Environmental Issues and the Geological Storage of CO_2 –

A discussion document

(Short Title – Environmental issues and geological storage of CO_2)

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Abstract

Increasing CO_2 emissions will lead to climate change and ocean acidification with severe consequences for ecosystems and for human society. Strategies are being sought to reduce emissions including the geological storage of CO_2. Existing studies operate within existing oil and gas regulatory frameworks, but if other non-oil reservoir geological formations are used these existing regulations may not apply. At national and European levels the potential environmental impacts of uncontrolled CO_2 releases from storage sites have been highlighted to be of significance for regulators. Thus a new regulatory framework may be needed. The precautionary principle is likely to be adopted by regulators, so it is important that the effects of acute and chronic exposures of ecosystems to CO_2 leakages are evaluated. Consequently, existing regulations are likely to be developed to include specific recommendations concerning leakages. This review shows that much basic data simply do not exist to assist regulators in this process.

Key words: Carbon dioxide, Geological storage, Ecosystems, Environment, Regulators,

Introduction

It is now widely recognised that increasing CO_2 emissions will lead to anthropogenic climate change and ocean acidification, which would have severe consequences for ecosystems and for sustainability of human society (International Panel on Climate Change (IPCC Third Assessment Report)). However, most economies are heavily dependent on the CO_2-emitting use of fossil fuels and worldwide strategies are now being sought to reduce such emissions. One potential technology is the geological storage of CO_2 (Holloway et al, 1997). The European Emissions Trading Scheme recognises that geological storage could be a valid mitigation option and the IPCC also recognises that CO_2 storage may be a viable option for bridging the gap to a more diverse energy economy (eg through generation of hydrogen from fossil fuels/biomass, renewables etc).

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 focussed on technological and economic viability, and whether 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 all 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 apply, especially in Europe. At national, European (Energy outlook to 2020) and international level (IPCC TAR) the potential environmental impacts of uncontrolled CO_2 releases have been highlighted to be of particular significance for regulators. Thus a new regulatory framework may be needed. The development of these regulations will involve national and European bodies, and will take account of current international and European legislation and its national implementation. Additionally, studies on public perception of CCS (Shackley, 2004) consistently indicate concerns about the effect of leakages on the environment.

It can be assumed that storage sites would be selected to minimise the potential for leakage. However, if leakages from storage sites did occur, they could be over small areas from discrete point sources, such as abandoned wells and, consequently, they could result in high concentrations of CO_2 - this could reach tens of percent levels in soil gas, well above any background levels. Uncontrolled leakages would have widespread implications for the environment. In economic terms, leaks into marine and freshwater systems might affect fisheries. 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 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 550ppm), levels of CO_2 in soils resulting from CO_2 leaks from engineered CO_2 storage sites underground could be several orders of magnitude above atmospheric levels. It is also important to consider the importance of potential environmental impacts resulting from impurities (such as H_2S, SO_2 and NO_x) that may be present in leaking CO_2. Thus the potential effects of such leakages ought to be evaluated both to provide information for a developing regulatory framework and to provide input into the development of a safety case methodology necessary to build confidence in the decision-making.

This paper seeks to give a brief overview of existing data on the potential effects of leakages, particularly of CO_2, on ecosystems. It attempts to identify the gaps that should be addressed to inform stakeholders particularly in the European context. Leakage is here defined as the transfer of CO_2 back to the readily accessible near-surface, surface and atmosphere following injection into a deep geological reservoir.

The Regulatory Context for Geological Storage

Although a detailed and specific regulatory framework for CCS (e.g. Stenhouse et al, 2004), and indeed the interpretation of existing international environmental law, is currently under discussion at national and regional (European) levels, it is worth noting that any regulations will have to fit within pre-existing broader regulatory frameworks. Internationally, the most important regulation for offshore geological storage is the broad framework of the United Nations Convention on the Law of the Sea, which provides the “global rules and standards” that subsequent, more detailed regional and national laws are based upon. The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972) and its later 1996 Protocol, known as the ‘London Convention’, provide a clear definition of the implementation of the principles set out in the UN Law of the Sea. At the regional level, the OSPAR Convention is the regional agreement of Western European signatories which, although similar to the Law of the Sea and the London Convention, is wider in scope and includes additional forms of waste.

In practice, the OSPAR Convention takes precedence over the London Convention and the UN Law of the Sea for Contracting Parties. In contrast, however, to the Law of the Sea and partly to the London Convention, the OSPAR Convention specifically and explicitly provides legally binding status to the precautionary principle and the polluter pays principle:

OSPAR Convention Article 2(2)a "*the precautionary principle, by virtue of which preventive measures are to be taken when there are reasonable grounds for concern that substances or energy introduced, directly or indirectly, into the marine environment may bring about hazards to human health, harm living resources and marine ecosystems, damage amenities or interfere with other legitimate uses of the sea, even when there is no conclusive evidence of a causal relationship between the inputs and the effects;*"

The OSPAR Convention's approach to the precautionary principle is proactive and positively requires preventative measures to be taken when there is reasonable apprehension of a hazard. In addition the possibility of damage does not have to be serious or irreversible:

"Article 3 of the 1996 Protocol states that in implementing this protocol, contracting parties shall apply a precautionary approach to environmental protection from dumping of wastes or other matter whereby appropriate preventative measures are taken where there is reason to believe that wastes or other matter introduced into the marine environment are

likely to cause harm even where there is no conclusive evidence to prove a causal relation between inputs and their harm effects." (Purdy and Macrory, 2003)

This paper is primarily concerned with identifying the information/knowledge needs of regulators for CCS and assumes that, as recent discussions have implied (e.g. OSPAR meeting, Trondheim, October 2004), it will be shown that geological storage offshore is sufficiently safe (through national/European safety cases) that the application of the precautionary principle will allow it to take place under the OSPAR Convention. Nevertheless, the application of the precautionary principle, among other European directives, will still require a demonstration of the safety of geological storage at a given site. Hence, unless it can be shown that CO_2 will not leak from the reservoir, or if it did, that the potential impacts would be tolerable, the application of the precautionary principle would prohibit CCS under the OSPAR Convention.

CO_2 is not explicitly listed as a waste in the London Convention (Purdy and Macrory, 2003). The question of whether CO_2 should be considered to be a waste has recently been debated among consultative parties to both the London and OSPAR Conventions, but no consensus was reached. The group of Jurist and Linguists of the OSPAR Commission evaluated the placement of CO_2 in the maritime area. They concluded that the placement of land-derived CO_2 via pipelines, in formations deep below the seabed, for the purposes of enhanced hydrocarbon recovery or for mitigating climate change, are not prohibited by the OPSAR Convention, though subject to strict authorisation or regulation (OSPAR 04/23/1-E, Annex 12). The exceptions to this are if CO_2 were to be defined as an industrial waste, geological storage via an offshore installation, vessel or from a structure in the maritime area that is neither part of a pipeline system nor an offshore installation (classified as ‘dumping’), would be prohibited. The interpretation of the legality, or otherwise, of the various methods of transporting and injecting CO_2 in deep geological structures below the seabed remains open and the Biodiversity Committee is currently considering how CCS relates to the OSPAR convention.

In Europe, several additional laws, known as ‘Directives’, provide a further regulatory framework for storage projects (inter alia):

- the Environmental Impact Assessment (85/337/EEC, subsequently amended by 97/11/EC)
- Strategic Environmental Assessment directives (2001/42/EC)
- the Environmental Liability Directive (2004/35/EC) which came into force on April 21, 2004 and must be implemented by member states by 2007
- the Directive establishing a framework for Community action in the field of water policy – the water directive (2000/60/EC). Some aspects of this directive may be pertinent to geological storage
- The Directive on the conservation of natural habitats and of wild fauna and flora (92/43/EEC).

The Environmental Impact Assessment (EIA) requires that the environmental consequences of projects are assessed before authorisation is given. CCS projects are not explicitly referred to in the EIA directive, although it can be argued that they would be included in ‘Annex II’ projects, because of their size, location and potential impacts. If an EIA is required, the statement should include information on the direct and indirect effects of a project on a variety of factors, including human beings, fauna, flora and the environment.

The Strategic Environmental Assessment (SEA) Directive, requires authorities preparing any plan or programme, to evaluate the potential environmental impacts at an earlier and broader, strategic level. This may be considered as providing the legal requirement of a national or European ‘safety case’, as has been published for several national radioactive waste programmes. This Directive came into force in 2001 and is mandatory for governments. Sweden has now implemented the Directive and the UK government is undertaking SEAs in a number of related industries (e.g. hydrocarbon exploration and production).

The Environmental Liability Directive defines the remit and nature of liabilities for operators under the ‘polluter pays’ principle. Offshore and coastal marine habitats, as defined in the ‘Water’ and ‘Habitats’ directives, are included.

The UK government has also ratified several international conventions that protect habitats:

- the Biodiversity Convention (1992);
- the Jakarta Mandate on Marine and Coastal Biological Diversity;
- the Bergen Ministerial Convention (concerned with balancing uses and conservation in the North Sea);
- Annex V of the OSPAR Convention addresses protection of marine biodiversity and ecosystems.

These imply that the potential impacts of geological storage on the marine environment will need to be assessed. In addition the European Habitats Directive requires identification of habitats and species that should be preserved and restored.

Effects of CO_2 leakages on the environment

Concentrations and fluxes of CO_2 in natural 'baseline' environments and in sites where CO_2 leakages are occurring naturally vary over a wide range, as shown in Table 1. The fluxes quoted are, however, difficult to compare because a spatial term of reference is often not given (e.g. 4.2×10^9 mol y^{-1} for the 'Albani Hills' (Chiodini and Frondii, 2001)). Nevertheless, concentrations can vary, for example, from <0.1% to ~95% of the total gas in soils and up to 95% CO_2 of the total gas from natural marine seepages. The high concentrations are generally associated with point sources (e.g. volcanic areas). It is difficult to compare these concentrations and fluxes with those that could arise from a CO_2 storage site. However, risk studies for land-based sites have estimated a cumulative probability of a leak from a reservoir over a 1000 year design lifetime of 0.34 (i.e. 34% probability of one leak in 1000 years) with the average size being 0.2% of the amount stored (Turley et al, 2004 based on DNV analysis). For the calculated storage capacity for the oil and gas fields in the entire North Sea of 30Gt of CO_2 (Chadwick et al. 2004), a 0.2% leakage would give a loss of 6×10^7 t CO_2 (60 Mt) over 1000 y (6×10^4 y^{-1}). With a cumulative probability of 34%, approximately 20 Mt of CO_2 potentially could be leaked over 1000 years. However, extreme caution should be given to these estimates as the magnitude of leakages and the likelihood of their occurrence will be site-specific. There is clearly a need for more research before profiles for geological reservoirs can be more realistically evaluated.

Although extensive physiological research is available, the environmental impacts of elevated CO_2 (whether through slow or catastrophic release) on terrestrial, subsurface and marine ecosystems are poorly understood. 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 including physiology, food preservation and botany, and some examples are given in Table 2. 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. Plant responses near natural springs (e.g. Raschi et al, 1997) and at Mammoth Mountain in USA (Hepple, 2004) have been examined but there are very few studies on entire ecosystems with long-term exposure to chronic CO_2 concentrations (below about 10%). There are no known studies on the effects of elevated CO_2 on subsurface microbial populations. In marine environments, experiments have been attempted to examine chronic exposure of CO_2 on deep-sea organisms (e.g. Shirayama, 1997; 2002). Yamada and Ikeda (1999) also indicate that tolerance to pH can vary in the pelagic stages of some species. Additionally, it is recognised that pH changes caused by increased CO_2 concentrations will have effects on calcifying organisms such as coccolithophores and corals, but it is not clear how this will influence the overall ecosystem (Turley et al. 2004). Studies on human volunteers exist and the medical consequences of exposure are well documented, although it should be noted that only healthy subjects were used. However, once again, no long-term epidemiological studies have been carried out to study the effects of long-term chronic exposure to CO_2 on large populations.

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. Thus for all ecosystems of interest, the potential indicator groups at the different trophic levels need to be identified and effects determined. It is likely 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 as they will interact with other species within an ecosystem and these may be more or less tolerant to CO_2 exposure.

Summary of Gaps in information

This paper has highlighted the gaps in information necessary to assess the potential impacts of CO_2 leakages on marine, terrestrial and subsurface ecosystems. These can be summarised as follows:

1. There appears to be no explicit acknowledgement or guidance in existing European and UK habitat and water regulations on the release of CO_2 from storage sites. No target species are identified and no limits at which any

species becomes intolerant to CO_2 are given. No environmental criteria for CCS have been defined. These will be needed in risk assessments and environmental impact assessments.

2. There are no data on long term, low-level exposure of CO_2 on any marine, terrestrial or subsurface ecosystem and few on any single or potential target species. There are no data on recovery rates following exposure to chronic or acute exposure to CO_2 leakages.
3. Tools to monitor impacts on target organisms in all environments need to be developed. These tools need to be pervasive and responsive to changes in ecosystems. They should also be tailored to the different challenges to be found in marine, terrestrial and subsurface environments.
4. Marine environments are likely to be a top priority in North Western Europe and information from key commercial fisheries is particularly crucial. Other key indicator species will need to be identified.
5. Confidence in risk assessments will be increased if biogeochemical processes and their effects can be satisfactorily represented.

Ways forward

To date, most CCS projects have operated within existing oil and gas regulatory frameworks, which may not apply if other non-hydrocarbon and associated reservoir geological formations are used. Thus a new regulatory framework may be needed and at national, European and international levels the potential environmental impacts of uncontrolled CO_2 leakages have been highlighted to be of particular concern to regulators. Existing regulations are likely to be developed and altered to include specific recommendations concerning leakages and it is clear from this review that much basic data simply do not exist to assist regulators in this process. The precautionary principle is likely to be adopted by regulators, so it is important that the effects of both acute and chronic exposures of CO_2 leakages are evaluated on ecosystems. This can be achieved by adopting two approaches:

1. Total environmental response evaluations using existing natural leakages to investigate responses;
2. Controlled long-term exposure experiments using key terrestrial and marine functional species. This would include organisms from different trophic levels including crop plants and commercial fish.

Such knowledge will provide CO_2 limits for regulators, provide information on recovery rates of organisms to chronic exposure and help to refine risk assessments. They will also help to develop and determine the most effective tools and methods to determine and assess ecosystem changes for future CCS sites.

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Table 1. Some examples of carbon dioxide concentrations and fluxes in natural environments.

Baseline levels	**CO_2 source**		**Concentrations**	**Fluxes**	**References**
Soils	Biogenic	Weyburn, Canada	0.5 –9% CO_2	0.2 – 48 g m^{-2} d^{-1} (over site)	Strutt et al, 2002
		Mammoth Mountain, USA	<0.1%		McGee and Gerlach, 1988; Rogie et al, 2001
Marine sediments	Volcanic	Mid ocean ridges		Total of 0.63-1.26×10^{12} mol y^{-1}	Turley et al, 2004
Atmosphere	Natural and anthropogenic		316 ppmv in 1959 376 ppmv in 2003	Annual increase of 2-3 ppmv y^{-1}	Keeling and Whorf, 2004
Naturally leaking CO_2 sites					
Groundwater	Volcanic	Crystal Geyser, Utah, USA	3.6g l^{-1} of water	Up to 360 g per eruption (50 – 100m^3 water per eruption)	Shipton et al, 2004
		Albani Hills, Italy		Total value of 4.2×10^9 mol y^{-1}	Chiodini and Frondii, 2001
		Montmiral, France	30-70% in deep waters(~2500m)		Pearce et al, 2004
Soils	Volcanic	Latera, Italy	Up to 98% dissolved in springs		Pearce et al, 2004
		Albani Hills, Italy	Up to 95%	6.1×10^8 mol CO_2 y^{-1}	Chiodini and Frondii, 2001
		Matraderecske, Hungary	20-90%	5 to 10 l m^{-2} h^{-1} but can reach 400 l m^{-2} h^{-1}	Pearce et al, 2004
		Horseshoe Lake, Mammoth Mountain Tree kill area		Total discharges in tree kill areas 50-150 tonnes CO_2 per day	www.lvo.wr.usgs.gov website
Lakes		Lake Nyos, Cameroon	Deep waters 60% saturation	20 Ml y^{-1}	Jones, 2001
Marine leaks	Volcanic	Hellenic Volcanic Arc, Mediterranean Sea	95% of total gas	0.2-0.8x10 mol y^{-1} (Milos submarine hydrothermal system)	Turley et al, 2004
Predicted scenarios					
Modelling potential escape routes from Forties Field, North Sea		Worst case prediction 37% of original CO_2 migrates in 1000 y	Migrates to 350 m above reservoir. No migration to surface		Cawley et al, 2004

Table 2. Examples of tolerances to CO_2 exposure in selected target organisms

	Exposure	**Effect**	**Reference**
Humans (Healthy adults)	Below 3%	No adverse effects but increased breathing, mild headache and sweating	Hepple, 2004
	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	
	Soil invertebrates		
	20%	Majority of any one species have 'behavioural changes'	Sutr 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	Trees, Mammoth Mountain, USA 20-90%	Tree killed probably by suppression of root zone respiration via hypoxia	Hepple, 2004
Fungi	15-20%	Significant inhibition of growth of spores for 2 types of fungi	Haasum and Nielsen, 1996; Tian et al, 2001
	30%	No measurable growth of spores	
	50%	No germination of spores	
Subsurface microbes	None known	Increased concentrations (from injection) are likely to have profound effects as aerobic organisms will be inhibited but anaerobic organisms eg 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, 2004 (Discussion paper)
Marine invertebrates	Commercial shellfish	Few data specifically on carbon dioxide effects. The little evidence is limited to effect of pH change	Turley et al, 2004 SMR, 1999
Marine Vertebrates	Fish	More sensitive to hypoxia than invertebrates. Mostly unknown effects on reproduction and development	Turley et al, 2004