Monitoring Methods Used to Identify the Migration of Carbon Dioxide and Radionuclides in the Geosphere

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Abstract The disposal of industrial wastes in the subsurface has been ongoing for some time. Effective monitoring methods are necessary to verify both the safety of the disposed materials and the reliability of the methods used under present and future conditions. Utilizing reliable monitoring and verification methods is critical to understanding what is happening to both carbon dioxide and radioactive waste sequestered in the subsurface. Information gained while monitoring is useful to help determine what remedial action can be taken in the event of premature or unexpected escape of such geologically sequestered materials. This chapter looks at some of the general technologies used for monitoring the behaviour of these wastes in the subsurface and provides a general comparison of the methods used. An example is provided of how one method being used to monitor the behaviour of carbon dioxide in the subsurface could be adapted to monitor radioactive waste.

Keywords Radioactive waste • Carbon dioxide • Monitoring • Drilled radioactive waste repository

1 Introduction

Within the earth, locations exist that are suitable for the disposal of industrial wastes. The ultimate safety of any geological repository is dependent upon the mobility of the fluids surrounding the rocks. If these fluids are contaminated by the

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waste, but are relatively immobile, the escaped material will be contained. If, however, the contaminated fluids are mobile, both the surrounding geosphere and, potentially, the biosphere are at risk of contamination. The suitable geological character of the containing system is therefore critical to safely dispose of carbon dioxide (CO_2) or radioactive waste (RW) underground.

The injection of anthropogenic CO_2, captured from large, single-point industrial emitters into deep saline aquifers or depleted hydrocarbon reservoirs is one method of significantly reducing greenhouse gas emissions. When CO_2 is injected into an aquifer, it tends to rise and migrate updip due to its buoyancy. The geological and hydrogeological characteristics of a host aquifer control this migration of CO_2 while it is still buoyant, and provide the conditions necessary for its ultimate neutralization in the aquifer.

RW contains fission products, which become harmless to humans and to the environment only through their natural decay over time. Since some isotopes take hundreds of thousands of years to decay, disposal solutions must be safe and secure for very long periods of time. Although competent engineered barriers will mitigate the escape of radionuclides, the migration of contaminating material into the geosphere surrounding the repository site can be effectively mitigated only by natural barriers intrinsic to the geosphere. Disposal methods currently being considered by regulators in many countries rely heavily upon the competence of highly engineered barriers placed within a supportive geological framework. It may be desirable to use disposal methods that provide for both secure containment and for material retrievability in the event that future societies wish to retrieve the material for currently unforeseen reasons.

Monitoring and verification methodologies proposed for both CO_2 and RW disposal are designed to identify contamination of the geosphere surrounding the disposal site so that mitigating action could be taken, but if leakage into the distant geosphere occurs, remediation may be very challenging. Eventual contamination of the distant geosphere should be expected.

The nuclear energy and fossil fuel energy industries are greatly influenced by their respective experience-based knowledge and conventions. Proposed RW disposal methods are, therefore, supported by known mining methodologies and CO_2 disposal methods have been influenced by oilfield drilling experience. Although the methodologies are different, both are subject to the application of fundamental engineering and geological principles.

This chapter provides a preliminary comparison of the application of geological disposal and monitoring methods used for CO_2 and RW. Although material management is accomplished by different 'industries', there are useful analogues to share.

This chapter also presents a conceptual model for developing RW disposal repositories beneath sedimentary basins. Disposing of waste under the proposed conditions will provide: (1) an effective and reliable monitoring platform that will be available indefinitely, and (2) greater utilization of natural barriers that may provide isolation and containment for geological periods of time.

2 Geological Disposal of CO_2

In geological basins where the conditions are favourable, the distribution and character of the sedimentary rocks have provided environments in which CO_2 has naturally accumulated, and the genesis, migration and accumulation of hydrocarbons have occurred.

Our current understanding of the movement and accumulation of buoyant fluids in aquifers is largely based upon principles developed for hydrocarbon exploration. The trapping of hydrocarbons demonstrates the long-term effectiveness of overlying rocks as seals that have prevented further migration. The entrapment conditions will also apply to anthropogenic CO_2 injected into appropriate regions of the subsurface. Sophisticated reservoir modelling and simulation applications used by the petroleum industry have been adapted to model CO_2 disposal. It is important to note, however, that our detailed knowledge of the behaviour of CO_2 in the subsurface is far from complete.

2.1 Monitoring and Verification of Injected CO_2

Monitoring the performance of the CO_2 injection and disposal operation requires observations both at the surface and in the subsurface. Surface equipment monitoring involves the application of standard oilfield practices for the regular inspection of the CO_2 distribution infrastructure, injection volumes and pressures, general well performance and regular scheduled maintenance. The petroleum industry has been injecting CO_2 into hydrocarbon-bearing aquifers since the 1970s in enhanced oil recovery (EOR) projects, so many practices are well established.

Monitoring programmes will extend from the pre-operational, through operational and post-operational periods. Pre-operational monitoring activities will provide baseline data that will be useful for the disposal site characterization, developing the safety case for the disposal system and for the development of performance models. Many of the methods used will continue into the operational phase of the project. Following the closure and sealing of the disposal site, monitoring methods used would ideally not compromise the integrity of the geological container. Seismic imaging is one very useful method that can be used repeatedly for as long as this information is useful.

Observation wells can be useful throughout all the operational periods. Wells that are located distant from the injection location, and are completed in the disposal aquifer and other strata, can be used to monitor the migration of CO_2 in the subsurface and for conducting various geophysical surveys. Information gathered can be used to verify the movement of the CO_2 and of the geochemical evolution of the native brines and host rock components. If leakage is detected there may be an opportunity to mitigate its escape into the biosphere. Observation wells can remain operational for a period of time far beyond the injection period, until such time as public confidence in the disposal method used can be assured. Eventually, observation wells will be abandoned according to regulated procedures. There is risk, however, that, if abandonment materials used fail prematurely, then CO_2 could potentially escape from the disposal aquifer.

The Intergovernmental Panel on Climate Change (IPCC) report on CO_2 capture and storage (IPCC 2005) has summarized both the direct and indirect methods used to monitor the movement of CO_2 in the geosphere. The following are examples of the types of methods used

- Time-lapse, 3-D seismic imaging to identify the development and geometry of the CO_2 plume, and seismic profiling and imaging techniques that help to detect the distribution of CO_2 in the aquifer and identify potential leakage through fractures and faults.
- Hydrogeological testing to assess aquifer properties, flow directions and rates, fluid densities and hydraulic heads, and to develop both local and regional models.
- Geochemical testing of fluids from observation wells to determine the degree of fluid interaction and trapping; tracers in the injected fluids may be utilized.
- Seismic assessments to estimate the probability and magnitude of tectonic events.
- Surface soil-sampling programmes that detect leakage to the biosphere.

Understanding the behaviour of CO_2 that has been injected into the geosphere has evolved significantly with the implementation of, and experience gained from, various carbon capture and storage (CCS) projects. Two world-class projects are being conducted, one at Sleipner in the Norwegian portion of the North Sea, and the other at Weyburn, Canada.

Beginning in 1996, Statoil has been injecting about one million tonnes of CO_2 per year into a deep saline aquifer in the Sleipner Field in the Norwegian sector of the North Sea. The International Energy Agency Greenhouse Gas R&D Programme (IEA GHG), with its industry partners and several research institutes developed a Best Practice Manual (Holloway et al. 2003) to share relevant information. The use of time-lapse seismic surveying is one technique that has been a reliable tool for monitoring the development and movement of the CO_2 plume at Sleipner (Arts et al. 2004; Holloway et al. 2003).

Since 2000, EnCana Corporation (then PanCanadian Petroleum) has been injecting over 5,000 t of CO_2 per day into the Weyburn oil reservoir as an EOR solvent to extract additional crude oil. Within the geoscience framework of the IEA GHG Weyburn CO_2 Monitoring and Storage Project, research has provided abundant information regarding the injection of CO_2. This CO_2 EOR project has provided a dynamic, commercial-sized laboratory where the geochemical and physical nature of the reservoir is being observed and documented as the conditions evolve with the continual introduction of CO_2.

Before the project was initiated, a robust information baseline about the character of the reservoir was developed so that effective monitoring of the changes could be observed. These efforts were focused on the anticipated physical and chemical effects, and on the tracking of the CO_2 as it spread in the reservoir and potentially outside the intended area (White et al. 2004). The results from the monitoring efforts are providing an ongoing verification of the modelling process, reliable estimates of the distribution of the CO_2, and confidence in the effectiveness of the disposal container. Analyses from production data provide an ongoing geochemical survey of the evolving aquifer, using reservoir pressure data and analysis of injected and produced products. Understood leakage routes have been identified (there may be others) and corresponding monitoring efforts have been initiated. Although detection and remediation strategies have been developed, based largely upon common oilfield practices, more experience will provide for increasingly effective mitigation efforts.

Time-lapse seismic imaging has been a very effective monitoring tool for identifying the shape of the CO_2 plume and its movement in the reservoir, and repeated sampling of soil–gas concentrations has so far indicated that no CO_2 is escaping to surface (White et al. 2004). Risk assessments have concluded that the geological setting of the Weyburn project is well suited for the secure, long-term disposal of CO_2 (Whittaker et al. 2004).

These operations and others in various stages of implementation provide critical background experience that can lead to improved CO_2-disposal, -monitoring and -verification methods. Standard protocols to verify geological disposal have not yet been fully developed, but long-term monitoring will be a likely requirement (Benson et al. 2005).

The concept of disposing of anthropogenic CO_2 in the deep subsurface is relatively recent, so modifications to existing and proposed practices are also evolving. For example, rather than injecting a relatively pure stream of CO_2 into the aquifer, it may be beneficial to pre-mix the CO_2 with brine from the intended disposal aquifer. As a result, the development of a CO_2 plume could be avoided and the CO_2 would be more widely dispersed in the aquifer. Greater dispersion would provide greater surface-area contact between the CO_2 and the native brines and minerals, potentially accelerating the rate of CO_2 neutralization. If this method of injection was deemed suitable, then monitoring methods would also require adjustment. Coincidentally, developing a brine-premix source well may also provide a geothermal energy source.

2.2 Containment and Potential Failure of Seals

Where sequences of sedimentary rock comprise aquifers interbedded with less permeable seals or aquitards, the contrast of high lateral permeability in the aquifers with low vertical permeability in the aquitards has provided some of the fundamental conditions necessary for the lateral migration and accumulation of hydrocarbons and will provide for the safe disposal of CO_2.

CO_2 is compressed to a supercritical or 'liquid-similar' density when injected into the disposal aquifer. The pressure necessary to maintain the CO_2 in this supercritical state is usually available at depths greater than 800 m (Gunter et al. 2004).

When injected into the aquifer, the CO_2 will move away from the point of injection and, due to its buoyancy, will tend to rise and migrate updip (Flett et al. 2005) subject to controlling mechanisms such as pressure gradients, natural hydraulic gradients, buoyancy, dissolution into formation fluids, and chemical interaction with rock-forming minerals. The intended disposal aquifer must effectively contain the CO_2 until the CO_2 reacts fully with the host rock and associated formation fluids, possibly requiring a period of many thousand years (Bachu et al. 1994). These natural conditions will both contain the CO_2 and ultimately provide for its permanent sequestration.

Primary seals are composed of impermeable rocks that provide a cap directly overlying the intended disposal aquifer. For as long as injected CO_2 remains buoyant and migrates updip in the aquifer, there is a risk that it will encounter a permeable breach in the seal. This risk must be carefully assessed, for naturally occurring fractures and faults in rocks can provide potential vertical conduits between aquifers. If the vertical conduit terminates, upward flow will cease or, if the relative permeability of an overlying intersected aquifer is greater, the flow of CO_2 may be recaptured by this ‘relief’ aquifer. The presence of secondary seals higher in the rock sequence provide additional barriers to vertical fluid movement.

Abandoned well bores from past drilling activity which intersect the CO_2 disposal aquifer create additional risk to CO_2 containment, as they provide potential conduits for the vertical movement of CO_2. As CO_2 migrates updip in the aquifer it may encounter a hole in a previously drilled oil exploration prospect. One intention of the site selection process is to identify these conditions so that the potential for cross-formational flow and contamination within the geosphere, and for contamination of near-surface potable water aquifers or escape to the biosphere are mitigated.

Depleted oil- and gasfields may also provide secure geological containers for CO_2 disposal because the hydrocarbon trapping mechanism has contained buoyant hydrocarbons for millions of years (Gunter et al. 2004; Shaw and Bachu 2002). However, in many depleted fields, particularly older ones where there are numerous (possibly hundreds) of well casings, the potential for escape is significant. The concern resides around the ageing of the materials in the wells and the resulting possibility of providing migration paths for the CO_2.

2.3 *Complete Neutralization of* CO_2

The disposal potential and ultimate sequestration of CO_2 in deep saline aquifers depends to a great extent upon the degree of reactivity between the injected CO_2, the formation fluids and the host rock constituents. Geochemical reactions will vary according to differences in mineralogy, formation-fluid chemistry, pressure, pH, temperature and many other aquifer characteristics (Gunter et al. 2004).

Physical trapping occurs when the CO_2 is confined as a supercritical ‘bubble’ (Bachu et al. 1994). Deep saline aquifers with extremely slow flow rates provide an effective geological container which can trap injected CO_2 hydrodynamically, as it takes from hundreds of thousands to millions of years for CO_2 to travel any significant distance by buoyant forces. As CO_2 moves through the aquifer, it also experiences solubility trapping when it dissolves into the brine and no longer migrates as a separate phase, then moving at the same rate as the brine in the aquifer. With the associated changes in pH, ionic trapping may occur with the formation of ionic species. With time, CO_2 will geochemically react with rock minerals, particularly feldspars and clays, becoming permanently trapped by mineral trapping (Gunter et al. 2004). At the tail of the rising plume, residual CO_2 will 'imbibe' to the host rock (Flett et al. 2005). As the character of the CO_2 plume evolves, the various trapping mechanisms interact in a complex way, both simultaneously and at different timescales. Over time, these mechanisms lower the potential for leakage because the CO_2 becomes less mobile (Benson et al. 2005). It may require several thousands of years for mineral trapping to be effectively complete (Bachu et al. 1994), so containment must be reliable for this length of time. Monitoring changes in the geochemical nature of the CO_2 and native brines taken from observation wells provides an opportunity to evaluate the evolution of the neutralization process.

3 Geological Disposal of Radioactive Waste

An RW repository must ultimately provide safety to humans and the environment, so final disposal solutions must be secure for many thousands of years (NEA 2004). Multiple safety barriers, both engineered and geological in origin, combine to provide this assurance. The expectations for developing a repository include isolation from the biosphere, confinement of the RW in the geosphere in the near term (10,000 years) and, due to anticipated material failure, mitigated release to the geosphere in the long term (Sykes 2003). As the character of the geosphere will provide the most reliable conditions for long-term, safe isolation of the RW, repositories must be sited in stable geological environments where the geomechanical, geochemical and groundwater-flow characteristics are favourable.

3.1 Disposal Systems

Disposal systems will be inherently passive in character. Isolation from the biosphere will be maintained by conditions that are not reliant upon any active measures in the future. Based upon the timely degradation of engineered barriers, escape of the radionuclides into the geosphere surrounding the disposal site will be retarded due to the robust nature of the multiple containment design (NEA 2004). The NEA (2006) summarizes the safety functions of an RW repository as described by the European Commission 'Testing of Safety and Performance Indicators' (SPIN) Project (Becker et al. 2002), where barriers identified for saturated formations perform both individually and collectively over relative periods of time and levels of radioactivity:

- During the early post-closure history of the repository, vessels that contain the RW will provide a watertight barrier that isolates the material; this represents the most transient period due to resaturation, the greatest level of heat and radiation release and pressure rebuilding.
- When container failure occurs groundwater will eventually come in contact with the RW and various physical and chemical processes will result in the very slow leeching of radionuclides into the buffer materials surrounding the container.
- Groundwater flow rates in the rock surrounding the repository site will be very slow (relatively stagnant), so the migration of dissolved radionuclides into the distant geosphere will be retarded; migration is retarded further due to sorption of some radionuclides onto minerals in the buffer and host rock materials.
- Long-lived radionuclides will eventually be mobile in the distant geosphere and may enter surrounding aquifers; by the time these materials enter parts of the biosphere they will be widely diluted and dispersed.

It is assumed that containment will be fully satisfied through the site-selection process and applied engineered methods, and that barrier failures will occur in a timely and predictable fashion.

Several countries are in various stages of investigating and developing deep geological repositories. For example, Finland, Sweden and Canada are investigating development in crystalline rock, and in France, Belgium and Switzerland development in sedimentary rocks is being considered (McCombie 2003).

At all the sites under consideration, traditional mining methods including the creation of shafts, tunnels and rooms up to 1,000 m below the ground surface are used. Proposals for disposal in crystalline rocks in Canada, Finland and Sweden envision that the spent nuclear fuel be placed in steel (or iron) and copper containers having a predicted lifetime of at least 100,000 years, and that these containers be placed in rooms which are subsequently backfilled with chemically and physically supportive bentonitic clays (McCombie 2003).

The proposed highly engineered barriers are expected to provide the greatest blockade to material escape. For example, in Sweden canisters housing the RW will be constructed to withstand the anticipated mechanical load and potential corrosive conditions of the repository, and supportive buffer materials around the canisters will protect them and mitigate the movement of radionuclides that escape; backfill materials will stabilize the repository and are intended to prevent groundwater flow in the tunnels (SKB 2004).

Although the use of highly engineered containers is also proposed for RW disposal in sedimentary-rock repositories in France, Belgium and Switzerland, greater reliance would be placed on the hydrogeological environment to contain eventual leakage into the geosphere (Mazurek 2004).

In the USA, a repository is being developed in volcanic tuff at Yucca Mountain, Nevada. Although the porous rocks surrounding the repository are considered to be unsaturated, fractures are common and could provide conduits for groundwater movement. Highly engineered containers and barriers would be used to keep stored material permanently dry and isolated (OCRWM 2001).

3.2 Methods Used to Monitor a Radioactive Waste Disposal Site

The primary objective of monitoring programmes is to assess the performance of the repository site and the reliability of the barriers, and to progressively update the safety case through each evolutionary phase of the project. Monitoring activities would begin during the siting process to establish baseline information under present or unperturbed conditions and would continue into the future, ending sometime following the closure of the facility. Collected data will be useful in the development of predictive models and in the assessment of those models over time. Pre-closure activities would include site selection and characterization, repository evaluation and construction, RW placement operations, decommissioning and repository closure. Post-closure activities would follow the final sealing of the facility, during which time institutional control is maintained (Simmons 2006).

Various monitoring methods can be utilized to confirm the performance of the barriers during pre-closure activities. Results from these efforts would assist operators in proceeding from one operational stage to the next. To assess the performance of the repository, instrumentation is placed within the host rock to monitor the conditions while access to the underground is available. Methods that require the use of boreholes in the host rock will require appropriate sealing when the site is being decommissioned so that sealing systems are not compromised. Examples of the types of methods utilized (Simmons 2006) include:

- Rock-mass monitoring to assess changes in stress, displacement and micro-seismic activity;
- Temperature monitoring to assess the role of heat load in rock stress;
- Hydraulic monitoring of the excavation site to assess the development of communication pathways;
- Hydrogeological monitoring to assess changes in pressure and groundwater flow;
- Geochemical monitoring to identify changes in groundwater composition.

The duration of the monitoring efforts being used must be sufficient so that reliable information provides confidence in the performance models, possibly for a few hundred years.

Following the closure of a facility monitoring would continue for some time to support ongoing performance assessments and, ultimately, to assure public confidence in the disposal methods used. The intention of all national RW disposal programmes is to not burden future generations with having to care for the RW, so only when the long-lived safety of the repository is assured will it be sealed (Stenhouse and Savage 2004). Therefore, long-term safety and security will be achieved using disposal methods that do not require active monitoring, maintenance or institutional control (NEA 2004).

4 Comparison of CO_2 and Radioactive Waste Disposal Monitoring Techniques

The concept of using deep geological repositories to safely dispose of CO_2 and RW may be becoming both socially and politically acceptable. The physical conditions and time frame necessary for implementation are, however, broadly different. For example:

- There is significant interest in reducing global anthropogenic greenhouse gas emissions as soon as possible, and the geological disposal of CO_2 is viewed by many as capable of making a significant contribution to these reductions. Several monitoring methods used for CO_2 disposal are being ‘field tested’ and are evolving concurrently with active disposal. The eventual disposal of RW in geological repositories is also practical but has a much longer time horizon for its implementation. With the exception of the Waste Isolation Pilot Plant (WIPP) site in New Mexico, USA, most national facilities are utilizing underground research laboratories (URLs) to conduct in situ monitoring (Stenhouse and Savage 2004).
- The quantities of material to store are widely different. Nuclear material is solid and dense, and the amount of product to store globally can be measured in tonnes per year, whereas CO_2 is light and buoyant, the amount being measured in millions of tonnes per day. The geological characteristics of the CO_2 repository will include well developed porosity, permeability and fluid-mobility potential, whereas those of the RW disposal site will be in excavated caverns where the rocks have very limited permeability and restricted fluid-mobility potential (i.e. the characteristics are opposite). Some of the methods used for the monitoring of both products will rely upon groundwater sampling during the RW pre-closure and CO_2 operational periods.
- The area required for disposal is potentially much greater for CO_2 than for RW. Monitoring methods used will be required to accommodate these widely different spatial requirements. Injecting millions of tons of CO_2 per year for several years at a single site could, depending on the thickness of the aquifer, result in the development of a plume over 100 km^2 in size, whereas a single RW repository would likely require a significantly smaller area. Monitoring programmes for CO_2 must be able to accommodate the large areas and volumes involved, so techniques with vertical resolutions in the order of metres to tens of metres are acceptable and even lower resolution may prove adequate. With RW disposal, the resolution required will need to be much finer in order to detect changes in the stresses in rock, fractures, backfill, the disposal containers and hydraulic features.
- The sites must provide safe disposal for as long as the products are potentially mobile and/or harmful. For CO_2 disposal, the period is probably less than about 10,000 years, whereas for nuclear material, containment must be safe for a much longer period of time. These temporal differences require durable containment systems that are effective, potentially over geological periods of time. There is an inverse relationship between risk and time when comparing the safe disposal of CO_2 and RW. The risk of escape of nuclear material increases with time due

to the potential for premature degradation of the engineered barriers, whereas the risk of leakage of free CO_2 decreases with time due to the ongoing process of its neutralization.

- Once CO_2 is injected into the disposal aquifer, it is the natural character of the geosphere that will provide the conditions necessary to contain it for as long as it remains buoyant, and for several thousands of years after that until it reacts completely with the rock-forming minerals—no reliance is placed on human-made barriers. Monitoring the distant geosphere will potentially confirm the migration and behaviour of CO_2 in the subsurface during the operational and post-operational periods. Under current strategies, the safety of RW relies on highly engineered barriers that are supported by the character of the geosphere. Monitoring the distant geosphere in the post-closure period could be conducted if methods used did not affect the passive safety of the RW repository.

Programmes have been established to monitor the safe disposal of CO_2 from the pre-operational, operational and post-operational periods and for RW from the pre-closure through post-closure periods. Table 1 identifies several of these monitoring methods.

5 Knowledge Transfer Potential

Many of the principles involved with CO_2 disposal are similar to those used in hydrocarbon exploration and development. Operators have benefited from their experience which has allowed them to modify operating procedures as previously unforeseen conditions have arisen. They have also been able to modify monitoring and verification techniques as the amount of practical knowledge increases.

Since there is no immediacy for the disposal of RW, a comprehensive, cautionary approach to disposal has been taken. The consequences of nuclear leakage into the biosphere have very long-term environmental implications, whereas an unintended release of CO_2 would likely have few lasting effects once the leak was remedied. This gradual approach to RW disposal allows for the development of policies and regulatory protocols, whereas with CO_2 disposal, many of these issues have yet to be resolved and some policies are being established by precedent 'as we go'. Several RW monitoring methods have been tested for many years in separate URLs in different countries. Monitoring the behaviour of anthropogenic CO_2 in the subsurface is more recent.

The body of monitoring experience is significant for both the RW and CO_2 research communities, and some of this knowledge and experience may be transferrable. For example:

- Abandoned wellbores provide potential pathways for CO_2 to escape to the biosphere. If current abandonment methods are successfully applied, then this risk is mitigated; however, there is the potential for premature failure of the materials used. Several RW monitoring methods require the use of boreholes

Table 1 Examples of carbon dioxide and radioactive waste monitoring methods

CO$_2$ monitoring	Purpose	Radioactive waste monitoring	Purpose
Pre-operational period		**Pre-closure period**	
Soil gas and near-surface hydrology	Establish baseline surface characterization	Environmental and near-surface hydrology	Establish baseline surface characteristics
Use of existing local and regional subsurface data: aquifer characteristics, geochemistry, hydrogeology, seismic	Establish baseline subsurface characterization	Use of existing local and regional subsurface data: geochemistry, hydrogeology, seismic	Establish baseline subsurface characterization
Remote sensing	Identify lineaments and surface-expressed faults to predict potential escape pathways	Hydrogeological monitoring using surface and subsurface boreholes; may include use of tracers	Establish baseline conditions and identify changes in hydraulic head and groundwater geochemical properties
Operational period			
Time-lapse 3-D seismic profiling	Track CO$_2$ plume development and migration patterns	Overcoring with borehole deformation instrumentation	Establish in situ rock mass stability during site characterization and construction
Time-lapse gravity measurements and electrical conductivity surveys	Detect and track migration of CO$_2$ in disposal and other aquifers	Seismic detection (seismometers, geophones, hydrophones, accelerometers, acoustic emission, microseismic)	Determine the location of seismic activity, including events caused by mining and operational activities
Use of observation wells:			
Pressure and temperature changes, fluid sampling; may include use of tracers	Track physical conditions and geochemical evolution of CO$_2$ and native fluids in disposal and other aquifers; on-going hyrogeological assessment	Displacement of rock mass following excavation	Confirm mechanical properties of the host rock
		Hydraulic monitoring following excavation	Assess the influence construction has on the development of communication pathways to the more distant geosphere
Borehole geophysical techniques (seismic tomography, cross-hole tomography, vertical seismic profiling, acoustic emission, microseismic and passive seismic)	Assess geomechanical stability and structural disturbances	Temperature monitoring during construction and operation	Assess the rock mass response to temperature changes

(continued)

Table 1 (continued)

CO_2 monitoring	Purpose	Radioactive waste monitoring	Purpose
Post-operational period		**Post-closure period**	
Continuation of surface procedures as is deemed necessary; borehole monitoring	Escape of CO_2 to the biosphere	Continued non-intrusive geophysical procedures as is deemed necessary	Possibly provide greater societal assurance
Time-lapse 3-D seismic profiling	Monitor continued evolution of plume development and dissipation	Monitoring is not required for safety beyond the period of institutional control but monitoring may be conducted if desired	Methods used must be non-intrusive to avoid compromising the passive safety of the disposal system

in the excavated areas and in the surrounding geosphere. These holes will eventually be sealed during the pre-closure period of the repository. Some aspects of the sealing methods and materials used for RW borehole closure may be useful for CO_2 well abandonment procedures.

- Downhole instruments are used by both research communities. The reliability and durability of these instruments have been ‘field tested’ for RW monitoring for a longer period of time than for CO_2 monitoring. Some aspects of this RW monitoring experience may be useful for monitoring CO_2.

6 Application of a CO_2 Monitoring Method to Radioactive Waste Monitoring

As described previously, observation wells located strategically distant from the CO_2 injection well can be used to track the movement of CO_2 in the surrounding geosphere. These wells will eventually be abandoned, likely during the post-operational period. There remains, however, the option to develop a new observation well at any time, allowing future decision makers the ability to ‘have a look’ anytime, and respond to the arising of currently unforeseen circumstances. Future societies may also desire additional monitoring.

If the geological character of the RW repository site is suitable, sampling groundwater from the geosphere surrounding a repository site may be useful if it can be conducted without compromising the integrity of the containment barriers. Sampling can be conducted over the short term (less than 300 years) or, indeed, indefinitely into the future beyond the decommissioning of the repository, if either technical conditions or public demand require further sampling.

Selection of a repository site which places its greatest reliance on suitable geological systems is more likely to provide for permanent isolation of the RW, particularly in the event of premature engineered-barrier failure. It is appropriate, therefore, to develop repositories where the natural environment provides reliability for geological periods of time—for millions of years. Locating RW repositories beneath suitable intracratonic sedimentary basins may provide: (1) an opportunity to monitor the integrity of the containment system indefinitely, and (2) permanent isolation and containment.

The Williston Basin, for example, is generally located in southern Saskatchewan, Canada, and North Dakota, USA, and conditions there may provide for this reliability (Brunskill 2006). An RW repository could be developed in the Precambrian Shield beneath the stagnant, dense brines (e.g. 250–350 g/l Total Dissolved Solids) which occupy aquifers at the base of the basin. As well as great depth (e.g. 3,000–4,000 m), the hydrogeological environment of the repository site will likely inhibit the vertical migration of contaminated material because the water that would carry the contaminating material would be unable to move significant vertical distances. The dense brines will potentially provide complete isolation of any leakage for a period of time far longer than any nuclear material would be harmful. Even following a significant tectonic event, contamination would likely remain in the very deep geosphere.

The development of these repositories is technically possible and may be economically feasible if, for example, surface-drilling methods currently utilized in the petroleum industry are used. The disposal space for the RW would be developed by drilling long, small-diameter ‘rooms’ that are lined with continuous, metallurgically suitable casing. Although nuclear material placed in this lateral section of the hole would be in the abandonment position, material could potentially be retrieved and inspected as deemed necessary. With this option of being readily retrievable for some time, future decision makers would have greater flexibility as new concerns and technologies arise.

In the Williston Basin example, the presence of this overlying aquifer also provides a means to conduct reliable and timely monitoring of the repository site without compromising the integrity of the repository. Observation wells can be placed strategically in and around the disposal site and be used to circulate native brines from the overlying aquifer across the repository area to the surface where any contamination can be detected. If deemed appropriate, remedial action may be taken.

Figure 1 provides a sectional view of a model RW disposal facility. In this scenario the hole is drilled vertically from the surface through the sedimentary section of rocks to a depth of about 3,000 m, now being roughly 300 m beneath the Precambrian surface. The hole would then be drilled laterally to its maxim depth of approximately 6,400 m. RW would be repackaged and placed in this lateral section. Radionuclides that eventually escape into the overlying, brine-filled aquifer would likely remain in the very deep geosphere and be subject to detection during the monitoring programme.

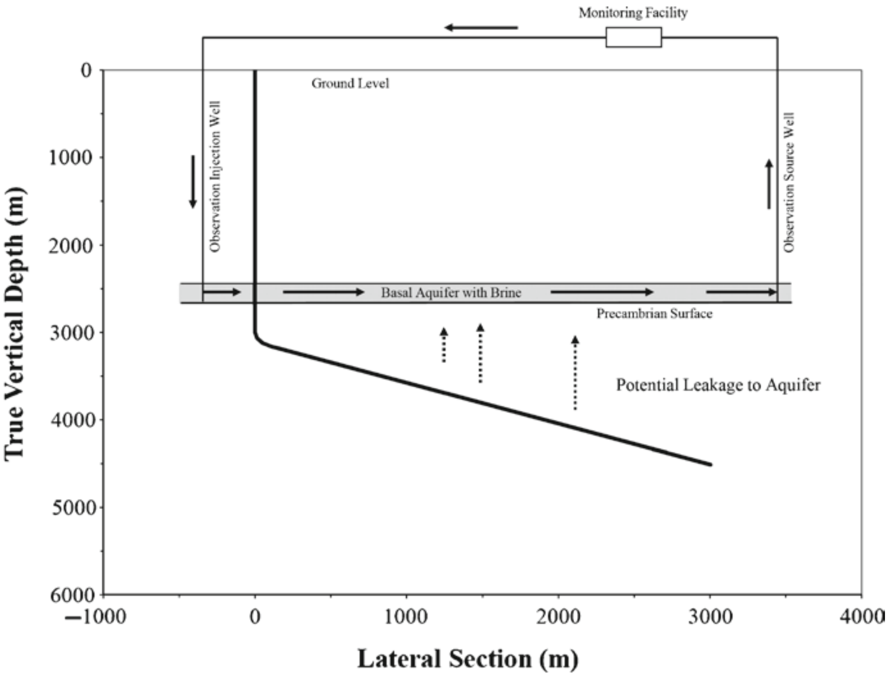

Fig. 1 Illustration of a drilled radioactive waste repository beneath the Williston Basin, Canada. Includes the brine circulation loop in the basal aquifer to monitor the migration of radioactive material that escapes into the overlying geosphere

7 Conclusions

In suitable locations the geological conditions provided by the geosphere can effectively isolate anthropogenic CO_2 and RW from the biosphere, although the conditions necessary for disposal are widely different. Once injected into the disposal aquifer, the containment of CO_2 relies upon the natural conditions provided by the geosphere. Under most current strategies, containment of RW is reliant upon highly engineered barriers that are supported by the character of the geosphere surrounding the repository.

Many of the monitoring methods used during the site-selection and geological characterization stages are similar for both RW and CO_2 disposal. Surface hydrology and subsurface geochemical and hydrogeological monitoring programmes contribute significantly to this process. During the operational stage of a CO_2 repository, geophysical evidence provided by time-lapse seismic surveys is one reliable monitoring tool and sampling aquifer fluids from observation wells support the confirmation of the geochemical evolution of CO_2 in the subsurface. Operating in RW excavations and URLs provide additional opportunities to develop effective techniques to monitor geomechanical and geochemical variations in the subsurface.

Both the RW and CO_2 disposal research communities are well experienced at 'field testing' various monitoring methods, and there is potential for a significant transfer of knowledge and experience between these communities.

Under the appropriate conditions, the geological disposal of both CO_2 and RW is a very effective way to safely and securely dispose of these products. The ongoing development of effective monitoring programmes will continue to provide both technical and societal confidence. Furthermore, the geological disposal of CO_2 is one method available today that can make a significant contribution to reductions in the emission of anthropogenic CO_2 in the very near term. Public confidence gained through the efforts of objective, 'third party' educators is critical to societal acceptance for the disposal of both CO_2 and RW.

Confidence in programmes that can effectively monitor and actively control materials like RW and CO_2 in the geosphere thousands of years from now and, indeed, over geological periods of time is unrealistic. Societies may evolve in such a way that they are no longer reliant on traditionally mined materials, and taking remedial action in response to premature leakage, for example, 2,000 years from now, may not be possible. Human understanding of highly technical issues is also very recent. To provide perspective, it has been only about 10,000–12,000 years since humans left the Paleolithic Period.

The development of very deep geological repositories for RW beneath sedimentary basins is technically possible. Great depth, the geological character and the hydrogeological environment could potentially provide the conditions necessary for safety and security for millions of years. A repository developed under these conditions would also provide for retrievability for some time and an option for future generations to conduct effective monitoring, particularly in response to currently unforeseen circumstances if they so desire. It may be beneficial to also support further investigations of this model in conjunction with continued research on current disposal strategies.

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References

Arts R, Eiken O, Chadwick A, Zweigel P, van der Meer L, Zinszner B (2004) Monitoring of CO_2 injected at Sleipner using time-lapse seismic data. In: Freund P, Kaya Y, Lior N (eds) Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies. Energy 29(9–10):1383–1392

Bachu S, Gunter WD, Perkins EH (1994) Aquifer disposal of CO_2: hydrodynamic and mineral trapping. Energ Convers Manage 35(4):269–279

Becker DA, Buhmann D, Storck R, Alonso J, Cormenzana JL, Hugi M, van Gemert F, O'Sullivan P, Laciok A, Marivoet J, Sillen X, Nordman H, Vieno T, Niemeyer M (2002) Testing of safety and performance indicators (SPIN). Nuclear Science and Technology, Final Report EUR 19965 EN. European Commission, Luxembourg

Benson S, Cook P et al (2005) Underground geological storage. In: Metz B, Davidson O, de Coninck HC, Loos M, Meyer L (eds) IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press, Cambridge and New York, pp 196–276

Brunskill B (2006) Discussion of an option for geological storage of used nuclear fuel beneath the Williston basin of southern Saskatchewan. In: Summary of Investigations 2006, 1:1–8. Misc Rep 2006–4.1. Saskatchewan Geological Survey, Sask. Industry Resources, Regina

Flett MA, Gurton RM, Taggart IJ (2005) Heterogeneous saline formations: long-term benefits for geo-sequestration of greenhouse gases. In: Rubin ES, Keith DW, Gilboy CF (eds) Greenhouse Gas Control Technologies: Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, vol 1. Elsevier, London, pp 501–509

Gunter WD, Bachu S, Benson S (2004) The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide. In: Baines SJ, Worden RH (eds) Geological Storage of Carbon dioxide for Emissions Reduction, vol 233, Geological society special publication. Geological Society of London, London, pp 129–145

Holloway S, Chadwick A, Lindeberg E, Czernichowski-Lauriol I, Arts R (eds) (2003) Saline aquifer CO_2 storage project (SACS) best practise manual. Report Number PH4/21. International Energy Agency Greenhouse Gas R&D Programme, Trondheim

IPCC (Intergovernmental Panel on Climate Change) (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (eds). Cambridge University Press, Cambridge and New York

Mazurek M (2004) Long-term used nuclear fuel waste management—Geoscientific review of the sedimentary sequence in southern Ontario. Technical Report TR 04–01. Institute of Geological Sciences, University of Bern, Bern

McCombie C (2003) Status of geological repositories for used nuclear fuel. Background Paper 6–3. Nuclear Waste Management Organization, Toronto

NEA (Nuclear Energy Agency) (2004) Post-closure safety case for geological repositories: nature and purpose. Report NEA No. 3679. OECD Nuclear Energy Agency, Paris

NEA (Nuclear Energy Agency) (2006) Advanced nuclear fuel cycles and radioactive waste management. Report NEA No. 5990. OECD Nuclear Energy Agency, Paris

OCRWM (Office of Civilian Radioactive Waste Management) (2001) Yucca Mountain Science and Engineering Report. DOE/RW-0539. US Department of Energy, Office of Civilian Radioactive Waste Management, Washington, DC

Shaw J, Bachu S (2002) Screening, evaluation, and ranking of oil reservoirs suitable for CO_2-flood EOR and carbon dioxide sequestration. J Can Petrol Technol 41(9):51–61

Simmons GR (2006) A framework for the long-term monitoring of a deep geologic repository for used nuclear fuel. Report 06819-REP-01300–10119-R00. Ontario Power Generation, Toronto

SKB (Svensk Kärnbränslehantering AB—Swedish Nuclear Fuel and Waste Management Company) (2004) RD&D-Programme 2004. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste, including social science research. SKB Technical Report TR-04–21. Svensk Kärnbränslehantering AB, Stockholm

Stenhouse MJ, Savage D (2004) Monitoring experience associated with nuclear waste disposal and its application to CO2 sequestration projects. In: Baines SJ, Worden RH (eds) Geological Storage of Carbon dioxide, vol 233, Geological Society Special Publication. Geological Society of London, London, pp 235–247

Sykes JF (2003) Characterizing the Geosphere in High-Level Radioactive Waste Management. Nuclear Waste Management Organization, Toronto, Background Paper 4–2

White D, Hirsche K, Davis T, Hutcheon I, Adair R, Burrows G, Graham S, Bencini R, Majer E, Maxwell S (2004) Theme 2: prediction, monitoring and verification of CO_2 movements. In: Wilson M, Monea M (eds) IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000–2004. Petroleum Technology Research Centre, Regina, pp 73–148

Whittaker S, Rostron B, Khan D, Hajnal Z, Qing H, Penner L, Maathuis H, Goussev S (2004) Theme 1: geological characterization. In: Wilson M, Monea M (eds) IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000–2004. Petroleum Technology Research Centre, Regina, pp 15–69