Environmental Protection Agency), Technical Program Overview, Underground injection control regulations, Office of Water 4606, EPA 816-R-02-025, Revised July 2001. http://www.epa.gov/safewater/uic/index.html

White, D.J., G. Burrowes, T. Davis, Z. Hajnal, K. Hirsche, I. Hutcheon, E. Majer, B. Rostron and S. Whittaker, Greenhouse gas sequestration in abandoned oil reservoirs: The International Energy Agency Weyburn pilot project, GSA Today, 14(7), 4-10, 2004.

Wilson, E.J., T.L. Johnson and D.W. Keith, Regulating the ultimate sink: Managing the risks of geologic CO_2 storage, Env. Sci. Tech., 37, 3476-3483, 2003.

Wilson, E.J., S.J. Friedman and M.F. Pollak, Research for deployment: Incorporating risk, regulation, and liability for carbon capture and sequestration, Environ. Sci. Technol., 41, 5945-5952, 2007.

Wilson and Bergan, this volume.

Witherspoon, P.A. and G.S. Bodvarsson, Introduction to Geological Challenges in Radioactive Waste Isolation: Fourth Worldwide Review. In: Geological Challenges in Radioactive Waste Isolation: Fourth Worldwide Review, edited by P.A. Witherspoon and G.S. Bodvarsson, Lawrence Berkeley National Laboratory Technical Report, LBNL-59808, 2006.

8 Tables

Table 1. Comparison between GCS and RWD in North America.[1]

Characteristic	GCS	RWD
Target geologic formations	Sedimentary basins with brine formations, sometimes also containing depleted hydrocarbon reservoirs known to have trapped oil and gas over geologic time	Unsaturated volcanic tuffs (U.S.), crystalline rock or clay (Canada)
Volume/mass	Very large volume/mass from power generation. Large coal-fired power plants will require multiple injection wells	Volumes of high-level waste small enough that storage in one national underground facility is generally possible
Transportation	Pipeline as liquid CO_2, injection through wells	Waste in containers likely to be transported by railroad
Form	Liquid or supercritical CO_2 at injection; supercritical in storage formation	Solid waste typically encapsulated in corrosion-resistant containers. Only container failure allows for waste form dissolution and radionuclide migration
Trapping or storage mechanism	Stratigraphic, residual phase, dissolution, mineral trapping	Multiple barrier concept, with engineered (waste form, container, bentonite) and natural barriers (low-permeability rock)
Time scale for isolation	Hundreds to thousands of years	Up to one million years
Possible migration mechanisms	Buoyant upward flow of CO_2; displacement of brine; seepage out of the ground	Radionuclide transport in groundwater; dispersal by future volcanic eruption
Retrievability	Injection and observation wells can be used as production wells to bring CO_2 and other fluids out of the formation if desired.	U.S. and Canada require that waste can be retrieved during the first decades to centuries after emplacement.

[1]See Bachu and McEwen (this volume) for comparison of GCS and RWD in general.

Table 2. Capacity estimates for North America as compiled by NATCARB.

GCS sink	Gt CO_2	
	Low	High
Oil and gas reservoirs	82	--
Unmineable coal seams	156	183
Saline formations	920	3400

Table 3. Comparison of challenges/opportunities for GCS and RWD in North America.

Challenge/Opportunity	GCS	RWD
Availability of sites to contain required volume	Good opportunities for the next 100 years or more	Volume is sufficiently small that capacity is not an issue
Transportation from source to site	Pipeline infrastructure needs to be built	Transport by rail and road is technically feasible but will be subject to protest and security concerns in practice
Public perception	Large opportunity to educate the public on GCS benefits and risks	Negative but potentially evolving as impacts of climate change become more well known
Suburbanization/land use changes	Large volumes of CO_2 that need to be injected may end up underneath the lands owned by neighbors	Not an issue for much smaller-volume and government-controlled RWD sites
Legal and liability issues	Uncertain and evolving	Well established that government will take long-term responsibility
Evolving drinking water standards	The classification of potable water may change to disallow injections into what are considered today non-potable water resources	Not an issue as the nation's water resources are not affected by the possible contamination of groundwater near one repository

9 Figures

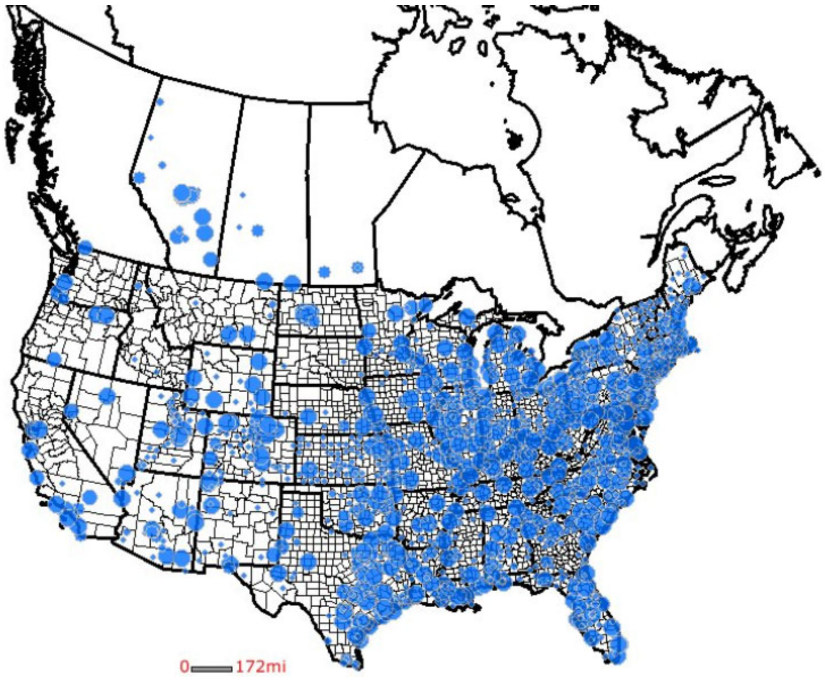

Figure 1. North American CO_2 sources from electricity generation.
(source: NATCARB: http://drysdale.kgs.ku.edu/natcarb/eps/natcarb_alpha_content.cfm)

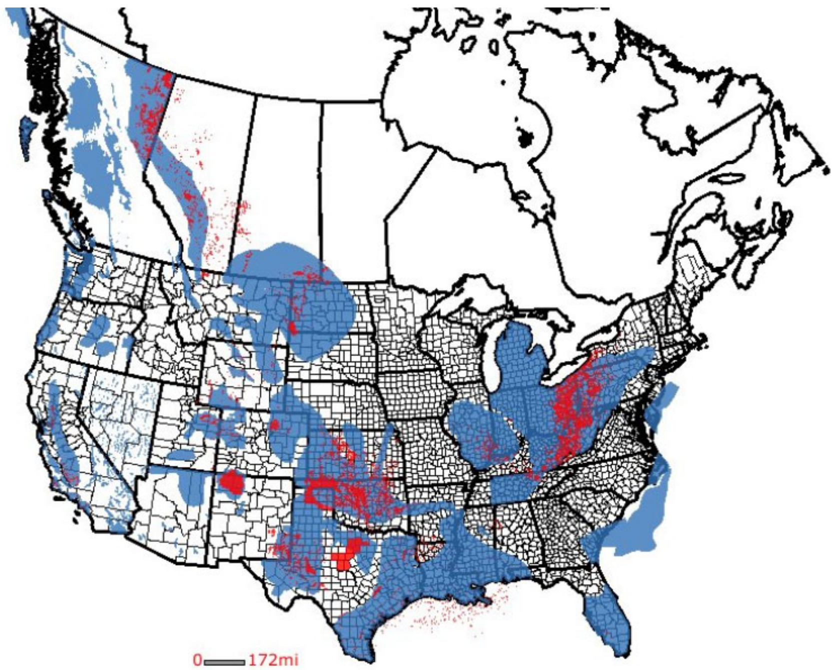

Figure 2. North American deep saline reservoirs (blue) and oil and gas reservoirs (red) potentially available for GCS.
(source: NATCARB: http://drysdale.kgs.ku.edu/natcarb/eps/natcarb_alpha_content.cfm)

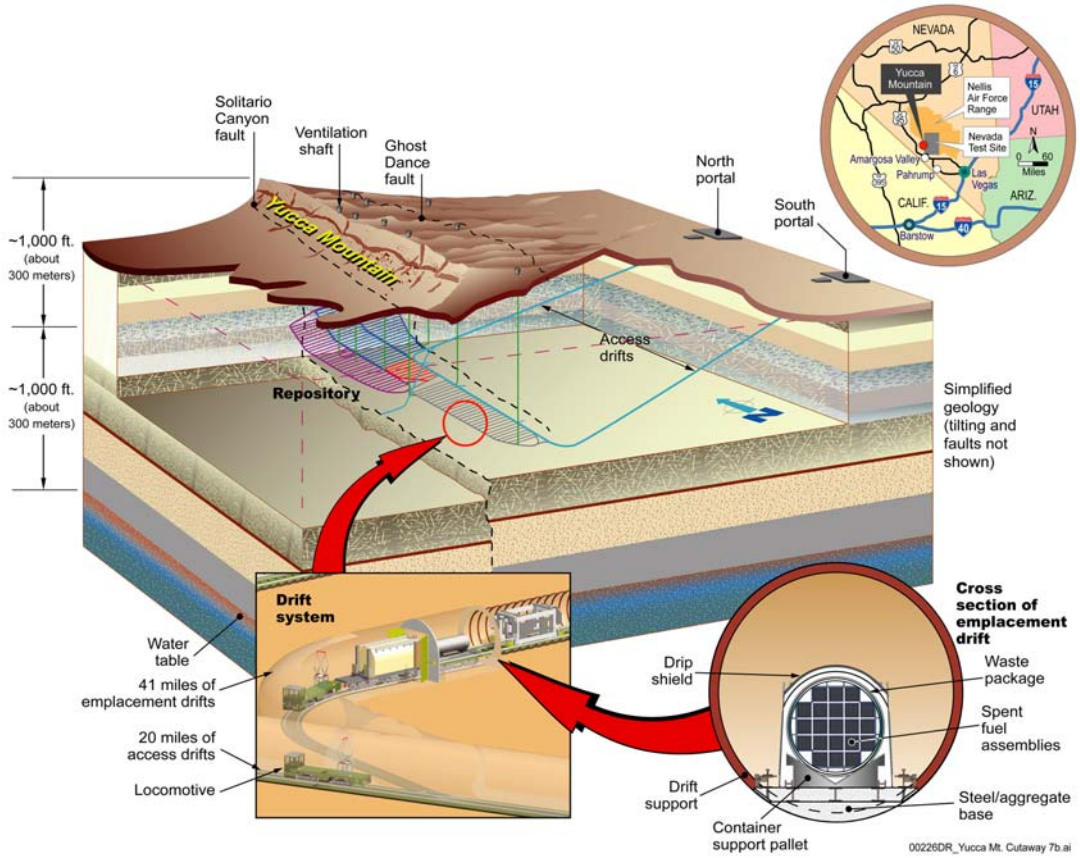

Figure 3: Location of Yucca Mountain and underground development design (source: Arthur and Voegele, 2006).