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Carbon Capture and Storage Technology

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Executive Summary

1. If geological storage of carbon dioxide is to make a significant contribution to the mitigation of anthropogenic emissions of carbon dioxide, potential impacts upon human health and the environment associated with this technology must be within acceptable limits.
2. Pressure-temperature-time considerations indicate that CO_2 initially stored as a supercritical phase in the geosphere will tend in the long-term[MJE1] (> 1 000 years) to be dissolved in formation fluids or physically trapped in carbonate minerals.
3. The large amounts of CO_2 (Tt worldwide) that will need to be stored geologically in order to affect climate change imply that some degree of leakage is inevitable. CO_2 migration back to the biosphere is likely to occur via both ‘natural’ and ‘anthropogenic’ pathways. Leakage rates in the order of 0.01 % per year are acceptable from climate change perspectives, but these rates may be large with regard to possible concerns regarding ‘local’ impacts upon human health and the environment. They therefore need to be assessed quantitatively.
4. Assessment models are currently at an early stage of development, but most follow approaches based upon an understanding of the storage system constructed through an analysis of relevant features, events and processes (‘FEPs’), the

development of scenarios to represent the evolution of the system, and calculations of potential impacts using mathematical models to represent key processes.

5. Currently-available assessment models have not been purpose-designed and most rely on commercial 'reservoir simulator' software (normally used to understand hydrocarbon behaviour in a reservoir). However, these models do not address all aspects of the storage system necessary for a complete assessment of safety/performance (such as long-term evolution of the geological system), so that targeted funding is required to develop a new generation of assessment software.
6. Identification of the most important CO_2 migration processes will depend upon the details of the storage system and the relevant timescales for the assessment, which may be many thousands of years. Because of these long assessment timescales, information from natural systems (in addition to those from demonstration storage projects) will be essential to enable these processes to be represented realistically.
7. Natural systems provide evidence that the nature of releases to the accessible environment could be more important than the magnitude; adverse impacts can occur where unusual concentrations mechanisms are present.
8. An appropriate regulatory regime needs to be established in parallel with the development of a capability of performing long-term safety assessments of the geological storage of CO_2. This regime should be developed through dialogue between storage site developers and regulatory bodies, taking full account of any concerns from the general public attached to the development of this technology.

Evidence

1. The feasibility of the geological storage of CO_2 depends on a number of factors. Firstly, the volumes available for geological storage must be sufficient to enable a significant reduction to be made in discharges of CO_2 to the atmosphere, and hence to make a significant contribution to reducing anthropogenic climate change. Secondly, capture and storage technologies need to be cost-effective.

Thirdly, the geological system to isolate the CO_2 from the atmosphere should be effective over a suitably long timescale. Lastly, potential impacts on human health and the environment from these technologies must be within acceptable limits.

2. The quantities of CO_2 that would need to be stored geologically in order to make a significant contribution to mitigating anthropogenic climate change are large. Worldwide, these quantities may be in the order of 100's to 1000's of gigatonnes (Hepple and Benson, 2003). The European Commission Joule II review (Holloway, 1996) concluded that it was possible to store 800 Gt CO_2 in geological formations beneath the North Sea, i.e. several hundred years of emissions from power generation in northern Europe at 1990 levels. Such large quantities of CO_2 inevitably pose significant potential for leakage to the surface.
3. Some concepts for CO_2 storage involve injection into geological structures that are known to have contained hydrocarbons for geological time periods. The isolation of CO_2 for such lengths of time can perhaps be expected with greater confidence in such structures than those without hydrocarbon accumulations. Volumetrically, however, oil and gas fields constitute only 3 % of the potential CO_2 storage volume beneath the North Sea (Holloway, 1996). Storage of CO_2 in the volumetrically more important 'saline aquifers' may involve greater uncertainty in terms of the guarantee of long-term isolation, due to a lack of basic geological information about these formations, particularly offshore.
4. Geological storage of CO_2 is most likely to take place in major provinces for oil and gas exploration and production, e.g. the North Sea. Given the number of pre-existing boreholes in these provinces, and the likelihood of degradation of borehole seals and future human intrusion, complete avoidance of leakage of any stored carbon dioxide over long timescales is probably unavoidable (Celia and Bachu, 2003). CO_2 migration back to the biosphere is likely to occur via both 'natural' and 'anthropogenic' (e.g. through boreholes) pathways.
5. Pressure-temperature-time considerations indicate that CO_2 initially stored as a supercritical phase in the geosphere will tend in the long-term (> 1 000 years) to be dissolved in formation fluids or physically trapped in carbonate minerals.

Eventually, migration of CO_2 may occur, either laterally and up-dip within the reservoir formation itself, or vertically through confining sealing formations. Driving forces include diffusion, buoyancy, and regional hydraulic gradients. Pathways may consist of more permeable strata, or fractures and faults. Dissolved CO_2 may also be transported towards the surface dissolved in groundwater, which may result in a change of phase behaviour, with possible gas ebullition as pressures decrease.

6. Regarding climate change mitigation, a maximum leakage rate of approximately 0.001 – 0.01 % per annum of stored CO_2 per annum has been suggested as being acceptable, taking into account possible scenarios for future CO_2 emissions through fossil fuel usage (Hepple and Benson, 2003; Pacala, 2003; Hawkins, 2003). A leakage rate of 0.01 % would ensure that 90 % of the carbon dioxide would remain underground over a 1000 year time period (Hepple and Benson, 2003). Leakage rates of 1 % imply that most of any stored carbon dioxide would return to the atmosphere after only 400 years (Hepple and Benson, 2003).
7. A 0.01 % annual leakage rate from 5000 Gt CO_2 stored worldwide in geological reservoirs would thus be 0.5 Gt CO_2 per year, which is considerably greater than the total annual volcanic emissions of CO_2 (0.15 Gt CO_2 per year – Benson et al., 2002). Leakage rates that are acceptable from a climate change perspective are thus relatively large. This implies that the possible effects of leakage on the 'local' scale will be more important than the global-scale. This in turn emphasises the need for the quantification of potential impacts and risks.
8. Implicit in the acceptance of specific leakage rates for geological reservoirs is that monitoring of storage operations is sensitive enough to detect leakage rates as low as suggested, so that mitigation strategies can be employed, and ratification of carbon credits can be achieved by regulators. Leakage rates in the order of 0.01 % per year are acceptable from climate change perspectives, but these rates may be large with regard to 'local' impacts upon human health and the environment and therefore need to be assessed quantitatively[MJE2].
9. Carbon dioxide is a non-toxic gas, with ambient concentrations in the atmosphere of about 370 ppm. Health and ecosystem impacts of carbon dioxide have been

reviewed by Benson et al. (2002). Their study has demonstrated that humans may tolerate concentrations of CO_2 up to 10 000 ppm (1 % CO_2) with no apparent physiological effects. At concentrations between 3 and 5 %, there are effects upon the rate of respiration, and above 5 %, physical and mental capabilities may be impaired, with potential loss of consciousness. Exposure to atmospheric concentrations above 10 % results in loss of consciousness and possible coma or death.

10. Other air-breathing animals have a similar tolerance to CO_2 as humans so that concentrations up to 20-30 % will kill all forms of life other than microbes, invertebrates and insects (Benson et al., 2002). Plants, insects, and soil organisms have a higher tolerance to CO_2 than most other life forms. Moderate increases in CO_2 concentrations may stimulate plant growth, but soil gas CO_2 concentrations of 20-30 % may result in root damage and plant demise. For example, extensive areas of tree-kill have occurred at Mammoth Mountain, USA due to volcanic out-gassing of CO_2 since1990 (McGee and Gerlach, 1998).
11. Geological storage of CO_2 beneath the North Sea implies future impacts of CO_2 leakage upon the marine environment. Impacts of CO_2 upon marine organisms is poorly-known and requires further research investigations.
12. CO_2 is denser than air, so that any release to atmosphere will tend to collect in topographic hollows (Britter, 1989). Dispersal by wind action is essential to mitigate the development of blanketing clouds of CO_2 (Oldenburg and Unger, 2003).
13. The effects of CO_2 released into water bodies depend upon the magnitude and rate of release, the chemical buffer capacity of the water body, and transport and dispersion processes. Volcanic releases of CO_2 at Mammoth Mountain, USA were dispersed rapidly through the surface water system and released quickly into the atmosphere (Benson et al., 2002). pH changes in water are directly related to the partial pressure of CO_2 and the chemical buffer capacity of the water. High CO_2 levels in water may impair respiration in fish, cause acidosis, and asphyxiation (Saripalli et al., 2003).

14. Migration of CO_2 into aquifers used for potable water supplies could lead to acidification of those resources, or their contamination by destabilisation of heavy metals naturally sorbed or precipitated on aquifer minerals such as iron oxyhydroxides. Heavy metals such as Cr, Cd, Mn, Cu, Pb and As may all be desorbed by lower pH and/or higher PCO_2 (van Geen et al., 1994; Schindler and Stumm, 1987). The potential for the displacement of brines into aquifers containing potable water supplies must also be considered. Other impacts could be associated with the mobilisation of naturally-occurring organic compounds, or gases such as hydrogen sulphide and radon.
15. Having identified potential impacts on the environment and human health, it is necessary to quantify the potential consequences of possible releases from geological storage and the likelihood that such consequences will be incurred. Methods for the assessment of the long-term performance and safety of the geological storage of CO_2 are at an early stage of development, and as yet, there are no published quantitative analyses for the whole system. Many of the advances made in the last twenty years in the field of safety assessments for the geological disposal of radioactive wastes e.g. Savage (1995) can be applied to CO_2 storage. As is the case for CO_2 storage, the disposal of radioactive wastes requires an understanding of complex coupled physical-chemical-mechanical processes occurring over thousands to tens of thousands of years. Most assessment models follow approaches based upon an understanding of the storage system constructed through an analysis of relevant features, events and processes (‘FEPs’), the development of scenarios to represent the evolution of the system, and calculations of potential impacts using mathematical models to represent key processes.
16. A generic FEP database for the geological storage of CO_2 has been developed by Quintessa as part of the IEA Weyburn project and funded by the EC and DTI (Riding et al., 2003) [http://www.co2captureandstorage.info]. The database includes around 200 FEPs in a hierarchical structure, with FEPs grouped into categories such as ‘assessment basis’, ‘external factors’ and ‘boreholes’. Each FEP has a text description and a discussion of its relevance to performance and

safety. The database can be accessed online and incorporates hyperlinks to other relevant sources of information (reports, websites, maps, photographs, videos, etc.). Essentially, the list of FEPs defines the process system and represents all the factors that help define CO_2 behaviour and migration. *It is important that this FEP database is maintained and further developed to help assess the suitability of future sites for the geological storage of* CO_2.

17. There are some important technical challenges for CO_2 assessment modelling. Firstly, the properties of CO_2 are very different in different parts of the system and its density and viscosity are complex functions of temperature and pressure. Secondly, CO_2 is not a 'trace' contaminant, so that the storage of large volumes of CO_2 at high pressures can directly affect the properties and evolution of the system into which it is injected. Lastly, the potential impacts resulting from CO_2 transport to the accessible environment may depend critically on the location of the release and the area over which that release occurs; impacts for a given flux to the surface may vary from insignificant to immediate loss of life depending upon the characteristics of the release.
18. Currently-available assessment models have not been purpose-designed and most rely on commercial 'reservoir simulator' software (used to understand hydrocarbon behaviour in a reservoir). *However, these models do not address all aspects of the system necessary for a complete assessment of safety/performance (such as long-term evolution of the geological system), so that targeted funding is required to develop a new generation of assessment software.*
19. The timescales over which a systems-level assessment should be performed will depend upon the context of the assessments and the impacts that are of concern. The assessment timescales influence the processes that must be considered in the assessment; different processes may be important over different timescales.
20. In general terms, there are two timescales of interest for geological storage of carbon dioxide. Firstly, there is that over which isolation of carbon dioxide from the atmosphere is necessary to mitigate climate change. Current views, taking into account various carbon dioxide emission scenarios, is that this timescale is of the order of a few hundred years at most, e.g. Lindeberg (2003). The second

timescale of interest is potentially much longer and is that pertaining to the assessment of potential impacts on human health and the environment. This timescale could be in the order of thousands to tens of thousands of years.

21. Safety studies for the geological storage of CO_2 are unusual in that they need to consider the evolution of natural systems over timescales considerably in excess of those considered in typical engineering projects. Most environmental assessments address periods of tens or occasionally hundreds of years. For radioactive waste disposal the long half-lives of some radionuclides play a part in defining the assessment timescales, but a recent review by the NEA/OECD (2002) emphasised that long assessment timescales need to be considered because: (a) well-sited geological disposal facilities imply leakage to the biosphere only very far into the future; and (b) ethical considerations mean that the same level of environmental protection should be applied in the future as today.
22. Natural systems provide evidence that the nature of releases to the accessible environment could be more important than the magnitude; adverse impacts can occur where unusual concentrations mechanisms are present.
23. An appropriate regulatory regime needs to be established in parallel with the development of a capability of performing long-term safety assessments of the geological storage of CO_2. This regime should be developed through dialogue between storage site developers and regulatory bodies, taking full account of any concerns from the general public attached to the development of this technology.

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