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Environmental Issues in the Geological Disposal of Carbon Dioxide and Radioactive Waste –

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Abstract

A comparative assessment of the post-closure environmental issues for the geological disposal of carbon dioxide (CO_2) and radioactive waste is made in this chapter. Several criteria are used: the characteristics of radioactive waste and CO_2; their potential environmental impacts; an assessment of the hazards arising from radioactive waste and CO_2; and monitoring of their environmental impacts. There are several differences in the way that the long term safety of the disposal of radioactive waste and CO_2 is regulated and evaluated. While the regulatory procedures relating to the development of a facility for the disposal of radioactive waste in many countries with nuclear power programmes are well defined having evolved over several decades, those relating to CO_2 disposal are less well developed. The results of this assessment show that, despite key differences, many of the approaches addressing environmental issues are similar. Additionally, much can be learnt from the radioactive waste disposal experience which will be particularly relevant to the assessments of site performance for CO_2 within a regulatory framework, particularly in the methods and approaches to long term site performance assessment.

Keywords

Carbon dioxide storage; Environmental impacts; Radioactive waste disposal; Technology Comparison.

1. Introduction

This chapter provides a comparative assessment of the environmental issues surrounding the geological disposal of carbon dioxide (CO_2) and radioactive waste. These are diverse and influence the entire disposal chain including transport and the construction and operation of facilities. However, the issues considered here are post-closure, that is after the closure of a radioactive waste repository or after CO_2 injection has ceased and the site has been formally closed. Consideration will be made of both terrestrial and marine environments although, for radioactive waste, the focus is mainly on terrestrial environments.

In carbon capture and storage (CCS), the injection of CO_2 into a geological formation is known as 'storage' although there is no intention to retrieve the CO_2 once it has been injected. This is also the case for radioactive waste because it is generally envisaged that waste emplacement, or 'disposal', at depth is permanent, though there may be a long phase of active management prior to the decision to initiate repository sealing and closure. However, both radioactive waste and most CO_2 could be technically retrieved.

Radioactive waste includes all waste materials that are too radioactive for disposal within an ordinary landfill facility. This will include wastes derived from nuclear power generation, including fuel reprocessing, medical wastes and laboratory wastes. It may also include naturally occurring radioactive materials (NORM) such as scale (removed from the inside of oil pipelines) which is naturally radioactive. It will include some long-lived Low Level Wastes (LLW), Intermediate Level Waste (ILW) and High Level Waste (HLW) and could include Spent Nuclear Fuel (SNF) and plutonium and uranium if these materials are considered to be waste. Most LLW is disposed of to surface or shallow disposal facilities and is not considered further here. CO_2 streams will comprise almost pure CO_2 captured from large point sources such as fossil-fuel based power stations, cement and some chemical and refinery plants.

For both technologies, post-closure environmental concerns focus on the impacts of either unpredicted releases of radionuclides or leakage of CO_2 into the biosphere which includes the shallow subsurface (the soil, vadose zone and potable aquifers); and surface ecosystem. Performance Assessment (PA) (described in the chapter by Maul (this volume)) is usually used to evaluate the (post-closure) evolution of repository systems with some of the output expressed in terms of risk to human health and the environment. PAs provide a rigorous and comprehensive approach to site appraisal and, in the context of project planning and regulatory decision making, they are crucial in developing the long term 'safety case' which, for the geological disposal of radioactive waste, is commonly extrapolated over a period in the order of 10^6 years (e.g. NIREX 1997). Currently, formal PA is not implemented in existing CO_2 storage projects because the technology is still evolving from the research and development stage. However, guidelines are being developed for the risk assessment of CO_2 storage such as the Convention for the Protection of the marine Environment of the North-East Atlantic (OSPAR) Guidelines for Risk Assessment and Management of Storage of CO_2 streams in geological formations (OSPAR 2007); and the European Commission's (EC) draft directive on the geological storage of carbon dioxide (see - http://ec.europa.eu/environment/climat/ccs/eccp1_en.htm. Accessed 27 April 2009) or, at an earlier stage, Strategic Environmental Assessments (SEA) which compares different management strategies. Environmental Impact Assessments (EIA) are undertaken in both technologies and these give 'an evaluation … … (of) impacts of a proposed activity, where the performance measure is overall environmental impact, including … … global measures of impact on safety and the environment' (IAEA, 2003). Thus EIAs have been used for construction and operational phases where, for example, physical and ecological effects are being evaluated. However, EIAs in the oil and gas industry, on which CO_2 storage practice is based, are normally concerned with environmental impacts during construction, operation and decommissioning and have not necessarily been used to consider potential impacts over the long term. Several CO_2 storage demonstration projects have also included an element of long-term risk assessment (e.g. Weyburn, Canada (Zhou et al. 2004; Stenhouse et al. 2005); Gorgon, Australia (Gorgon Joint Ventures (GJV) 2005a.b) and Schweinrich, Germany (Svensson et al. 2005).

When examining the environmental issues surrounding radioactive waste disposal and CO_2 disposal, several criteria need to be examined. These include:

- The characteristics of radioactive waste and CO_2;
- The potential environmental impacts of radioactive waste and CO_2;
- Assessment of the hazards arising from radioactive waste and CO_2;
- Monitoring of environmental impacts.

The environmental issues for the two technologies are discussed in the following sections with particular emphasis on these criteria. A comparative assessment is then made, using the above criteria, highlighting similarities and differences between the two areas. The conclusions from these comparisons are then discussed in terms of future research and policy.

2. Geological Storage of Carbon Dioxide – Environmental Issues

2.1. International regulatory background

Globally, emissions of CO_2 from fossil-fuel use in the year 2000 totalled about 23.5 Gt with 60% attributed to large (>0.1 Mt CO_2 yr^{-1}) stationary emission sources such as power stations, cement production and refineries (IPCC 2005). Clusters of these sources are found in North America, Europe, East Asia and South Asia and a variety of mitigation strategies, including carbon capture and storage (CCS), will be required to reduce CO_2 emissions from these sources.

To date, the major projects demonstrating CO_2 capture and storage (CCS) at Weyburn, Canada (Wilson and Monea 2004) and Sleipner, in the North Sea (Torp and Gale 2002) have particularly focussed on technological and economic viability, and whether these sites could leak. Consequently, these studies are focussing on monitoring, verification and risk assessment – it is intended that such work will assist regulators and reassure other stakeholder groups (especially the public) that the sites will not leak. These projects operate within existing oil and gas regulatory frameworks. At Weyburn, for example, injection of CO_2 is used to enhance oil recovery from an existing oil field. However, if CCS is conducted outside hydrocarbon-related operations these existing regulations may not be appropriate.

At the time of writing, the regulatory frameworks governing geological CO_2 storage are being developed (described in the chapter by Wilson and Bergan (this volume)). In general, current projects are licensed under petroleum legislation. However, OSPAR has provided guidance on the steps it requires before geological storage in reservoirs at depth below the seabed can be allowed in marine jurisdictions of contracting parties (OSPAR 2007). Further, a draft EC Directive enabling European

Member States to enact legislation of the regulation of CCS is currently under discussion (see - http://ec.europa.eu/environment/climat/ccs/eccp1_en.htm. Accessed 27 April 2009). However, within these draft regulations, it is recognised that issues of leakage and potential long-term stewardship must be addressed if the potential for CO_2 capture and storage to provide substantial reductions in atmospheric CO_2 emissions is to be realised (Mace et al. 2007; Zakkour and Haines 2007). Additionally, studies on public perception of CCS (see, for example, Shackley et al. 2004) indicate concerns about the effect of leakages on the environment.

2.2. Environmental impacts of CO_2

It can be assumed that storage sites will be selected to "permanently" store the injected CO_2. However, if leakage from storage sites did occur after formal closure of the injection site, it could be over small areas from discrete point sources, such as abandoned wells, resulting in locally high concentrations of CO_2. This could reach tens of percent levels in soil gas (West et al. 2005); well above any background levels and which will impact on organisms (Table 1). Although extensive physiological research is available, the overall environmental impacts of localised elevated CO_2 concentrations on terrestrial, subsurface and marine ecosystems are still poorly understood and, as a result, are areas of active research (see following section).

Essentially, respiratory physiology and pH control are the primary physiological mechanisms controlling responses in organisms to elevated CO_2 exposures. Information is available from a diverse research base and some examples are given in Table 1. These data, however, are mostly from studies on organisms exposed to either slightly elevated concentrations of CO_2 or the high concentrations that give a lethal response.

INSERT TABLE 1

In economic terms, leaks from a storage site into marine and freshwater systems might affect fisheries by altering pH with accompanying physiological effects (Turley et al. 2004). For terrestrial systems, leakages might damage crops, groundwater quality and/or human and animal health. Other concerns include acidification, changes in biological diversity and species composition, and asphyxiation at high CO_2

concentrations. In addition, biogeochemical processes may be affected as increased CO_2 concentrations could change pH, microbial populations and nutrient supply. It is also important to understand the local effects in comparison to global increases of CO_2 concentrations on the environment and habitats. In contrast to studies of the effects of elevated atmospheric CO_2 concentrations (say a rise from current levels to 550 ppm), levels of CO_2 in soils resulting from leaks from engineered storage sites underground could be enhanced by several orders of magnitude above atmospheric levels causing damage or, in the worst case, serious damage to an ecosystem.

Organisms close to a leakage could be exposed to acute and perhaps lethal concentrations whilst those at increasing distances from the leakage could be exposed to firstly acute and then to chronic concentrations. How such exposures will influence an existing ecosystem as a whole, or the individual species within an ecosystem is unknown and further work is required to obtain a better understanding. Thus for all ecosystems of interest, the potential indicator groups at the different trophic levels need to be identified and effects determined. At an economic level, it can be envisaged that particular concern will lie with certain key receptors. For example, in marine environments key fishery groups and their food sources may be specific target receptors, whilst in terrestrial systems these may include humans and crop plants. However, such key receptor groups should not be seen in isolation because they will interact with other species within an ecosystem.

CO_2 leakage could also affect subsurface and surface biogeochemical processes by changing, for example, pH and possibly redox conditions. CO_2 mobilisation of trace metals is also a common geological process, albeit typically on long timescales and at slow rates. The potential for heavy metal mobilisation via leaking CO_2 has been proposed by several authors (e.g. Kharaka et al. 2006) though, as yet, little direct evidence from analogue systems has been obtained. It is also important to consider the impact of potential environmental impacts resulting from impurities (such as H_2S, SO_2 and NOx) that may be present in leaking CO_2. Such changes could have significant implications for groundwater quality in terms of acidification of supplies and possible dissolution of minerals and mobilisation of heavy metals. Little work has been undertaken in this area, although Onstott (2005) and Stenhouse et al. (2009)

have undertaken some preliminary modelling work. H_2S is a toxic gas and as such poses a hazard to humans and is closely regulated. H_2S, SOx and NOx could, if they were co-transported within a leaking CO_2 plume, alter pH and redox conditions in the soil environment, which could result in changes in nutrient supply, microbial and plant diversity and habitats (International Energy Agency – Greenhouse Gas Research and Development Programme (IEA-GHG) 2004).

2.3. Current Research

At the time of writing, several projects are underway to examine the environmental impacts of CO_2 leakage into both terrestrial and marine systems. CO2GeoNet is a European Network of Excellence (http://www.co2geonet.com. Accessed 27 April 2009) for geological storage of CO_2 involving 13 partners. Some of its research activities have focussed on studying the ecosystem responses to natural CO_2 leakages at sites in Italy and Germany (e.g. Beaubien et al. 2008, Krüger et al. 2009) and a generic system model is also being developed (described in the chapter by Maul (this volume) and in West et al. 2006). Field sites are also being developed to study impacts of CO_2 leakage on agricultural crops (Artificial Soil Gassing and Response Detection (ASGARD) site, Nottingham, UK - West et al. 2009; and see http://www.nottingham.ac.uk/geography/asgard/. Accessed 27 April 2009); and to test monitoring technologies and models (Zero Emission Research and Technology Center (ZERT) site, Montana, USA - Spangler et al. 2009; and see http://www.montana.edu/zert/index.html. Accessed 27 April 2009). Specific work is also being undertaken on the impacts of CO_2 leakage on marine systems by the Research Institute of Innovative Technology for the Earth (RITE), Japan with CO2GeoNet partners (Ishida et al. 2006) and by Plymouth Marine Laboratory (PML), UK (Turley et al. 2004). However, all these projects are in their early stages with only limited results currently available.

2.4. Gaps in knowledge

As detailed above, no explicit acknowledgement or guidance is available in any existing regulations on the release and environmental impacts of CO_2 from terrestrial and marine storage sites. Additionally:

- No indicator species for specific ecosystems have been identified. While to some extent ecosystems will be site specific, basic supporting research on generic processes is still needed to build confidence.
- No data on total ecosystem responses to a CO_2 leak and their recovery times are available.
- No specific data are available on the potential impacts on groundwater or surface water quality. Though the potential for CO_2 mobilisation of trace metals, other gases and hydrocarbons has long been recognised, little data have been generated.
- Co-transported and -injected species have received little attention so far but could include low to trace concentrations of O_2, SO_2, NO, H_2S, CO, Hg, Cd, Ar, N_2, H_2O, and NH_3. Hg and Cd are likely to be at ppb levels (Aspelund and Jordal 2007 and references therein). Many of these potentially co-injected gases (e.g. O_2, SO_2, H_2S) are biogeochemically important and could alter microbial populations either in the reservoir, or if released with CO_2, in the overburden and near surface environment. We are not aware of any research that has determined the fate of co-injected species during CO_2 storage.
- Few data exist on impacts on the soil environment from high concentrations of CO_2 emerging from depth.
- There is currently a lack of integration between considerations of potential impacts of CO_2 leaks on terrestrial and marine ecosystems and PAs. EIAs have traditionally been used to assess the impacts of engineering schemes over the lifetime of the project, which have included legacy issues such as site abandonment, clean-up, remediation and liability following the end of the project. However, CO_2 storage projects present new challenges because of the very long timescales that need to be considered after the injection project has finished, particularly when considering performance.

3. Geological disposal of radioactive waste

3.1. International regulatory background

Radioactive wastes comprise less than 1% of total industrial toxic wastes with a total arising of 81,000 $m^3\ yr^{-1}$ (~210 kt yr^{-1}) of conditioned wastes in the Organisation for Economic Cooperation and Development (OECD) countries (McGinnes 2007). The composition and characteristics of radioactive wastes vary and a recent summary of waste classes defined by the International Atomic Energy Agency (IAEA) is given in Table 2. In countries which use nuclear power, roughly 90% of the volume is LLW containing 1% of the total radioactivity, 7% is ILW with 4% of total radioactivity and 3% is HLW, containing 95% of the radioactivity (McGinnes 2007).

INSERT TABLE 2

3.2. Environmental impacts of radionuclides in radioactive wastes

Radioactive waste contains radioisotopes of a wide range of elements which will emit alpha, beta, gamma and neutron radiation. While minimal shielding will protect people and the environment from alpha and beta radiation, external exposure to high levels of gamma radiation or neutrons is harmful and can be fatal to some species, including humans. Internal exposure to alpha or beta radiation sources, for example through inhalation or ingestion, is also harmful at high levels and can be fatal in serious cases. Some radioactive elements are also chemically toxic. Additionally, some radioactive wastes also contain chemically toxic materials, such as lead from shielding but these are not considered further here.

The nature of radioactive elements means that their impacts on organisms are very complex. Moreover, interpretation of data is further complicated by the debate surrounding the relationship between radiation dose and subsequent biological impacts. As a result, it is not possible to produce a definitive summary of the impacts of radionuclides on organisms (as has been given for CO_2 in Table 1).

Radioactivity is easily measured and controversy exists as to whether it is harmful at low levels. Even in regions with naturally high background radiation (e.g. uranium ore deposits in Africa (Bowden and Shaw 2007) and Brazil (Chapman et al. 1992), it does not necessarily have any identifiable effect on the surface environment or local plant, animal or human populations. Following the Chernobyl accident in April 1986 a large amount of work has been undertaken in evaluating the environmental impact of the disaster including monitoring the response of the natural environment to radiation exposure (IAEA 2005). Within the 30 km exclusion zone, localised sites of acute adverse effects on animals and plants have been recorded in areas of higher radiological exposure. However, no adverse effects have been reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy absorbed dose during the first month following the accident (IAEA 2005).

In order to isolate higher activity radioactive waste from the environment, most waste management organisations are proposing geological disposal of these wastes in deep (greater than 200 m) repositories. Wastes will be conditioned and emplaced in engineered barrier systems designed to minimise radionuclide migration, within a suitable geological environment which will isolate the waste for an extended period of time. In most geological settings it is inevitable that there will eventually be some dispersion of the radionuclides from the repository, but this will be very slow and occur only in the distant future, when the hazard from the waste has been considerably reduced by radioactive decay. The processes in the engineered and geological barriers will reduce mobility of the majority of any radionuclides that 'escape' ensuring that only a small fraction will ever reach the near surface and surface environments. Additionally, their dispersion will ensure that they only contribute a small fraction to the doses received by plants and animals, including humans, when compared to doses received from natural radiation sources.

The IAEA specify that the annual dose to a member of the public from a closed geological repository in the future should not exceed 0.3 mSv (IAEA 2006). This compares to the global annual average effective dose from natural background radioactivity of 2.4 mSv (United Nations Committee on the Effects of Atomic Radiation (UNSCEAR) 2000). However, regulators in many countries require a target more stringent than 0.3 mSv. For example, for land-based disposal of radioactive waste, the UK environmental agencies have defined that the assessed radiological risk to an individual of developing a fatal cancer or a serious hereditary defect should be less than one-in-a-million per year (Environment Agency (EA) 2009). This compares to the 1 in 100,000 per year risk constraint suggested by the IAEA Safety Requirement of 0.3 mSv and the 1 in 1,000 to 1 in 10,000 as a result of exposure to natural background levels (2.23 mSv (Watson et al. 2005)) in the UK. Thus the accepted dose from a repository in the UK is between one hundred and one thousand times below the radiological risk to which members of the population are exposed as a result of natural background radiation levels.

Studies of natural and anthropogenic analogues provide information on the impacts of environmental exposure to radiation; how radionuclides behave over geological time scales; and an understanding of how the materials used in a radioactive waste repository are likely to perform in the long term. Examples of work include the impacts of exposed/near surface uranium mineralisation on the local habitat (Needles Eye, Scotland; Poços de Caldas, Brazil) (Miller et al. 2000) and the behaviour of reactor products in the geological environment produced by a natural reactor 2 billion years ago (Oklo, Gabon) (Miller et al. 2000). Such studies are important in helping to predict the future performance of a repository and also have a significant role in promoting confidence in the wider stakeholder community that a repository will provide the intended isolation of the waste.

3.3. Examples of current work

Significant effort has been directed over many years, particularly by national waste management programmes, into designing waste packaging and the engineering of a repository and its backfill to ensure optimum retention of the radionuclides within the repository; understanding the processes by which radionuclides may eventually be released from a repository and how they may migrate or be retained within the geosphere (Alexander and McKinley 2007). Extensive databases on their potential impact on reference plant and animal species and on humans in various uptake pathways have also been compiled (International Commission on Radiological Protection (ICRP) 2007).

Many studies are site specific, relating to particular waste types in defined geological environments. Other studies are generic and are aimed at understanding, for example, the processes that may be involved in radionuclide migration. Considerable experimental work is also being undertaken in several underground research facilities (including Äspö (Swedish Nuclear Fuel and Waste Management Company - SKB, Sweden), Bure (Agence nationale pour la gestion des déchets radioactifs - ANDRA, France), Grimsel and Mt Terri (National Cooperative for the Disposal of Radioactive Waste - NAGRA, Switzerland) and Mol (Belgian Nuclear Research Centre -

SCK•CEN, Belgium)) into how repositories in different rock types will perform during operational and post-closure phases. This is supported by extensive work on natural analogue systems (Miller et al. 2000). Examples of other recent work includes the palaeohydrogeological studies carried out under the European Union EURATOM funded EQUIP (‘Evidence from mineralogy and geochemistry for the evolution of groundwater systems during the Quaternary for use in radioactive waste repository safety assessment’) and PADAMOT (‘Palaeohydrogeological data analysis and model testing’) projects (Degnan and Bath 2005) that included mineralogical studies to elucidate the impacts of glaciations on groundwater systems. Ongoing research is examining the role that microbial activity, including biofilms, has in retarding or enhancing radionuclide migration through different geological environments (Coombs et al, 2009). The Large Scale Gas Injection Test (Lasgit) experiment in the Äspö Underground Research Laboratory (Harrington et al. 2007) is studying bentonite saturation and gas migration though the bentonite backfill of a full scale deposition hole.

3.4. Gaps in knowledge

Compared to CCS, radioactive waste disposal is a relatively mature science with a fifty year history (Parliamentary Office of Science and Technology (POST), 1997; McKinley et al. 2007). During this time significant advances have been made in understanding and assessing the long-term performance of a repository. Appropriate sites will be selected to allow radioactive wastes to be disposed of with confidence that the impacts on the near surface and surface environment will be minimal over very long time periods; in fact much more securely than we currently dispose of many other wastes, some of which are also highly toxic (Savage 1995). Radioactive waste disposal is also highly regulated, ensuring that it is undertaken safely and appropriately.

However, there are still some issues that are not fully understood and which additional research will clarify and permit more robust predictions to be made on repository behaviour and overall performance. For the purposes of this chapter, it is relevant to note that these include:

- Gas generation within a repository and its subsequent migration through the engineered systems and into and through the geological environment;

- Understanding the processes that may help to reduce the mobility of conservative isotopes, such as ^{14}C, in the repository and geological environments and thus mitigation to reduce their migration can be introduced;
- Further understanding of the processes of the migration of radionuclides at the interfaces between the repository and the surrounding geosphere (the rocks in which the repository is sited) and the geosphere and the biosphere (the plants and animals, including humans, in the near surface and surface environment).

4. Technology Comparison

Having described the environmental issues surrounding both technologies, it is now possible to make comparisons between them using the criteria outlined in the introductory section above. These are also summarised in Table 3.

INSERT TABLE 3

4.1. Characteristics of radioactive waste and CO_2

The nature, composition and volumes of the two wastes are very different, as detailed in previous sections, and thus are important considerations for environmental impacts. Radioactive waste is toxic at high concentrations and much is long-lived, with the highest activity material being so radioactive that heat generation is a real issue when considering handling, storage and disposal. Thus the appropriate management of waste is required to ensure the safety of workers, the general public and the surrounding environment because of the radiation emitted. However, not all radioactive waste has the same level of potential hazard to the environment and so classification of waste makes it easier to determine how they can be handled and helps to identify suitable disposal options (Table 2). Additionally, repositories often have individual limits for specific radionuclides which are defined as part of the licensing of facilities. Waste inventories are also very well defined. The production of radioactive wastes is not limited to nuclear power generation but is generated wherever radioisotopes are used (e.g. nuclear medicine, military applications, research). Additionally, the use of raw materials such as rocks, soils and minerals containing NORM in certain industrial activities can concentrate their natural radioactivity e.g. oil pipeline scales, soap manufacture from phosphate.

In comparison, CO_2 is a non-radioactive, naturally occurring gas, asphyxiating at higher concentrations, which is being emitted into the atmosphere in huge volumes. CO_2 waste streams from many sources, particularly power plants, will probably also contain impurities. There is considerable uncertainty in the estimates of volumes of these impurities although it is important to note that some, for example H_2S, are in themselves toxic. Thus, in contrast to radioactive waste, the specifications of some CO_2 streams have yet to be clearly defined.

4.2 Environmental impacts of radioactive waste and CO_2

Impacts from the disposal facilities

The relatively low volume of radioactive waste produced by the nuclear industry means that it can be managed and disposed of in relatively small, usually national facilities; and the understanding and regulation of environmental issues can be similarly constrained. Both surface and underground infrastructure will be required to ensure isolation of the wastes. In contrast, CO_2 storage facilities will be numerous and probably large-scale. Surface infrastructure will be needed for injection with associated transport facilities. Consequently, evaluating post-closure performance will be more diverse and challenging, particularly in terms of environmental issues.

For radioactive waste disposal, it is important to recognise that all repository designs use an engineered multi-barrier system approach and these barriers, in themselves, can alter the surrounding host rock environment. An example is the generation of a hyper-alkaline plume from a repository containing cementitious materials, which will alter the mineralogy and porosity of the surrounding rock. Because of radioactive decay, radioactive wastes become progressively less radioactive with time and, within a million years of its removal from a reactor, spent fuel is less radioactive than the uranium ore from which it was made (Chapman and Curtis 2006). If disposed of in a deep geological repository it is likely to be much more isolated from the near surface environment by the intervening strata and so have much less environmental impact than the original ore deposit, many of which lie near the surface. For vitrified HLW, which has had the potentially valuable long-lived uranium and plutonium removed by reprocessing, the reduction to natural uranium ore deposit levels of radioactivity is within a few thousand years (Chapman and Curtis 2006).

With the exception of the well completions, no engineered barriers will be used for CO_2 storage and, as a result, it is possible for the CO_2 to change the environment both chemically (alteration of groundwater conditions though CO_2/rock interactions) and, in extreme cases, physically. However, the degree of risk to the environment from CO_2 leakage from the geological environment will significantly reduce with time from the end of injections, as a combination of initially physical (such as residual trapping and pressure decreases) and subsequent chemical trapping mechanisms become more effective e.g. chemical reactions with minerals (Benson 2005; Intergovernmental Panel on Climate Change (IPCC) 2005).

Impacts of leakages on biological systems

Radiation, from whatever source, represents a potential danger to biological systems and hence to the environment. The actual danger from radioactive waste depends on many factors such as the nature of the radionuclides in the waste and the type and energy of the radiation emitted; its rate of exposure and the type, age and health of the receiving receptor (usually human). At high radiation exposures, death will occur within months or less; at moderate levels, radiation exposure increases the chance that an individual will develop cancer; at lower levels the cancer risk decreases although the relationship between cancer risk and the magnitude of exposure is unclear. In order to minimise and control these risks, national radiation protection agencies have issued rules with legal force on dose limitations and limits of intake of radioactivity as well as guidelines for working with radioactive substances. The International Commission on Radiological Protection (ICRP) regularly publishes recommendations and guidelines and is currently considering a framework for assessing the impact of ionising radiation on non-human species. In this framework the ICRP proposes the use of 'reference animals and plants' because there is now an increasing need to demonstrate, directly and explicitly, that the environment is being protected even under planned radiation exposure situations (see draft report at - www.icrp.org/draft_animals.asp. Accessed 27 April 2009).

Although it is an asphyxiant at high concentrations, CO_2 has a fundamental role in the global biogeochemical cycle which is well recognised. This chapter has identified some of the impacts of elevated CO_2 on the environment in the context of CO_2 storage. However, no equivalent of the ICRP exists and no guidance is currently available on the release and environmental impacts of CO_2 from terrestrial and marine storage sites. No 'reference animals and plants' have been identified and, indeed, little information is available on total ecosystem responses to a CO_2 leak and their recovery times. Consequently, the scientific understanding of the environmental impacts of CO_2 leaking from a storage site, which is needed to assist in the development of regulatory guidelines, is not yet fully understood.

4.3 Assessment of the hazards arising from radioactive waste and CO_2

Radioactive waste inventories vary and, consequently, so does the radiological hazard and the duration of that hazard. Thus any particular repository design will need to reflect the nature of the radioactive wastes to be emplaced, and the associated hazard. For example, waste will be emplaced in a matrix which will provide a stable waste form that is resistant to leaching and gives slow rates of radionuclide release for the long-term. This will be decades for less hazardous LLW but will need to be up to hundreds of thousands of years for very hazardous HLW. In contrast, although CO_2 could be mixed with impurities on injection, it is only hazardous in high concentrations. However, this hazard will remain constant at higher concentrations.

The risks of leakage of CO_2 from a geological storage site to the environment can be classified as either global or local. Global risks involve the release of CO_2 that may contribute significantly to climate change if there is a large leakage from a geological formation into the atmosphere – although this risk should be compared to that arising if there is no storage. This risk, although low, is higher during the injection phase when reservoir pressures are highest. With regard to local risks, these include sudden and rapid CO_2 leakage from an injection well or from abandoned wells; or gradual leakages through undetected faults, fractures, caprock or leaking wells. Risks of this type of leakage are higher early post-closure before other trapping mechanisms reduce the mass of buoyant CO_2. Consequently, much emphasis is placed on assessing post-injection performance, before formal closure. Leakage from a post-closure radioactive waste repository would also be a local risk to the environment and would include unpredicted failure of the engineered barriers coupled with subsequent migration of radionuclides through the host rock. While unlikely, much work has been undertaken to evaluate and manage risk of leakages from radioactive waste repositories using low probability/high consequence scenarios, particularly in the context of PA and the repository 'safety case'; and a similar holistic system model approach is now being proposed for CO_2 (described in the chapter by Maul (this volume)).

4.4. Monitoring environmental impacts

Monitoring is an important aspect of the development and operation for both technologies and will also provide confidence in successful containment of the wastes Stenhouse and Savage 2004). It will be important to obtain baseline information on the undisturbed site and, for environmental impacts, it will be crucial to obtain near-surface and surface data using a variety of ecological, chemical and physical parameters. Subsequent operational and post-injection monitoring data can then provide meaningful inputs to assessments. It is unlikely that there will be radionuclide releases from a repository soon after closure because of the engineered barrier system so surface monitoring will be relatively unimportant and is dependent on regulatory requirements. However, the integrity of the geological containment of CO_2 may be tested soon after closure because there are no engineered barriers in place, as is the case for a radioactive waste repository. A range of standard protocols would be needed to undertake effective environmental monitoring for CO_2 and these are currently being developed. Environmental monitoring is likely to become less important with time as retention processes become more important. However, the decision on when to cease monitoring of any kind will be one that can only be made when the necessary regulatory framework is in place.

5. Conclusions

Given the discussions and comparisons above, several key points emerge which can be summarised in two general areas: Science and Policy.

5.1. Science

Both CO_2 and radioactive waste can be hazardous to a wide range of organisms although their effects on life processes are very different. Much is known about radiological effects on organisms. In contrast, little is known about the effects of CO_2

leakages from a storage site on ecosystems and subsurface environments and this is currently an active area of research.

The volume of radioactive waste is very small when compared to CO_2 emissions from stationary sources. Consequently, the numbers and relative sizes of radioactive waste repositories and CO_2 storage sites will be very different. Moreover, this means that radioactive waste management and disposal can be tightly constrained. Additionally, repositories are usually considered as national facilities whereas CO_2 storage projects are often considered to be regional in nature. Currently, most CO_2 emissions from stationary sources are directly into the atmosphere with no management – effectively this means that there is 100% leakage. If CCS is to be a successful mitigation technology, then it will be crucial to demonstrate that the environmental impacts of the technology, particularly in the long-term, are acceptable when compared to those of global warming.

Radioactive waste repositories use an engineered multi-barrier approach for containment and these barriers can alter the environment. In contrast, CO_2 storage relies on the integrity of the geological environment for containment and this is likely to be tested early post-closure. Additionally, the CO_2 itself will also alter the geological environment. Consequently, it will be important to develop protocols for monitoring environmental changes as a result of CO_2 leakage. Methods will be needed for monitoring the shallow subsurface, ecosystems and reference organisms.

Much work has been undertaken to evaluate and manage risk of leakages from radioactive waste repositories, particularly in the context of PA and the repository ‘safety case’ and much can be learned from this considerable experience. A similar system model approach is now being proposed for CO_2 (described in the chapter by Maul (this volume)). This will help to ensure a systematic approach to assessing environmental impacts for any CO_2 storage site.

5.2 Policy

The criteria that a radioactive repository must satisfy for long-term, post-closure safety are very well defined internationally. Currently, no similar specific regulatory framework for geological CO_2 storage is in place (described in the chapter by Wilson and Bergan (this volume)) although it is recognised that leakages to the environment must be addressed. Currently, most EIAs for existing CO_2 storage projects under existing oil and gas regulations have focused on the operational period, but it is increasingly recognised that long-term performance will form a critical component when assessing potential environmental impacts and site liability issues. Although the two technologies are different, an examination of the approaches used for regulating radioactive waste repositories could be very useful for the development of the CO_2 storage regulatory framework.

Regulators will also require information on impacts of CO_2 on 'yet to be defined' reference organisms in order to establish appropriate threshold and safety criteria. Recovery rates will also need to be defined. Additionally, the impacts on groundwaters will need to be assessed.

In conclusion, it is worth noting that many countries around the world continue to face difficulties with implementing programmes for geological disposal of radioactive waste. Technically speaking, although geological disposal is well understood and regulated, the general public has concerns and fears about the long-term safety of a repository which focus on the effects of leaks on human health and the environment. Clearly without addressing these concerns, the implementation of waste disposal programmes will continue to flounder and this is now being recognised by the nuclear industry. Recent studies of the public's perception of CCS have revealed the same concerns about the effects of leakages of CO_2 from a storage site on the environment (as described in the chapter by Reiner and Nuttall (this volume) and by Shackley et al. 2004). The radioactive waste disposal experience strongly suggests that it is crucial that these perceived CO_2 leakage concerns are addressed if the technology is to gain public acceptance and be successfully implemented.

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Table 1. Examples of tolerances to CO_2 exposure in selected organisms (from West et al. 2005)

	Exposure	**Effect**	**Reference**
Humans (Healthy adults)	Below 3%	No adverse effects but increased breathing, mild headache and sweating	Hepple 2005
	4-5% for 'few minutes'	Headache, increased blood pressure and difficulty in breathing	
	7-10% up to 1 hour	Headache, dizziness, sweating, rapid breathing and near or full unconsciousness	
	15%+	Loss of consciousness in less than one minute. Narcosis, respiratory arrest, convulsions, coma and death	
	30%	Death in few minutes	
Terrestrial Invertebrates	Insect (Rusty Grain beetle - *Cryptolestes ferrugineus*)		Mann et al. 1999
	15%	Death after ~ 42 days	
	100%	Death after ~2 days	
	40%	Used to preserve food from microbes and fungi	Benson et al. 2002
	Soil invertebrates		
	20%	Majority of any one species have 'behavioural changes'	Sustr and Siemk 1996
	11-50%	Lethal for 50% of species	
Terrestrial Vertebrates	Rodents 2% Gophers 4% Birds 9%	Observed in burrows and nests	References in Maina 1998
Plants	>0.2%	Stimulation of C3 photosynthesis plants (includes temperate cereal crops such as wheat)	Hepple 2005
	15-40%	Acid tolerant grasses dominate pasture. Few dicotyledonous plants.	Beaubien et al. 2008
	Trees, Mammoth Mountain, USA 20-90%	Tree killed probably by suppression of root zone respiration via hypoxia	Hepple 2005
Fungi	15-20%	Significant inhibition of growth of spores for 2 types of fungi	Haasum and Nielsen 1996
	30%	No measurable growth of spores	Tian et al. 2001
	50%	No germination of spores	
Subsurface microbes	None known	Increased concentrations (from injection) are likely to have profound effects because aerobic organisms will be inhibited but anaerobic organisms e.g. Fe (III) reducers, S reducing reducers and methanogens will respond to rock/water/carbon dioxide interactions and are likely to increase in population size and activity	Onstott 2005 (Discussion paper)
Marine invertebrates	Commercial shellfish	Few data specifically on carbon dioxide effects. The little evidence is limited to effect of pH change on e.g. shells.	Turley et al. 2004; Senter for Miljo-Og Ressursstudier (SMR) 1999
Marine Vertebrates	Fish	More sensitive to hypoxia than invertebrates. Mostly unknown effects on reproduction/development	Turley et al. 2004

Table 2. Details of radioactive waste classes by the IAEA (from McGinnes, 2007)

Waste Class	Typical characteristics	Possible disposal options
Exempt waste (EW)	Activity levels at or below clearance levels	No radiological restrictions, normal landfill
Short-lived (L/ILW-SL)	Restricted long-lived radionulide concentrations, e.g. long-lived α-emitters average <400 Bq/g or 4000 Bq/g maximum per package	Near-surface or geological repository
Long-lived (L/ILW-LL)	Long-lived radionuclide concentrations exceeding limitations for short-lived wastes	Geological disposal facility
High-level waste (HLW)*	Thermal power greater than about 2 kW/m^3 and long-lived radionuclide concentrations exceeding limitations for short-lived wastes	Geological disposal facility

*If spent fuel is considered a waste then this falls into this class

Table 3. Comparison of the environmental issues relevant to the geological disposal of CO_2 and radioactive waste (post-emplacement)

Comparison criteria	**Geological storage of CO_2**	**Geological disposal of radioactive waste**
Characteristics	Large volume/mass (emissions from fossil fuels 23.5 Gt CO_2 yr^{-1} (2001)). Naturally occurring gas. Not radioactive. Asphyxiant at high concentrations. Waste streams may contain other impurities; uncertainty in estimates of volumes of impurities.	Small volume/mass (81,000 m^3 yr^{-1} or ~ 210 kt yr^{-1} conditioned wastes in OECD countries). Radioactive but some isotopes not found in nature. Toxic at high concentrations. Some low concentrations have health hazard. Generally a very complex composition. Inventories are usually very well-defined.
Environmental impacts	Many sites needed (potentially large area, kms depth). Mostly surface infrastructure Depends entirely on geological isolation. CO_2 will be able to alter the geological environment. Small research database on the impacts of CO_2 leakages from storage sites. No regulatory framework currently exists.	Few sites needed (small area, 1km depth). Surface & underground infrastructure. Geological isolation critical but complemented by engineered barriers. Repository barriers and gases from degradation of waste and barriers will be able to alter the geological environment. Large research database on impacts on biological systems (particularly humans). Exposure and dose limitations are highly regulated.
Assessment of hazards	Hazard as long as concentrated. Containment using geological environment only. Likely to be tested early post-closure. Post-closure, leakage could occur through caprock, undetected faults, fractures, abandoned, leaking wells. Risk of leakage will decrease with time because trapping mechanisms become more efficient. Emphasis on expected post-injection performance.	Hazard as long as concentrated but decreases with time due to radioactive decay. Repository design tailored to waste type and will involve an engineered multi-barrier approach. Post-closure, leakage could result if both the engineered barriers and geological environment failed. Emphasis on low probability, high consequence scenarios over long term.
Monitoring environmental impacts	Baseline environmental information needed from undisturbed site. Monitoring high profile in safety case. Range of monitoring requirements is	Baseline environmental information needed from undisturbed site. Monitoring, if any, depends on regulatory requirements (not in safety case).

	being refined. Duration of monitoring requires regulatory framework.	Technical background on monitoring available.