Study of Potential Impacts of Leaks From Onshore CO_2 Storage Projects on Terrestrial Ecosystems

Technical Study

Report Number: 2007/3

Date: July 2007

This document has been prepared for the Executive Committee of the IEA GHG Programme.
It is not a publication of the Operating Agent, International Energy Agency or its Secretariat.

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

DISCLAIMER

This report was prepared as an account of work sponsored by the IEA Greenhouse Gas R&D Programme. The views and opinions of the authors expressed herein do not necessarily reflect those of the IEA Greenhouse Gas R&D Programme, its members, the International Energy Agency, the organisations listed below, nor any employee or persons acting on behalf of any of them. In addition, none of these make any warranty, express or implied, assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights, including any party's intellectual property rights. Reference herein to any commercial product, process, service or trade name, trade mark or manufacturer does not necessarily constitute or imply an endorsement, recommendation or any favouring of such products.

COPYRIGHT

Copyright © IEA Greenhouse Gas R&D Programme 2007. All rights reserved.

ACKNOWLEDGEMENTS AND CITATIONS

This report describes research sponsored by the IEA Greenhouse Gas R&D Programme. This report was prepared by:

British Geological Survey,
Keyworth,
Nottingham
NG12 5GG

The principal researchers were:

- J. M. Pearce
- J. M. West

To ensure the quality and technical integrity of the research undertaken by the IEA Greenhouse Gas R&D Programme (IEA GHG) each study is managed by an appointed IEA GHG manager. The report is also reviewed by a panel of independent technical experts before its release.

The IEA GHG Manager for this report : John Gale

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "Study of Potential Impacts of Leaks From Onshore CO_2 Storage Projects on Terrestrial Ecosystems, 2007/3, July 2007".

Further information or copies of the report can be obtained by contacting the IEA GHG Programme at:

IEA Greenhouse R&D Programme, Orchard Business Centre, Stoke Orchard, Cheltenham Glos. GL52 7RZ. UK
Tel: +44 1242 680753 Fax: +44 1242 680758
E-mail: mail@ieaghg.org
www.ieagreen.org.uk

ASSESSMENT OF POTENTIAL IMPACTS OF LEAKS FROM ONSHORE CO_2 STORAGE PROJECTS ON TERRESTRIAL ECOSYSTEMS

Background to the Study

One of the key issues that need to be fully resolved for CO_2 Capture and Storage (CCS) is that CO_2 can be injected into suitable geological storage reservoirs both safely and with minimal environmental impact. The safety aspect predominantly relates to good design and operational practices and strict adherence to accepted health and safety procedures. Any environmental impacts that may arise will occur as a result of CO_2 migration from a geological storage reservoir followed by subsequent seepage to the surface. Seepage is likely to occur at low levels over long time periods (possibly 100's to 1,000's of years) and will result in localised environmental impacts as observed from those natural accumulations of CO_2 that have been observed to have migration and seepage occurring. It is expected that migration and seepage can be minimised or prevented through a combination of effective site selection and design, risk assessment and monitoring. However, there is still a need to attempt to quantify the migration/seepage conditions that might lead to environmental impacts on the surface from on-shore geological storage projects. For CCS technologies to be acceptable to the general public, environmental bodies, commercial operators and regulatory bodies alike, operators must be able to demonstrate a deep and thorough understanding of the possible long and short term effects of CO_2 seepage on ecosystems, both at the surface and subsurface level.

The aim of this scoping study was to assess the extent of information currently available on the effects of CO_2 seepage on on-shore ecosystems. The objective of the scoping study was to assess what gaps in knowledge exist and what further research needs to be commissioned to address these gaps. The need for this scoping study was first identified by the International Research Network on Risk Assessment in 2005 (for further information, please see www.co2captureandstorage.info). The scoping study was aimed to complement a broader study that was underway that assessed the current Environmental Impact Assessment (EIA) and Strategic Environmental Impact Assessment frameworks for use with CCS[1]. One of the gaps identified by this study was the need for further research on the environmental impacts of CO_2 on on-shore environments.

The scoping study was undertaken by experts from the British Geological Survey.

Results and Discussion

The following aspects of the scoping study are discussed in this overview. Full details on all these topics are presented in the main report:

- Are there any possible risks and impacts of CO_2 seepage?
- Summary of information available,
- Research underway,
- Data needs for on-shore CCS projects,
- Knowledge gaps,
- Proposed research plan.

[1] IEA Greenhouse Gas R&D Programme (IEA GHG), "Environmental Assessment for CO_2 Capture and Storage", 2007/1, March 2007

Are there any possible risks and impacts of CO_2 seepage?

Risks

The scoping study considered any possible risks of geological storage of CO_2 and found that they could be separated into two distinct groups. These groups were:

- Short term risks; involved with fugitive emissions during the physical process of injection, although this is more of an operational issue, and if it occurred, it would be closely monitored during the injection phase of a project and therefore could be rectified and remediated swiftly.
- Long term risks; centred on migration and seepage from the storage reservoir after injection has been completed.

Impacts

Also it was noted that when considering the impacts of seepage on on-shore ecosystems it is important to differentiate between global effects and local effects of increases in CO_2 levels, as increases in atmospheric CO_2 are measured in ppm (parts per million), soil concentrations would be considerably higher, and could easily reach levels where measurement is at percentage levels.

The consultants identified a number of possible effects that could arise as a result seepage of CO_2 occurring from a geological storage reservoir on the on-shore environment. Possible effects could include:

- Detrimental effects on the health of both humans and animals,

- The inhibition of plant growth - although atmospheric CO_2 can promote plant growth, increased concentrations in the soil (>10%) could lead to root asphyxiation and plant death rather than improved growth and development,

- Altered biological diversity throughout the ecosystem, and changes to the composition and numbers of species in the local environment,

- Changes in the biogeochemical processes present in the subsurface, possibly leading to changes in the pH of the soil. This would have associated negative effects on any microbial populations within the soil, leading to a change in the nutrients present which would progress up the food chain, affecting the entire ecosystem.

- Changes in the quality of the groundwater, in particular the pH and heavy metals content. This would subsequently have serious consequences on water resources in the surrounding area.

It should be stressed that these impacts are unqualified, and therefore should be considered as theoretical only at this stage. Nor should the list presented be considered as giving an implication of a ranking order for these impacts. Only when sufficient research data is available can these possible impacts be quantified and their scale of impact assessed.

While the biological effects of increased CO_2 concentrations on species can be determined and predicted with a relatively high degree of accuracy, the physical response of individual organisms is uncertain. An organism may detect the gradual change in CO_2 concentration outside of its tolerances, and seek an alternative habitat. It is noted that this could have a subsequent effect on the ecosystem the organism moves into, although this is unlikely as the organism in question would likely seek an ecosystem suited to its environmental tolerances and requirements, and it is possible that others of its species may already be present.

Summary of information available

The scoping study considered the information currently available in the technical literature from work completed to date[2] on the listed effects, and drew the following conclusions:

1. There is a considerable body of information available on effects of elevated concentrations of CO_2 on ecosystems especially plants

2. Despite regional differences, generalised characterisation can be performed, and indicator species will need to be identified for all potential ecosystems, whether they are in a temperate, arid, semi-arid or tropical environment, and regardless of land use – agricultural, forested, urban or wilderness.

3. Combining various sets of research data, the following broad conclusions on CO_2 tolerance can be made:
   - Non-human mammals are more resistant than humans to the toxic effects of $CO_{2,}$
   - All mammals are affected, irrespective of species.
   - Insects are more tolerant than mammals.
   - Plant thresholds appear to be around 20 – 30%, depending on exact species.

4. It can be concluded that permissible levels of CO_2 would depend on the life forms and species present in a given ecosystem, for example if humans were present, the permissible level would necessarily have to be set much lower than if the predominant land use was arable farming land.

5. Effects of a leak would decrease in severity in a series of concentric rings, with those organisms closest to a leak suffering from acute or even lethal concentrations of CO_2, and those living at ever increasing distances suffering from acute to chromic concentrations, until the effects were no longer discernable.

6. The range of effects on terrestrial ecosystems are not limited to single species effects, but can extend to entire ecosystems, and can be chronic, acute or even lethal depending on the species affected and the concentrations of CO_2.

7. Data on the effects of naturally released CO_2 on local ecosystems which could be used as a reference source was limited. The natural releases studied tend to be of a volcanic nature and hence have other gas species present such as H_2S or SO_2 which are toxic at low concentrations and would cause ecosystem impacts themselves. Differentiating between the effects of other gas species and CO_2 is difficult.

8. Although many studies have been published on the subject of the effects of CO_2 on humans, and the medical results are well documented, all of these studies have been performed on healthy volunteers. There would be no such discrimination in the event of a leak from a storage reservoir. It is anticipated that acute exposure (>3%) or prolonged exposure (>1%)

[2] An extensive review of the existing literature was undertaken by Julia West of BGS prior to this study that work is summarised in the main report.

would have detrimental effects on potentially high risk segments[3] of a population of humans.

The issue of relative importance of these conclusions was addressed, and it was decided that although there was no data to support an order of significance, these conclusions would not be ordered, but that the order should not be treated as an order of significance.

The scopingstudy also considered the current and planned research that is underway, which is summarised in Table 1 overleaf[4] and assessed whether this research addressed any of the effects listed. This review indicates that there is only a limited amount of research underway on this topic and whilst that research is addressing some of the issues identified there is a lot more research required.

Table 1: Summary of Current Research

Researchers/ projects	Research Work Underway
CO_2GeoNet[5]	Modelling of responses of terrestrial ecosystems to CO_2 leakage at various analogue sites in Europe and at a controlled CO_2 seepage site, see ASGARD project. Development of a generic system model. Status: Ongoing
Biomonitoring	Preliminary identification of soil micro-organisms to act as bio-indicators of increases in CO_2 concentrations. Status of work: unknown
ASGARD	Artificial test site to observe and monitor/measure the effects of variable concentrations of CO_2 on various crops and plants, soil microbes / invertebrates and soil geochemistry. Status: Ongoing.
Ohio River Valley	Impact assessment model developed to assess impacts of CO_2 migration on groundwater. Status: Ongoing
Uppsala University, Sweden	Study of natural super-saturation of CO_2 in lake by bacterial mineralisation and subsequent release of CO_2 to the atmosphere. Not directly relevant to geological storage. Status: Unknown.
ZERT [6]	Field injection test facility established to allow the testing of monitoring technologies and tools, improvement of modelling techniques. Target is Co2 dispersion from the vadiose zone to the atmosphere. Status: Ongoing

Data needs for on-shore CCS projects

One key aspect of this scoping study was to determine what data would be required to demonstrate that there were minimal environmental impacts when CO_2 was injected into geological storage reservoirs onshore. The information considered to be necessary is given below.

[3] It is surmised that high risk segments of the population could include; babies, those suffering from respiratory disorders, heart disease and the elderly.
[4] The research work that is currently underway id discussed in more detail in the main report
[5] European Centre of Excellence on Geological Storage of CO2, details can be found at www.Co2GeoNet.com
[6] ZERT – Zero-Emission Research and Technology Centre

- *Identification of target species / organisms* - identifying species to act as early indicators of increases in CO_2 concentrations, and determining limits whereby species become unable to tolerate CO_2.

- *Environmental criteria* - there is a need to define the environmental criteria for the storage of anthropogenic CO_2, for use in both risk assessments and EIA's.

- *Exposure levels and effects* - data on long-term, low level exposure for both surface and subsurface terrestrial ecosystems is required to further our understanding of the impacts of leaks from storage reservoirs. Post-exposure recovery rates also need investigating.

- *Effects on groundwater* - there have been no studies to monitor the effects of CO_2 on groundwater quality after an occurrence of seepage, resulting in virtually no data available in the area of heavy metal mobilisation or acidification through storage reservoirs to groundwater systems.

- *Gas mobilisation* - a greater understanding the behaviour and migration of co-injected gasses (or elements mobilised by the migration of CO_2) and the processes by which they travel to the surface is necessary.

- *Monitoring techniques* - there is a need for the development of a suite of monitoring tools (dictated by the risk assessment procedure) enabling a thorough assessment of the impacts of CO_2 leaks on organisms and ecosystems in storage areas.

Knowledge gaps

This information available was than compared with existing data sources and the data needs to highlight gaps in the current state of knowledge and indicate requirements for further research with the aim of building a complete and thorough understanding of the environmental risks involved with such projects. These gaps should not be viewed as a necessary prelude to instigation and commencement of CCS projects, rather as a parallel activity to run in conjunction with existing practical R&D work.

1. *Long-term, exposure effects and thresholds.*
   Although there is a wide range of available data regarding the recorded effects of slight changes in CO_2 concentrations, and also lethal concentrations, for many species of flora and fauna, no data is available on long term exposure of individual organisms, or of entire ecosystems, under the conditions that could be experienced following seepage from a storage reservoir.

2. *Acceptable levels of CO_2 concentration for ecosystems.*
   There has to date been no clear definition of 'acceptable' CO_2 concentrations or thresholds in typical ecosystems found in the near surface area surrounding storage reservoirs. This threshold definition is expected to vary depending on the type of ecosystem present, and the variety of organisms found within the ecosystem.

3. *Identification of key indicator organisms.*
   There are currently no strategies or research projects in operation for the identification of key indicator organisms or suitable CO_2 concentration thresholds for specific ecosystems. This leads to a lack in the effectiveness/ability of risk assessments to accurately identify the

risks inherent to CO_2 injection practices. This shortcoming in turn leads to an inability to produce an economically viable, environment-specific monitoring programme.

Proposed research plan

The scoping study then went on to propose a generic work programme to identify impacts and their significance and the need for monitoring and remediation. Such a programme for a specific test site would:

1. Start by defining the scenario – this would use risk assessment techniques like FEP[7] analyses to identify potential leakage pathways, fluxes etc.
2. Characterise the ecosystems – based on step 1 define the surface and subsurface ecosystems most at risk and identify key receptor species
3. Assess possible impacts of CO_2, - identify possible impacts on both indicator species and whole effected ecosystem and definition of threshold levels.
4. Apply monitoring techniques – deploy fauna and floral monitoring systems to monitor key species and ecosystems ,
5. Integration of with system models – system models can be improved iteratively as data becomes available.

It is expected that the research programme would deliver:

a) Identify the target species to monitor at an injection site,
b) Allow the development of appropriate remediation plans,
c) Develop a monitoring protocol for near surface ecosystems,
d) Provide data on species recovery rates,
e) Identify appropriate thresholds and allow the development of safety criteria.

The consultants then set out a series of specific R&D activities that were considered necessary to provide an integrated approach to this activity; these are set out in Table.2 with indicative costs attached.

Table 2: Recommended work packages to address current gaps in knowledge.

Activity	Details	Estimated Cost
Regular Annual Meetings	Meetings including regulators, researchers and stakeholders to share experiences, approaches and data. This will allow the development of a 'Best Practice' approach.	€150,000 over 5 years
Development of System Models	Extrapolating existing models to cover all potential ecosystems encountered in a storage programme.	€150,000 per model
Identification of Indicator Species	To include identification of organism responses, impacts and recovery rates. Establishment of several experimental sites in the environments incorporating the ecosystem types discussed in the study.	€2.5 million per site
Monitor Long-term effects of CO_2	Opportunities to monitor long-term effects of seepage from naturally occurring CO_2 leaks, as these effects are not readily duplicated in experimental situations.	€700,000 per site

[7] Features, Events and Processes

Expert Review Comments

The draft report on the study was presented at the Risk Assessment network meeting held in San Francisco in September 2006. In addition, the draft report was also sent to a panel of expert reviewers and to a number of IEA GHG's members who had expressed interest in reviewing it.

In general the report was well received at the network meeting and initiated considerable discussion. A number of new research activities were identified that were included in the review.

Conclusions

The assessment has highlighted a key knowledge gap for CCS that needs to be addressed. The seepage of CO_2 to the surface is a major concern with both environmental NGO's and regulatory bodies and the CCS community needs to be in a position to suggest what the impacts of any seepage might be. This piece of work has demonstrated that we are not yet in a position to do so and that current / planned research will not fully address the technical issues identified in this study. A further intensive programme of directed research on ecosystem impacts therefore needs to undertaken in the near future.

Recommendations

The key recommendation from this assessment is that members need to consider the research programme highlighted by this study to address the gaps in knowledge that have been identified here.

Monitoring activities of the type discussed here should be built in wherever practicable to future demonstration project activities

Furthermore, it is proposed that IEA GHG co-ordinate a meeting with key research and regulatory groups to consider how this gap might be addressed in the future. This may lead to the development of an International Research Network in the future.

British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Study of potential impacts of leaks from onshore CO_2 storage projects on terrestrial ecosystems.

Sustainable and Renewable Energy Programme

BRITISH GEOLOGICAL SURVEY

SUSTAINABLE AND RENEWABLE ENERGY PROGRAMME

Study of potential impacts of leaks from onshore CO_2 storage projects on terrestrial ecosystems.

J.M. Pearce and J.M. West

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Ordnance Survey licence number Licence No:100017897/2006.

Keywords

Environmental impact assessments, CO_2 capture and storage, onshore.

Bibliographical reference

Pearce, J.M. and West, J.M., 2006. Study of potential impacts of leaks from onshore CO_2 storage projects on terrestrial ecosystems.*British Geological Survey*. 62pp.

Copyright in materials derived from the British Geological Survey's work is owned by the Natural Environment Research Council (NERC) and/or the authority that commissioned the work. You may not copy or adapt this publication without first obtaining permission.
Contact the BGS Intellectual Property Rights Section, British Geological Survey, Keyworth, e-mail ipr@bgs.ac.uk You may quote extracts of a reasonable length without prior permission, provided a full acknowledgement is given of the source of the extract.

© NERC2006. All rights reserved

Keyworth, Nottingham British Geological Survey 2006

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

Keyworth, Nottingham NG12 5GG
☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU
☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 028-9066 6595 Fax 028-9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491-838800 Fax 01491-692345

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ
☎ 029–2066 0147 Fax 029–2066 0159

Parent Body
Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

SUMMARY

This report reviews the types of information that may be required in Environmental Impact Assessments (EIAs) for geological CO_2 storage projects in onshore locations. It also identifies gaps in our current understanding of the environmental impacts of putative CO_2 leaks from geological storage reservoirs, and proposes an outline research programme to address the most important of these gaps.

There is no regulatory framework specifically governing geological CO_2 storage in place at present, either at the national (or jurisdictional), regional or international level - current projects are licensed under petroleum legislation. However, a number of important regulatory developments are under way:

- The OSPAR and London Conventions are considering the status and legality of CO_2 storage at depth beneath the sea bed.
- The IPCC has paved the way for acceptance of geological CO_2 storage as a valid means of reducing national greenhouse emissions by including it in the 2006 revision of the guidelines for compiling national greenhouse gas inventories.
- The inclusion of geological CO_2 storage within the UNFCCC's Clean Development Mechanism (CDM) and the EU Emissions Trading Scheme (EU ETS) is under consideration.
- Regulatory frameworks are under development in many jurisdictions (e.g. Australia and the UK) and regions (e.g. the European Union).

It is recognised by all stakeholders that issues of leakage and potential long-term stewardship must be addressed in regulatory frameworks if the potential for CO_2 capture and storage to provide substantial reductions in atmospheric CO_2 emissions is to be realised. EIAs are common, widely-used and well-established procedures for assessing environmental impacts during the commissioning, operation and decommissioning of large industrial projects, including those of the oil and gas industry. They would be an effective way to assess the potential environmental impacts of, and create a safety case for, geological CO_2 storage projects. Most EIAs performed for other project types do not

address the long-term issues relevant to geological CO_2 storage as a greenhouse gas mitigation option, but they could be expanded to do so. For a robust EIA of a CO_2 storage project, it will be important to assess the local effects of a CO_2 leak from depth. Much of the existing data are from studies of global atmospheric rises (e.g. to 560ppm atmospheric CO_2 concentration, in contrast to soil gas concentrations which could reach percent levels).

The likely environmental impacts of CO_2 leakage from an onshore geological storage reservoir are:

- Effects on human and animal health
- Inhibition of plant growth or, in high concentrations, root asphyxia and plant death
- Changes in biological diversity and species composition, with asphyxiation at high concentrations
- Changes in subsurface biogeochemical processes as increased CO_2 concentrations could change pH, microbial populations and nutrient supply

There are wide gaps in our knowledge of the above. Key gaps are:

1. Although there are data on the effects of slightly increased CO_2 concentrations and lethal concentrations on species, there are no data on long term chronic exposure following a leak from a CO_2 storage reservoir, on either target species or total ecosystems.
2. Acceptable limits or thresholds for CO_2 concentrations in a variety of near-surface ecosystems have yet to be established.
3. Currently, there is no strategy or research program for identifying key organisms or appropriate thresholds for specific ecosystems. This constrains the capabilities of risk assessments to accurately identify important risks and consequently the formulation of appropriate, cost-effective monitoring protocols and remediation plans.
4. Current best practice in environmental impact assessments defines the scope of assessments as the operational lifetime of the project and include those legacy issues primarily associated with infrastructure and site decommissioning. Timeframes of relevance to geological storage are not normally considered.

5. The impacts of elevated CO_2 on humans during acute exposure have been documented, though largely for healthy adults. Acute and chronic exposure to other sections of populations has still to be evaluated.
6. There is currently a lack of integration between performance assessments and assessments of potential impacts of CO_2 leaks on terrestrial ecosystems.

The overall approach of a research programme to address these gaps should be to integrate an understanding of the potential impacts with risk assessments; as a comprehensive assessment of risks can not be achieved without a knowledge of the potential impacts of a leak. An integrated approach for all the activities described above is needed to develop a systematic, rigorous and coherent appraisal of potential impacts. This will promote greater acceptability by operators, regulators and other stakeholders.

Key components of the research programme should be:

1. Scenario definition: to identify relevant scenarios including leakage pathways, fluxes and anticipated CO_2 plus other contaminants in receptor environments.
2. Characterise surface and subsurface ecosystems in terms of flora and fauna. Identify key indicator species (most susceptible, those showing biggest change).
3. Identify impacts of CO_2 on indicator species and total ecosystem. Define appropriate thresholds and safety criteria. Identify recovery rates. Scope impacts on groundwaters via modelling and experiments, if appropriate.
4. Develop floral and faunal monitoring techniques.
5. Improve system models by integrating key processes and indicators in an iterative manner.

Key outputs from such a research plan would be:

- Identification of target species for monitoring and recommendations for appropriate, cost-effective monitoring techniques.
- A monitoring protocol for near-surface ecosystem impacts.
- Identification of recovery rates.
- Identification of appropriate safety criteria, thresholds and trigger events.
- Development of appropriate, cost-effective remediation strategies.

CONTENTS

1. INTRODUCTION

At the August 2005 meeting in Utrecht, the Environmental Impacts working group of the IEAGHG Risk Assessment Network[1] identified a need to define data requirements for environmental impact assessments and to compile and review existing datasets, providing a state of the art report. The IEAGHG has commissioned the British Geological Survey to address these needs for terrestrial environments.

This report reviews the information potentially needed to submit an environmental impact assessment for a CO_2 storage project in the terrestrial environment and compares these requirements against the available data. Current and planned research in this area that the authors are aware of, is also highlighted. Gaps in our current understanding that may need to be filled to better understand the potential impacts of a leak from a CO_2 storage site on the terrestrial environment are then identified and prioritised. Finally, a general research programme that would address these gaps is proposed.

This report was circulated to Network members for comment, and presented and discussed at the Risk Assessment meeting in October 2006, held at Lawrence Berkeley National Laboratory, Berkeley, California. These comments have been taken on board during production of this final version.

The contents of this report are:

- Summary of regulatory framework
- Case studies of (partial) risk assessments and an Environmental Impact Assessment
- Existing data and likely data needs
- Current research
- Priorities

[1] See http://www.co2captureandstorage.info/networks/riskassess.htm

2. SUMMARY OF EXISTING REGULATORY FRAMEWORKS FOR ANALOGOUS ACTIVIES, AND CONSIDERATIONS FOR A CCS REGULATORY FRAMEWORK

Clearly, effective regulation of CCS operations will be essential to ensure that they proceed in a safe and environmentally acceptable manner and that responsibilities for any impacts from leakages are clearly defined for all procedures, especially in terms of liability (de Figueiredo et al, 2006). Additionally, this will encourage industry 'best practice' and also, crucially, provide the transparency necessary for public acceptance. While short-term liability is a very important issue in an assessment of environmental impacts, this report focuses on the question of long-term liability.

Currently, a detailed and specific regulatory framework for all carbon dioxide capture and geological storage activities (CCS) does not exist and, indeed, the interpretation of existing international environmental law, is under discussion at national, regional (e.g. European) and international levels as illustrated by IPCC (2005), Stenhouse et al (2004) and at the special session on regulatory issues at the recent GHGT8 conference in Trondheim, Norway. The IPCC Special Report on CCS (2005) summarises current relevant national regulations and standards that may be relevant to CO_2 disposal, citing as examples the disposal of acid gases in Canada, the US Safe Drinking Water Act and USEPA Underground Injection and Control Program and identifying various EC Directives.

This section gives an overview of the regulatory frameworks surrounding CCS, which particularly pertain to environmental impacts of CO_2 from onshore storage projects. Overall, there are few regulatory frameworks specific to CO_2 storage sites. Many demonstration sites are licensed under existing oil and gas regulations.

Hendriks et al. (2005) has recently reviewed the main environmental and safety risks related to CCS, analysed the relevant EU and international law and provided recommendations for the further development of legislation to address these risks. For all

CCS operations, the authors viewed environmental and safety risks as either local (e.g. impacts of CO_2 release on people, living organisms and the local environment) or global (CO_2 affecting global climate and biodiversity). Risks associated with geological storage were viewed as either short-term (releases during CO_2 injection) or long-term (releases during the storage period). The report reviewed 56 international conventions, regional conventions and EU Directives for their potential impacts on CCS operations. These documents were analysed in themes varying from waste management to transport and liability to water and to nature conservation. The specific conclusions from this review, which have direct relevance to the environmental impacts of leakage from a storage site, are:

- The lack of information on the long-term impacts of CO_2 storage on the environment, the absence of information on the storage effectiveness of particular sites, and the absence of information on the human and environmental impacts of accidental releases from pipelines and individual storage sites. The precautionary principle requires that conservation measures be taken where scientific knowledge is not complete.
- Substantial information is needed to issue permits with appropriate permit conditions. Substantial information is also needed to determine that there is not a 'likelihood of significant environmental impacts' from CCS activities undertaken in particular locations.

Zakkour (2006) identified a broad range of 'additional permitting considerations', which will need to be further considered for CO_2 storage sites. These are listed below, and those which can be considered to be of particular relevance to environmental impacts are highlighted in bold:

- Permits for undertaking surveying activities for site selection and characterisation, such as well drilling and seismic surveying;
- Permissions from landowners overlying storage sites. The conferring of mineral storage rights upon storage site developers;

- **Responsibility and liability issues associated with managing any leakage of CO_2;**
- **Concerns over ecological and human health risks posed by any leakage of CO_2 from storage reservoirs, both to the air directly above the storage reservoir and into adjacent soil and groundwater;**
- Issues over liability and responsibility for undertaking long-term stewardship of storage sites to ensure that the CO_2 remains safely sequestered. There are also issues associated with trans-boundary subsurface migration of stored CO_2;
- How CO_2 storage sites can be monitored, how data on any leakage can be determined and reported, and how this can be incorporated into the permitting process;
- How CCS could be included under emissions trading schemes, given the potential for some of the CO_2 to be released to the atmosphere over time;
- **Any potential legacy that stored CO_2 could create for future generations, and how this might be managed through an effective permitting process.**

Zakkour (2006) then examined existing permitting regimes in the European Union (EU) (the UK as a Member State was selected as a case study), USA, Canada and Australia to determine the relevance and applicability to CCS. Many conclusions were drawn from this analysis and those which are of particular significance in terms of the environmental and health impacts of leakage are listed here.

Specifically:

- The … Environmental, Social and Health Impact Assessment (ESHIA) process is likely to play a central part in any CO_2 storage site licensing and permitting regime developed.

And, more broadly:

- No parts of existing permitting regimes can satisfactorily accommodate all issues associated with sub-surface storage of CO_2. Whilst the oil and gas industry has a mature and carefully regulated environmental, health and safety permitting regime, this cannot be directly conferred onto CO_2 storage, as the long-term containment of pressurised fluids underground presents a range of new considerations. The US Underground Injection Control and Canadian Provincial regulations for acid-gas injection present the closest analogue permitting regimes, but these may need to be adjusted to take into account more widespread uptake of CO_2 storage activities. More importantly, no analogous regimes exist in the other regions (EU and Australia).

Hendriks et al. (2005), Mace et al. (2006) and Zakkour (2006) agree that many legal frameworks are relevant to CCS (see the list cited in Appendix 2 of Hendriks et al., 2005) but only a few explicitly address CCS activities (eg Kyoto Protocol, EU Monitoring and Reporting Guidelines). There is a clear need for a regulatory framework for CCS as 'regulatory certainty will facilitate use of CCS in cost-effective solutions' (Hendriks et al., 2005). Zakkour and Haines (2006) conclude that 'There is a need for new government-led regulation to ensure safe and secure storage of CO_2 in the sub-surface…. The principles for this regime could be led at national, regional or international level via different channels, such as the EU or the United Nations Framework Convention on Climate Change'.

2.1 REFERENCES

DE FIGUEIREDO, M. HERZOG, H. OYE, K AND REINER, D. 2006. *The Liability of Carbon Dioxide Storage*. 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway.

HENDRIKS, C. MACE, M. J. AND COENRAADS, R. 2005. *Impacts of EU and International law on the implementation of carbon capture and geological storage in the European Union*. European Commission, Directorate General Environment. ECS04057.

MACE, M. J. HENDRIKS, C. AND COENRAADS, R. 2006. *Impacts of EU and International law on the implementation of carbon capture and geological storage in the European Union*. 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway.

ZAKKOUR, P. 2006. *Permitting issues for CO_2 capture and geological storage: A review of regulatory requirements in Europe, USA, Canada and Australia.* IEA Greenhouse Gas R and D Programme. Technical study 2006/3.

STENHOUSE, M., WILSON, M., HERZOG, H., CASSIDY, B., KOZAK, M. AND ZHOU, W. 2004. *Regulatory issues associated with the long-term storage of CO_2.* IEA Report PH/4/35. 97 pages.

ZAKKOUR, P. AND HAINES, M. 2006 *Permitting issues for CO_2 capture, transport and geological storage: A review of Europe, USA, Canada and Australia*. 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway.

3. CURRENT CO_2 STORAGE PROJECTS AND ENVIRONMENTAL IMPACT ASSESSMENTS

Currently, most CO_2 storage projects are feasibility, research or demonstration projects are associated with oil and gas production (see Section 2). As such, they form part of existing oil and gas operations and as yet, are not eligible to generate credits for reducing atmospheric CO_2 emissions. As has been stated above, most EIAs focus on the short-term operational potential impacts of pipelines, capture plants, injection platforms, etc. Typically, EIAs do not routinely consider the longer-term impacts of a project. However, a consideration of the longer term implications of CO_2 storage is generally accepted as being a necessary part of the safety case for each project. Zakkour et al. (IEAGHG, 2006) proposed that EIAs will be a key process that will be central to successful permitting of CO_2 storage facilities (see Section 2).

3.1 THE SAFETY CASE

Before identifying the specific data needs for a generic storage site, it is necessary to define the safety case. It should be emphasised again that currently no specific regulatory framework exists for CO_2 storage but it is commonly assumed by industrial, research, regulatory and environmental groups that a safety case will have to be made for each storage site. The safety case will be specific to that site and the regulatory environment within which it is located. Much of the operational safety is likely to be covered by local HSE requirements and will include safe working practices for personnel in all parts of the CO_2 capture and storage chain, and may be distributed amongst several contractors with separate responsibilities. However, this review is concerned with the long-term safety case that will be the responsibility of the operator.

The safety case or environmental impact statement seeks to demonstrate that storage of CO_2 will be safe in the long-term and will comprise several components, brought together into a coherent document, that sets out the reasons for the expected continued safe storage of CO_2 within the storage reservoir or reservoirs, based on evidence, analyses and arguments. It may well be revised periodically throughout the project lifetime. The EIA could include:

- A description of the site selection and characterisation,
- A description of the project including anticipated injection mass, injection rates, number of wells, their locations and well construction, and the planned number of years of injection,
- Long-term simulations of CO_2 movement within the reservoir which have been matched against data obtained from monitoring during (pressure rising) and after injection (pressure decreasing),
- Long-term monitoring options if required,
- Appropriate remediation plans with responsibilities and commitments identified
- An assessment of the risks, consequences of and liabilities for leakage, for a range of realistic possible future site evolutions or scenarios.
- Closure plan
- Post-closure engineering aspects of the site, such as well completions and surface installations (if any),

Together these components seek to demonstrate that future risks are as low as reasonably practicable (ALARP). The safety case is likely to be presented initially to a regulator during an application for a licence to inject but is likely to develop iteratively through consultation with regulators and other stakeholders, and may well be updated on a regular basis as the project progresses.

Performance Assessment

The term ‘performance assessment’ describes the review of a storage site’s behaviour over a predefined future timescale against predefined health and safety criteria. The storage site could include the geosphere, biosphere (including humans), land surface and atmosphere that could be potentially affected by CO_2 migration and leakage. The site behaviour is considered to represent the future evolution of the site. In addition, fundamental definitions of timescales and safety criteria have yet to be defined for CO_2 storage. The environmental impact assessment approach could be expanded to provide a performance assessment.

3.2 STRATEGIC ENVIRONMENTAL ASSESSMENTS

A Strategic Environmental Assessment (SEA) is a systematic process for evaluating the environmental impacts and, increasingly, sustainable development, of proposed policies, plans and programmes, which are typically large-scale in nature and often in the public domain (Eriksson et al., 2006). In Europe, an EC Directive on Strategic Environmental Assessment (Directive 2001/42/EC) applies to public authorities for drawing up policies, plans and programmes that may have significant environmental effects and have a spatial reference. SEAs are undertaken at an early stage in the decision-making process, prior to project-specific EIAs.

For example, the UK DTI has performed a series of six SEAs for specific regions of UK offshore oil and gas exploration and production, and offshore wind farms (DTI, 2005). The DTI SEA process for offshore energy has the following components:

- Establishment of a SEA Steering Group with wide representation from a range of stakeholders (if it does not already exist)
- A formal scoping step with wide stakeholder involvement
- Integrated management of survey, consultation and assessment processes
- Facilitation of public consultation through a dedicated website
- Publication of reports on website, CD as well as hard copy where requested
- Widespread dissemination of data and information
- Development of modular documents applicable to more than one SEA
- Syntheses of data to facilitate access
- Commissioning of expert underpinning studies
- Involvement of authors of expert underpinning studies and other users in an assessment workshop

- Stakeholder workshop meetings
- A streamlined public consultation document
- Continuing development of the methods for the consideration of cumulative and synergistic effects

An SEA may be undertaken for CO_2 capture , transport and geological storage by national governments, federal states or provinces, and may help to inform the development of appropriate licensing frameworks, where necessary.

Eriksson et al (2006) have carried out a strategic environmental assessment of CO_2 capture, transport and storage. The approach taken is to evaluate the effects and results of alternatives relating to capture, transport and storage, including a baseline case and a 'no action' (i.e. no capture and storage) alternative. In addition to several capture, transport and storage options, Eriksson et al. (2006) also considered two alternative cases (or scenarios) of short-term, high flux leakage (for example well-bore failure) and long-term, low-flux leakage (for example, migration along a fault zone) from a storage reservoir. For each part of the CCS chain, project stage (construction, operation and post-operation) and technical option, the authors identified potential impacts to specific environmental components; water use, use of chemicals/hazardous materials, energy consumption, emissions to air, emissions to water, waste and noise. Once potential impacts were identified, effects on the environment and ecosystems were considered. Only those aspects relating to the onshore geological storage components are reviewed here. Potential impacts identified by Eriksson et al (2006) for the baseline and leakage scenarios were compared with the 'no action' scenario. They included:

- Changing pH and chemistry of shallow groundwaters
- Mobilization of metals, sulphate and chloride
- Changing water quality (odour, taste, colour)
- Root asphyxiation in the soil zone with concentrations above 5% being harmful and concentrations above 20% being phytotoxic
- Changing soil pH, which, in turn will alter nutrient balance, such as phosphorous availability decreasing with lowering pH and possible increasing aluminium solubility at very low pH.

- Changing soil pH, which will affect soil microorganisms, leading to reductions in beneficial organisms and increases in harmful ones.
- Potential impacts on freshwater such as lakes. Different impacts may be experienced by eutrophic (affecting nutrient balance and productivity) and oligotrophic lakes (affecting pH and the carbonate system).

It was noted that sandy soils are likely to be more sensitive to increased CO_2 concentrations relative to clay-rich soils, which have a greater buffering capacity. The effects on terrestrial ecosystems as a whole were also recognised as being of importance. The authors make the point that although high atmospheric CO_2 concentrations can promote plant growth, in the case of a leak from a storage reservoir, plants are unlikely to realise this benefit since soil CO_2 concentrations will be very much higher than related atmospheric concentrations and root asphyxiation is likely to be the dominant process. Long-term exposure to increased CO_2 concentrations may change ecosystem species compositions (Saripalli 2002).

In order to compare the various technical options defined at the scoping stage, Eriksson et al performed an environmental valuation, with reference to 15 official Swedish Environmental Quality Objectives (EQOs). For each EQO, each case was assessed for its environmental impact by assigning a valuation score, to create a valuation matrix. This approach highlighted that, for the various technological options and scenarios examined, long-term low leakage rates have the worst effects on the environmental objectives. Further, leakages in sandy soils with lower buffering capacities or into oligotrophic lakes containing low amounts of biomass have larger impacts than leakages into clay-rich soils or eutrophic lakes.

3.3 CASE HISTORIES

Current environmental impact assessment practices in other industries typically limit the scope of the assessment to the project lifetime, and legacy issues over the timescales of relevance to CO_2 storage are rarely considered. However, several current and past CO_2 storage demonstration projects have included an element of long-term risk assessment and three of these that directly consider the terrestrial environment, the Weyburn, Gorgon and Schweinrich projects, are very briefly reviewed below.

3.3.1 Weyburn

Possibly the best-documented case history can be found in the Weyburn project, which was the first to use formalised methods of assessing long-term site evolution in the context of risk assessments (Zhou et al., 2004). At Weyburn the aim of the performance assessment was to "identify the risks associated with geological storage and assess the ability of the Weyburn reservoir to securely store CO_2 for an extensive period of time". This was achieved through the development of a Features Events and Processes (FEP) list from which a base scenario describing how the system was expected to evolve was developed. Reservoir simulations over 5000 years from the end of the EOR period were performed. The fate of CO_2 was assessed through a deterministic approach that identified the main controls on CO_2 migration within the geosphere. Stochastic assessments of well leakage indicated that the estimated *maximum* cumulative leakage of CO_2 for an estimated 1000 wells may be up to 0.14% of the total CO_2-in-place over the 5000 year period.

In addition, probabilistic risk assessments also estimated that between 0.005% and 1.3% of the total CO_2-in-place may be released to the biosphere, comparing well with the stochastic approach. Considerations of the potential impacts for the estimated maximum release rates described above were limited to a preliminary assessment of acceptable indoor air concentrations and the required CO_2 flux from the ground necessary to achieve this concentration. At Weyburn, the acceptable indoor air concentration was defined as 0.35%, based on various lines of evidence (see Zhou et al., 2004 for details), requiring a flux of $1.3x10^5$ $gm^{-2}d^{-1}$. Background CO_2 flux rates were measured at between 12.7 and 65.8 $gm^{-2}d^{-1}$, several orders of magnitude below those needed to reach the 0.35% threshold level. During Phase 1 of the Weyburn project, potential impacts on ecosystems or water quality were not considered in any way.

3.3.2 Gorgon EIS

The Gorgon Joint Venture (GJV) is perhaps one of the most environmentally sensitive CO_2 storage projects to be undertaken to date, since CO_2 will be stored under Barrow Island, a

Class A nature reserve. As a result, the GJV has produced a very detailed environmental impact statement. The executive summary (Gorgon Venture, 2005a) for this is 122 pages long and the main report, divided into two volumes, is 802 pages – both are publicly available from www.gorgon.com.au.

The Gorgon project plans to inject between 2.7 and 3.2 million tonnes of CO_2 that will be separated from the natural gas produced from the Gorgon and Jansz fields, offshore Western Australia. The CO_2 will be injected into the Dupuy Formation, a saline sandstone aquifer at a depth of over 2000m. This is underlain by a bottom seal of the Dingo Claystone (4000-6000 m thick) and capped by the overlying siltstones consisting of the deltaic Barrow Group and the regional Muderong Shale (300-500 m thick); the latter is a proven seal to buoyant fluids trapping many oil and gas accumulations in the basin. Extensive and detailed oil and gas exploration, including over 700 wells drilled on Barrow Island, have enabled a detailed geological model to be constructed of the Barrow Sub-basin. The fact that Barrow Island is also a classified nature reserve means that the there is also considerable baseline ecological data that covers a period of several decades. The geological and ecological data is summarised in the draft EIS.

An initial Environmental, Social and Economic Review was performed that included feasibility studies for several alternatives to the Barrow Island development. It highlighted the three most critical environmental management issues: quarantine management, geological storage of CO_2 and risks to biodiversity and conservation values of Barrow Island and its surrounding waters. In accordance with both Western Australian state and Commonwealth legislative requirements, the Gorgon Venture is required to submit an Environmental Impact Statement. The first stage in this process was to publish in April 2004, a scoping document that identifies the relevant issues which should be addressed in the Environmental Impact Statement/Environmental Review and Management Programme. Once completed, the EIS was then drafted. Both documents were made available to the public and revised following public comment.

The environmental scoping document defines the remit and contents of the Gorgon Environmental Impact Statement (Gorgon Ventures, EIS/ERMP Scoping document, April 2004) and states that the environmental impacts of successful storage and consequences of failure in that storage will be reviewed in the EIS itself. In addition, the impacts of venting the CO_2 to the atmosphere if geological storage is uneconomic at Barrow Island will also be explored.

Since oil production commenced in the 1960s there have been several surveys of the flora and fauna, including subterranean fauna on the island. The following environmental factors in the terrestrial biophysical environment were identified as being relevant to the EIS:

- flora and vegetation communities (inc. threatened and introduced species)
- fauna (inc. threatened, migratory and introduced species)
- subterranean fauna (inc. meiofauna)
- soil and landform
- foreshore
- water (surface and ground – important for stygofauna and therefore not commercially exploited and requiring protection from potential CO_2 leaks)

The regulator highlighted the impacts of potential CO_2 leakage as one of several issues the EIS should consider and required that the EIS should address potential impacts that should be considered at the ecosystem, species and 'Evolutionary Significant Unit' level.

To address these regulator requirements, a risk-based assessment approach was undertaken. The overall approach to the environmental impact assessment process involved the following key steps:

- Identification of impacts and assessment of significance
- Development of strategies to avoid, mitigate or manage significant impacts
- Identification of residual impacts and analysis of their level of significance.

The EIS for the terrestrial environment is concerned predominantly with the construction, operational and decommissioning phases of the gas processing project, including the CO_2 compression and injection facilities. The Gorgon project has a stated development life of 60 years. Risks to the terrestrial environment have been identified and mitigation strategies put in place. The environmentally sensitive nature of the site has resulted in detailed and comprehensive surveys of many aspects of the terrestrial ecosystems have been collected over many years. These provide a comprehensive baseline.

As part of the EIS process the Gorgon Venture considered a range of options to reduce greenhouse gas emissions and selected geological storage of up to 2 Mt CO_2 per annum into the Dupuy Formation at ~2000 m depth. The EIS provides a brief summary of reservoir modelling studies that show predicted migration over 1000 years and states that a monitoring programme to track this CO_2 movement is being developed (September 2005). This plan will focus on three elements:

- Routine observation and recording of injection rates and surface pressures
- Health, environment and safety-oriented surveillance to detect surface leaks before they can pose a risk to personnel or the environment
- Verification via seismic surveys and/or observation wells of the migration of the CO_2 plume in the subsurface.

Section 13.4, pages 619-677, of the 800-page EIS describes the CO_2 injection component of the Gorgon project. The selection of the Dupuy Formation as the target reservoir was made following consideration of 17 potential sites against specific selection criteria (Gorgon Ventures, 2005b) and was selected for the following reasons (Gorgon Ventures, 2005b):

- The depth of the Dupuy Formation allows the CO_2 to remain in a supercritical phase
- The reservoir properties of the Dupuy Formation provide effective trapping of the injected CO_2
- The structure of the Dupuy Formation provides predictable migration pathways
- There is little potential to jeopardise current or future production of hydrocarbons
- Injection wells that penetrate into the Dupuy Formation would allow access to other saline reservoirs (Flacourt and Malouet Formations) as mitigation/upside options
- The Dupuy Formation can be accessed from onshore and close to the source of CO_2, removing the need for subsea wells and offshore platforms and thereby reducing risk and cost

- 2-D and 3-D seismic data and stratigraphic information from 27 wells provide a comprehensive data set on which to base technical studies.

The location of the injection site on Barrow Island was selected to maximize the distance between injection wells and major faults identified by seismic and well data. Reservoir simulations indicate that after 1000 years the CO_2 plume is predicted to have encountered six oil and gas exploration wells, in addition to the CO_2-injection wells, that penetrate the Dupuy Formation and a number of subsurface faults. The most important of these faults acts as a sealing fault preventing oil migration, although geomechanical data indicates it may allow limited vertical migration at the Dupuy Formation level. However, the injection plan will seek to prevent the CO_2 plume encountering the main faults or their damage zones and reservoir pressure thresholds will be set conservatively to avoid fault and seal leaks. Differences in salinities and pressures between the Dupuy and overlying reservoir sands indicate the effectiveness of basal shales and inter-formational faults and fractures within the Barrow Group as seals.

Monitoring to detect CO_2 plume migration and well integrity during the injection period may include, inter alia, CO_2 detection equipment within the compression and injection facility, pipeline and well pressures, seismic, wireline logging and formation water geochemistry. The duration of the monitoring program is not specified though the Gorgon Joint Venturers propose to continue some day-to-day management in the post-injection period. If the monitoring detects CO_2 plume migration that could pose an environmental, health or safety risk, a number of remediation options have been identified. In addition, a series of "uncertainties" or FEPs have been identified that may lead to a "worse than expected outcome". For each of these uncertainties, the worse than expected outcome is described, together with parameter(s) to be monitored, method(s) of monitoring, timing and management actions. The two principal uncertainties identified by the Gorgon Venturers, of relevance to this review are:

- Containment failure via fault migration that may be detected as 'ecological impacts' observed at the surface. These ecological impacts are not defined.

- Containment failure via existing well penetrations enabling CO_2 leakage at the surface, which would be monitored by atmospheric and soil gas detectors, vegetation surveys and visual well head inspections.

The Gorgon Joint Venturers indicate that modelled flux rates for CO_2 along faults could lead to a detrimental impact on flora within and above the soil environment, though the precise nature of these impacts is not specified. In addition the karstic nature of underlying carbonates and presence of caves on Barrow island also mean that near-surface cave systems have been identified as potential spaces where CO_2 concentrations could increase even at relatively low leakage flux rates.

As part of the preparations for the EIS for the Gorgon gas processing development, detailed vegetation surveys around the proposed gas processing infrastructure and the seismic monitoring area were performed at several times to reflect seasonal variations. Seventy-two vegetation plots, each containing 25 10x10m quadrats were surveyed and 68 families, 180 genera and 406 vascular plant taxa were identified on the island, including two protected species (though not within the Gorgon development area). Several communities were identified as being of conservation significance. In addition to flora, mammals, reptiles and amphibians, invertebrates, stygofauna (subterranean fauna living in caves or porespaces) land and seabirds were also surveyed. Within these, specific groups of receptors and key receptor species were identified and formed the focus of subsequent risk assessment. Potential stressors were defined for atmospheric, terrestrial and marine environments, including a CO_2 discharge, either from pipelines, wells or via a reservoir leak. Definitions of consequence category and likelihood category were combined to form a risk matrix, enabling medium and high risks to be identified, and management measures to be developed. No high risk stressors were identified in the terrestrial environment, possibly with the exception of risks to stygofauna especially from a CO_2 leak, largely reflecting the lack of data on distribution and diversity of these fauna.

The overall probability of unpredicted migration of CO_2 to the surface is considered remote. Potential mechanisms for such a leak have been identified:

- failure of the CO_2 injection compressors, pipelines or wellheads

- unpredicted migration along existing or decommissioned well penetrations, faults or fractures
- failure of structural seals.

Resulting flux rates have been estimated at between 1 and 100 micromol/m^2/sec. At the upper limit, localised effects on terrestrial vegetation may be expected. Though the Gorgon Joint Venturers do not define these effects in detail, they do state that prolonged exposure to high CO_2 concentrations may result in localised plant mortality or increased risk of asphyxiation for some fauna. A management plan is outlined that includes initial CO_2 injection design to reduce likelihood of leaks, establishing a CO_2 monitoring program for the reservoir and an environmental monitoring program, well remediation and abandonment plans, design validation and testing, installation of manual and automatic emergency response systems, including the identification of restricted vegetation communities and flora that will be preferentially protected. At the time of publication, the draft EIS identified risks to stygofauna from acidification of groundwater or asphyxiation as being medium, pending further study of their distribution within near-surface karst.

3.3.3 Schweinrich site

The Schwarze Pumpe-Schweinrich case study is a pre-feasibility study based on existing data only, prior to any future site exploration and further characterisation, as an R&D exercise within the EC-funded CO_2Store project (www.co2store.org). It should therefore be emphasised that the scope of the safety assessment was very limited and was undertaken with the specific aims of developing a suitable approach and identifying broad areas where additional information would be required to further reduce uncertainties.

The Schwarze Pumpe lignite-fired power plant emits around 10 Mt CO_2 per year. Previous studies of storage capacity have identified some natural gas reservoirs as offering some storage potential. For example the Upper Rotliegend Altmark reservoir, may provide suitable storage capacity with the possibility to combine with EGR. May et al (2006) estimate storage capacity within the Altmark reservoir of the Salzwedel-Peckensen gas field may be up to 500Mt of CO_2.

In addition, a series of stacked saline aquifers offers the potential for multi-barrier storage, capped by the regional Tertiary Rupelian clay. Identification of the Schweinrich site was based on estimated required reservoir properties to accommodate an injection of 10Mt of CO_2 per year, over the 40-year operational life (Meyer et al., 2006). A regional, GIS-based review identified 23 potentially suitable structures that met the defined reservoir criteria. The nine largest candidate sites were then evaluated at an expert workshop and analysed using the following criteria, with Schweinrich being the preferred site:

- Protected areas: Military, nature resources, lakes & rivers, and Nature 2000.
- Existing use/rights: Industrial
- Landscape picture: Pipelines, power plant
- Population density
- Interest groups

Areas of cultural interest and recreation were not included due to lack of information.
The Schweinrich site is situated beneath the village of Schweinrich, 250 km northwest of the Schwarze Pumpe power plant. Pipeline transportation over this distance means that the route taken determines the feasibility of the transport option. The pipeline options were analysed using the following criteria:

- Extensive use of existing routes.
- Avoidance of residential areas & topographic depressions
- Avoidance of high ground to minimize pumping costs
- Avoidance of protected areas.
- Minimisation of overall length and number of crossings.

The geological site characterisation was based on existing 2D seismic data and extrapolation from adjacent exploration well information (Meyer et al., 2006). The Hettangian/Contorta reservoirs were identified as having the most appropriate reservoir properties in terms of porosity, thickness, permeability, and areal extent underneath the closure, lying at between 1300 and 1800 m below sea level. The reservoir is capped by several hundred metres of Lower Jurassic claystones interlayered with siltstones and sandstones. This is in turn overlain by a thick sequence of Tertiary unconsolidated Rupelian clay, interlayered with variable silt, sand and coal. The age and quality of seismic data available during this pre-feasibility study severely constrained the identification of faulting within the system.

Reservoir simulations, based on existing data, modelled injection of 400 Mt of CO_2 over 40 years, via 10 injection wells. These simulations suggest that a large regional aquifer may be needed to compensate for the consequent pressure increases and identified this as area requiring further investigation. Geochemical simulations indicate approximately 38 mol% of injected CO_2 will dissolve in the saline porewater and much of the CO_2-saturated water will migrate into secondary marginal troughs of nearby salt diapirs.

Svensson *et al.*, 2005 performed a feasibility stage safety assessment of the long-term storage at Schweinrich within the CO_2Store project with the specific purpose of identifying the key safety factors that should be examined in a subsequent phase of the project evaluation. The following boundary conditions were set:

- A FEP analysis was performed to cover 1000 years. Hazards and reservoir simulations were evaluated for 10000 years.
- The spatial domain included the reservoir, seal, overburden, faults and well but not the shallow subsurface, atmosphere or underburden.
- No assessments of the probabilities of different scenarios were made.
- As mentioned above, only pre-existing, often rather old, 2D seismic and geological data was used to develop the geological model, which constrains the ability to accurately evaluate key features.

The leakage processes have not been verified against other data such as that derived from natural analogues.

A five-step process was followed during the safety assessment:

A. Definition of the assessment basis, including assessment objectives, geographical and geological description including storage concept and the containment concept.
B. A Features, Events and Processes (FEPs) analysis – based on TNO's (see Wildenborg et al., 2005) and Quintessa's (see

http://www.co2captureandstorage.info/riskscenarios/riskscenarios.htm) FEP databases.

657 FEPs were evaluated via an expert workshop, against specific criteria, allowing exclusion of many and inclusion of 250 events and processes (EPs) and 80 features. Each EP was ranked according to the potential impact (significant, marginal, negligible) and probability (very likely, likely, unlikely, very unlikely) and then matched against a risk matrix, allowing definition of the following groups:

- EP Reference scenario: 43 EPs with a probability of very likely.
- EP Variant scenario: 68 EPs that have a medium or high risk.
- EPs that are excluded: 139 EPs with low and very low risk were excluded for further analysis.

The scenario-defining EPs were further reduced by expert-based analytical EP grouping. EPs were then correlated with system features to establish causal relationships. These relationships were represented on interaction matrices and influence diagrams. Groups of EPs could then be identified, such as the 'geochemical EPs' and 'geomechanical EPs'. Such grouping is necessary in this bottom-up approach to reduce the number of combinations that must be managed.

C. Safety scenario formation. Scenario formation involved the formation of three specific zones – the containment, migration and biosphere zones, plus the fault and well compartments. The biosphere zone was not considered in the CO_2Store study.

Four scenarios were evaluated:

- The reference scenario of no failure of containment.
- A leaking seal scenario.
- A leaking well scenario. Note that no well design, location or completion plans were available during this assessment, so reference was made to the SAMCARDS study and generic assumptions were made.
- A leaking fault scenario.

D. Model development and simulations of scenarios.

The potential impacts from the simulations derived using the SIMED II flow model were CO_2 flux and maximum concentration in the shallow subsurface. However, the researchers recognized that to quantitatively compare performance against HSE criteria requires simulations in coupled multi-phase, multi-component simulator codes.

Model simplifications were significant and included the exclusion of mechanical and chemical processes such as CO_2 solution and geochemical reactions, very simplified geological representation and no consideration of capillary entry effects or changes in relative permeabilities.

The model comprised 14 geological layers, and a single injection well in the stochastic model.

Of the four scenarios the leaking fault scenario (and leaking well scenario - not considered in detail) indicated CO_2 reaches the shallow subsurface (noting the simplifications described above and boundary conditions). For the leaking fault fluxes were comparable to those observed at natural systems.

E. Safety evaluation.

The leaking fault scenario resulted in CO_2 concentrations in the shallow subsurface that Svensson et al. (2005) considered may lead to adverse effects on ecosystems, through broad comparisons with published data such as is listed in Table 2. Similarly estimates of CO_2 concentration in the shallow subsurface for the leaking well scenario exceed the limits of lethal effects on ecosystems, when compared to previously published information.

3.4 REFERENCES

DTI, 2005. *Strategic environmental assessments for offshore energy licensing.* http://www.offshore-sea.org.uk/site/. Accessed 16 August 2006.

ERIKSSON, S., ANDERSSON, A., STRAND, K. AND SVENSSON, R. 2006. *Strategic Environmental assessment of CO_2 capture, transport and storage – Final report*. Vattenfall Internal Report No U05:137, February 2006, 124 pages.

GORGON JOINT VENTURES, 8 April 2004. *Environmental scoping document for an environmental review and management programme for the proposed Gorgon development*. 77 pages. Available from www.gorgon.com.au. Accessed 8 August 2006.

GORGON JOINT VENTURES, September 2005a. *Draft Environmental Impact Statement/ Environment Review and Management programme for the Proposed Gorgon Development: Executive Summary*. 120 pages, available from www.gorgon.com.au. Accessed 8 August 2006.

GORGON JOINT VENTURES, September 2005b. *Draft Environmental Impact Statement/ Environment Review and Management programme for the Proposed Gorgon Development: Main Report*, available from www.gorgon.com.au. Accessed 8 August 2006.

IEA GREENHOUSE GAS R&D PROGRAMME (IEAGHG), *Permitting issues for CO_2 capture and geological storage*, Report No 2006/;3, January 2006, 176 pages.

IPPC 2005: *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O., de Coninck, H.C., Loos, M. and Meyer, L.A. (eds.)] Cambridge University Press, United Kingdom and New York, Ny, USA, 442 pp.

MAY F., HENKE C., BERG C., PUSCH G., REINICKE K., MEYN R., REBSCHER D. AND OLDENBURG C.M. 2006. *Storage of CO_2, a future option for the mature Altmark gas field?* Eighth International Conference on Greenhouse Gas Technologies, 19-22 June, Trondheim, Norway.

MEYER R., MAY F., KRULL P., DURST P., GAUS I., KREFT, E. VAN DER MEER, L.G.H. GEELS, K. SVENSSON R. AND BERNSTONE, C. 2006 *Geological characterisation of the structure Schweinrich - a suitable candidate site for industrial scale CO_2-storage in Germany?* Eighth International Conference on Greenhouse Gas Technologies, 19-22 June, Trondheim, Norway.

SARIPALLI K. P., MAHASENAN N. & COOK E. M., 2002. *Risk and hazard assessment for projects involving the geological sequestration of CO_2.* Sixth International Conference on Greenhouse Gas Technologies, 1-4 October, Kyoto, Japan.

SVENSSON R., BERNSTONE C., ERIKSSON S., KREFT E., ARTS R., OBDAM A. AND MEYER, R. 2005. *Safety Assessment of Structure Schweinrich. Part of CO_2STORE case study Schwarze Pumpe*. Internal unpublished CO_2Store report, 93 pages.

WILDENBORG, A.F.B., LEIJNSE A.L., KREFT E., NEPVEU M.N., OBDAM A.N.M., ORLIC B., WIPFLER E.L., GRIFT B. VAN DER, KESTEREN VAN W., GAUS I., CZERNICHOWSKI-LAURIOL I., TORFS P. & WÓJCIK R., *Safety Assessment Methodology for CO2 Sequestration (SAMCARDS), Report 2.1.1, Final Repor*t, TNO Netherlands Institute of Applied Geoscience, DE-FC26-01NT41145, December 2003.

ZHOU, W., STENHOUSE, M., SHEPPARD, M., and WALTON, F., 2004. Theme 4: Long-term risk assessment of the storage site. In: WILSON, M., and MONEA M. (Editors). *IEAGHG Weyburn CO_2 Monitoring and Storage Project Summary Report 2000-2004*. Pg 211-268., Petroleum Technology Research Centre, Regina, Canada.

4. EXISTING DATA AND LIKELY DATA NEEDS

This section gives a brief overview of existing data on environmental impacts and likely data needs for future work, referring to other sources as far as possible.

4.1 WHAT ARE THE LIKELY IMPACTS?

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 in the near-surface - this could reach tens of percent levels in soil gas, well above any background levels. Uncontrolled leaks would have widespread implications for the environment (West et al., 2005). For terrestrial ecosystems, localised CO_2 leakages might:

- Affect human and animal health (including farm animals).
- Inhibit crop growth or, in high concentrations, cause root asphyxia with resulting plant death
- Change biological diversity and species composition, and asphyxiation at high CO_2 concentrations
- Change subsurface biogeochemical processes as increased CO_2 concentrations could change pH, microbial populations and nutrient supply.

Leakages may also:

- Alter groundwater quality (acidification, mobilisation of heavy metals in aquifers etc) with implications for water resources

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.

4.2 CO_2 IN NATURAL ENVIRONMENTS

Holloway et al, (2005) reviewed the natural occurrences of CO_2 in a variety of geological environments and drew comparisons with CO_2 storage projects. Their principal conclusions were:

- Most natural CO_2 is produced in volcanic regions, which are unsuitable areas for geological storage of anthropogenic CO_2. Most documented CO_2-related impacts on humans, animals and ecosystems also occur in volcanic regions and can not be considered appropriate examples of the likely fate of CO_2 injected in storage projects.
- However, some natural CO_2 concentrations, especially those less common examples occurring in sedimentary basins can be considered more analogous to storage projects. Well-documented examples were compared with current CO_2 storage projects.

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 'Alban Hills' (Chiodini and Frondini, 2001)). Nevertheless, concentrations can vary, for example, from <0.1% to ~95% of the total gas in soils and up to 95% CO_2 in 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.

4.3 BRIEF REVIEW OF INFORMATION AVAILABLE ON ENVIRONMENTAL IMPACTS OF ELEVATED CO_2

4.3.1 Impacts on human health and on ecosystems

A review of health effects of elevated CO_2 concentrations on humans and other vertebrates was undertaken by Rice (2004) in a confidential report. Rice (2004) also made a limited evaluation of the impacts of elevated CO_2 on insects and plants. Some of the findings from this review were presented at the first IEA Risk Assessment meeting in London in 2004 (see www.co2captureandstorage.info for a report of this meeting) . However, 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 (West et al., 2005, 2006). 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. This table provides information on a range of organisms including, for completeness, marine species.

The data in Table 2 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, 2005) have been examined but there are very few studies on entire ecosystems with long-term exposure to chronic CO_2 concentrations (below 10%). 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 (Table 2). Rice (2004) suggest that acute exposure of human populations to CO_2 concentrations >3% and prolonged exposure to concentrations >1% may affect health in the general population. However, 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 a given 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. In terrestrial systems, these may include humans, farmed animals 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. For example, Rice (2004) suggests that non-human mammals seem more resistant to the toxic effects of CO_2 than are humans, but that all mammals are affected. Insects are more tolerant than mammals whilst for plants, the critical threshold level seems to be concentrations of between 20 to 30% (Hepple, 2005). This would have implications for setting of ‘permissible levels’ for any particular target group in any given ecosystem. For example, if human health was the key concern then the ‘permissible level’ maybe somewhat lower than that required for a particular crop.

4.3.2 Other environmental impacts

CO_2 leakage from onshore storage projects could also affect subsurface and surface biogeochemical processes by changing, for example, pH. 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) has undertaken some preliminary modelling of the effects of CO_2 leakage on pH and activity of microbial populations in four groundwater types (‘dolomitic’ and low, medium and high salinity waters – see Onstott, 2005 for more information).

Most trace elements found in coals are normally removed during particulate removal or during cooling. IEAGHG’s report on the impact of impurities on CO_2 capture, transport and storage (IEAGHG, 2004), which addressed issues of co-capturing and injection of sulphur (SOx and H_2S) and NOx, indicated that the most important impurities expected in captured CO_2 were:

- H_2S - from IGCC plants with pre-combustion capture, up to 3.4% depending on fuel and capture processes

- SO_2 – from conventional steam plants with post-combustion capture, with concentrations of up to 2.9% depending on fuel and capture processes.
- NOx 1400ppm depending on fuel and capture processes
- Hydrogen in IGCC plants, up to 1.8% depending on fuel and capture processes
- CO – from IGCC plants, up to 0.2% depending on fuel and capture processes
- N_2
- Ar
- O_2
- Hg - up to 5.6×10^{-5} μg/Nm^3
- As – up to 8.6×10^{-4} μg/Nm^3
- Se – up to 3.2×10^{-5} μg/Nm^3

It should be noted that the authors thought the trace element levels determined above had a high degree of uncertainty and recommended that further studies should be performed to more accurately assess the likely trace element levels that might be expected.

Studies of natural systems where CO_2 leaks within volcanic terrains (see Section 5.1 and Pearce, 2005 and references therein) indicate that CO_2 can act as a carrier gas for sulphur gases including H_2S, radon, methane and other trace components. In addition, CO_2 mobilisation of trace metals is a common geological process, albeit typically on long timescales and at slow rates. 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. In addition, the potential for heavy metal mobilisation via leaking CO_2 has been proposed by several authors, though as yet, little direct evidence from analogue systems has been obtained.

4.4 LIKELY DATA NEEDS

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 storage sites. Additionally:

- 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.
- There are no data on long term, low-level exposure of CO_2 on any 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.
- There are almost no data available on the effects of CO_2 leakage on groundwater quality, particularly in terms of acidification or mobilisation of elements e.g. heavy metals from minerals.
- Little information is available on the potential for co-injected species, or those mobilised during migration, to be transported to the surface with the CO_2 during a leak. Their impacts on the terrestrial environment could be readily inferred from other research and regulations are already in place in many countries to protect the near-surface environment (i.e. groundwater and soil threshold values).

Therefore

- 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.
- Confidence in risk assessments will be increased if biogeochemical processes and their effects can be satisfactorily represented.

Table 1. Some examples of carbon dioxide concentrations and fluxes in natural environments (from West et al, 2005)

Baseline levels	**CO_2 source**		**Concentrations**	**Fluxes**	**References**
Soils	Biogenic	Weyburn, Canada Mammoth Mountain, USA	0.5 –9% CO_2 <0.1%	0.2 – 48 g m^{-2} d^{-1} (over site)	Strutt et al, 2002 McGee and Gerlach, 1988; Rogie et al, 2001
Marine sediments	Volcanic	Mid ocean ridges		Total of 0.63-1.26x10^{12} mol y^{-1}	Turley et al, 2004
Atmosphere	Natural and anthropo-genic		316 ppmv in 1959 376 ppmv in 2003	Annual increase of 2-3 ppmv y^{-1}	Keeling and Whorf, 2004
Naturally leaking CO_2sites					
Groundwater	Volcanic	Crystal Geyser, Utah, USA Albani Hills, Italy Montmiral, France	3.6g $l^{-1}$of water 30-70% in deep waters(~2500m)	Up to 360 g per eruption (50 – 100m^3 water per eruption) Total value of 4.2x10^9 mol y^{-1}	Shipton et al, 2004 Chiodini and Frondini, 2001 Pearce et al, 2004
Soils	Volcanic	Latera, Italy Albani Hills, Italy Matrad-erecske, Hungary Horseshoe Lake, Mammoth Mountain Tree kill area	Up to 98% dissolved in springs Up to 95% 20-90%	6.1x10^8 mol CO_2 y^{-1} 5 to 10 l m^{-2} h^{-1} but can reach 400 l m^{-2} h^{-1} Total discharges in tree kill areas 50-150 tonnes CO_2 per day	Pearce et al, 2004 Chiodini and Frondini, 2001 Pearce et al, 2004 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, Mediterra-nean 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		Worst case prediction 37% of original CO_2	Migrates to 350 m above reservoir. No migration to surface		Cawley et al, 2004

Sea		migrates in 1000 y			

Table 2. Examples of tolerances to CO_2 exposure in selected target organisms (updated 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'	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
	Fish 1-6%	Significant stress	Saripalli (2002)
	Fish >2%	Can be lethal	
Plants	>0.2%	Stimulation of C3 photosynthesis plants (includes temperate cereal crops such as wheat)	Hepple, 2005; Rice 2004
	Trees, Mammoth Mountain, USA 20-90%	Tree killed probably by suppression of root zone respiration via hypoxia	
	>5%	Deleterious effects on plant health and yield.	Saripalli (2002)
	5-30%	Severe effects expected.	
	>30%	Defined as a lethal concentration.	
	>20%	Long-term exposure leads to dead zones with no macroscopic flora.	Benson et al (2002).
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	Onstott, 2005 (Discussion paper)

		rock/water/carbon dioxide interactions and are likely to increase in population size and activity	
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

4.5 REFERENCES

CAWLEY S.,. SAUNDERS M, LE GALLO Y., CARPENTIER B., HOLLOWAY S., KIRBY G. A., BENNISON T., WICKENS L., WIKRAMARATNA R., BIDSTRUP T., ARKLEY S.L.B., BROWNE M.A.E., KETZER J.M. 2004, *NGCAS Project – Assessing the Potential for EOR and CO_2 Storage at the Forties Oilfield, Offshore UK*. In: S.M. BENSON, ed. (2004) The CO_2 Capture and Storage Project (CCP) for Carbon Dioxide Storage in Deep Geologic Formations for Climate Change Mitigation, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification, Elsevier Publishing, Oxford, UK. 713-750.

CHADWICK, R. A., HOLLOWAY, S., BROOK, M. S. AND KIRBY, G. A. 2004 *The case for underground CO_2 sequestration in Northern Europe*. In: BAINES, S. J. AND WORDEN, R. H. (eds) 2004. Geological Storage of Carbon Dioxide. Geological Society, London, Special Publications, 233:17-28.

CHIODINI, G. AND FRONDINI, F. 2001 *Carbon dioxide degassing from the Albani Hills volcanic region, Central Italy*. Chemical Geology, 177:67-83.

HAASUM, I. AND NIELSEN, P. V. 1996 *Preincubation of Penicillium commune conidia under modified atmosphere conditions: influence on growth potential as determined by an impedimetric method.* J. Stored Prod. Res., 32(4):329-337.

HEPPLE, R. P. *Human Health and Ecological Risks of Carbon Dioxide.* In: S.M. BENSON, ed. (2005) The CO2 Capture and Storage Project (CCP) for Carbon Dioxide Storage in Deep Geologic Formations for Climate Change Mitigation, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification, Elsevier Publishing, Oxford, UK. 1143-1172.

HOLLOWAY S., PEARCE J.M., OHSUMI T., AND HARDS. V.L. 2005. *A Review of Natural CO_2 Occurrences and their Relevance to CO_2 Storage*. IEAGHG Report 2005/08, 117 pages.

IEAGHG, 2004. *Impact of Impurities on CO_2 Capture, Transport and Storage*. IEAGHG Report PH4/32, August 2004, 86 pages.

ISHIDA, H. FUKUHARA, T. WATANABE, Y. SHIRAYAMA, Y AND GOLMEN, L. (2006) *Assess the effect of high concentration of CO_2 on deep-sea benthic microorganisms using a benthic chamber system.* 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway.

JONES, N. 2001 *The monster in the Lake*, New Scientist, 2283:36-40.

KEELING, C.D. AND WHORF, T. 2004. *Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

KURIHARA, H. SHIMODE, S. AND SHIRAYAMA, Y. (2004) *Effects of raised CO_2 concentration on the egg production rate and early development of two marine copepods (Acartis steueri and Acartia erythraea)*. Marine Pollution Bulletin, 49:721-727.

MAINA, J. N. 1998 Zoophysiology Vol. 37: *The Gas Exchangers – Structure, Function and Evolution of the Respiratory Processes*, Springer-Verlag, Berlin, Germany.

MANN, D. D., JAYAS, D. S., WHITE, N. D. G. AND MUIR, W. E. 1999 *Mortality of adult Cryptolestes ferrugineus (Stephens) exposed to changing CO_2 concentrations*. J. Stored Products Res. 35:385-395.

MCGEE, K A AND GERLACH, T M. (1988) *Annual cycle of magmatic CO_2 in tree-kill soil at Mammoth Mountain, California: Implications for soil acidification*. Geology 26:463-466.

ONSTOTT T C. 2005 Impact of CO_2 injections on Deep Subsurface Microbial Ecosystems and Potential Ramifications for the Surface Biosphere. In: S.M. Benson, ed. (2004) *The CO_2 Capture and Storage Project (CCP) for Carbon Dioxide Storage in Deep Geologic Formations for Climate Change Mitigation*, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification, Elsevier Publishing, Oxford, UK. 1217-1250.

PEARCE, J.M., CZERNICHOWSKI-LAURIOL, I. LOMBARDI, S. BRUNE, S. NADOR, A. BAKER, J. PAUWELS, H. HATZIYANNIS, G. BEAUBIEN, S. E. FABER, E. 2004 A review of natural CO_2 accumulations in Europe as analogues for geological sequestration. In: Baines, S. J. and Worden, R. H. (eds) 2004. *Geological Storage of Carbon Dioxide*. Geological Society, London, Special Publications, 233:29-42.

PEARCE, J.M. (Editor) 2005. *Final report of the Nascent project.* Available as IEAGHG Report 2005/06. 115 pages.

RASCHI, A. 1997 *Plant Responses to Elevated CO_2*. Cambridge University Press, Cambridge, UK.

RICE. S. A. 2004 *Health effects of CO_2*. EPRI, Palo Alto, CA. California Energy Commission, Sacramento, CA, Oglethorpe Power, Tucker, GA. And Tennessee Valley, Chattanooga, TN: 1009613.

ROGIE, J, KERRICK D, SOREY, M, CHIODINI G AND GALLOWAY, D. (2001) *Dynamics of carbon dioxide emission at Mammoth Mountain, California*. Earth and Planetary Science Letters. 188:535-541.

SHIPTON, Z. K., EVANS, J. P., DOCKRILL, B., HEALTH, J., WILLIAMS, A., KIRCHNER, D., KOLESAR, P. T. 2004 *Natural Leaking CO_2-Charged Systems as analogues for Failed Geologic Storage reservoirs*. In: S.M. BENSON, ed. (2004) The CO_2 Capture and Storage Project (CCP) for Carbon Dioxide Storage in Deep Geologic Formations for Climate Change Mitigation, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification, Elsevier Publishing, Oxford, UK.

SENTER FOR MILJO-OG RESSURSSTUDIER (SMR) 1999 *CO_2 and marine life: report from a workshop in Bergen, Norway 16-18 February 1998*. Senter for Miljo-og Ressursstudier (SMR) – report 30/99.

SHIRAYAMA, Y. 1997 *Biodiversity and biological impact of ocean disposal of carbon dioxide*. Waste Management, 53 (1-2):147-161.

SHIRAYAMA, Y. 2002 *Towards a comprehensive understanding of impacts on marine organisms due to raised CO_2 concentrations.* In: Proceedings of the 5th International Symposium on CO_2 Fixation and Efficient Utilisation of Energy, Tokyo Institute of Technology, Tokyo. 177-181.

STRUTT M H, BEAUBIEN S W, BEAUBRON J C, BRACH M, CARDELLINI C, GRANIERI R, JONES D G, LOMBARDI S, PENNER L, QUATTROCCHI F AND VOLTATORNI N. 2002 *Soil gas as a monitoring tool of deep geological sequestration of Carbon dioxide: Preliminary results from the Encana EOR Project in Weyburn Saskatchewan (Canada)* GHGT-6 p391.

SUSTR, V. AND SIEMK, M. 1996 *Behavioural responses to and lethal effects of elevated carbon dioxide concentration in soil invertebrates.* Eur. J. Soil Biol., 32:149-155.

TIAN, S., FAN, Q., XU, Y., WANG, Y. AND JIANG, A. 2001 *Evaluation of the use of high CO_2 concentrations and cold storage to control Monilinia fructicola on sweet cherries.* Postharvest Biol. Technol., 22:53-60

TURLEY, C., NIGHTINGALE, P.,RILEY, N., WIDDICOMBE, S., JOINT, I., GALLIENNE, C., LOWE, D., GOLDSON, L., BEAUMONT, N., MARIOTTE, P., GROOM, S., SMERDON, G., REES, A., BLACKFORD, J., OWENS, N., WEST, J., LAND, P., AND WOODASON, E. 2004. *Environmental Impact of a gradual or catastrophic release of CO_2 into the Marine Environment following carbon dioxide capture and storage*. Report to UK Dept for Environment, Food and Rural Affairs (DEFRA) (DEFRA:MARP 30 (ME2104) 31 March 2004).

WEST J M, PEARCE J P, BENTHAM M AND MAUL P. *Issue Profile: Environmental Issues and the Geological Storage of CO_2.* European Environment 2005 15:250 –259.

WEST, J. M. PEARCE, J. BENTHAM, M. ROCHELLE, C. MAUL, P. AND LOMBARDI, S. (2006) *Environmental Issues and the geological storage of CO_2 – A European Perspective*. 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway.

www.lvo.wr.usgs.gov/co2.html - Information on Mammoth Mountain

YAMADA, Y. AND IKEDA, T. 1999 *Acute toxicity of lowered pH to some oceanic zooplankton.* Plankton Biology and Ecology 46(1-12):62-67.

5. CURRENT RESEARCH

5.1 CO_2GEONET

CO_2GeoNet is a European Network of Excellence for geological storage of CO_2 with 13 European research partners (see www.CO_2GeoNet.com). The current total budget for the Network, which started in April 2004 and Phase 1 of which is due to last 5 years, is approximately €9 million. Several Joint Research Activity Projects (JRAPs) are being undertaken within the Network including one entitled 'Ecosystem responses to CO_2 Leakage-Model Approach', a large component of which consists of studying terrestrial ecosystems. The total budget for this project, which started in July 2005, is €400,000 from EC and partner contributions, over 2 years. 6 Network partners are involved: BGS (Coordinators: UK), BGR (Germany), BRGM (France), NIVA (Norway), OGS (Italy) and University Rome "La Sapienza" (Italy). Quintessa (UK) is also participating. The project has links with DTI (UK), Nottingham University (UK) and RITE (Japan).

The aim of the project is to provide holistic integrated site investigation tools enabling stakeholders to assess the long-term potential risks of geological storage on subsurface, terrestrial and marine ecosystems. There are 4 tasks:

1. Development of a system model for assessment of near-surface long-term impacts.
2. Feasibility studies to set up European Test Facilities.
3. Development of a Decision Support Tool.
4. Dissemination.

There has been considerable progress in the project – particularly in the terrestrial studies where the partners have been characterising ecological effects and impacts of CO_2 exposure at several analogue sites including Latera, Italy and Laacher See (a lacustrine site), Germany. Additionally, work is also being undertaken at a controlled CO_2 injection site at the University of Nottingham in the UK see section 5.3.

Work at the Latera site is particularly advanced because the area has been subject to long-term escape of CO_2 to the atmosphere in an agricultural setting and because much of the detailed and essential geological information is already available (e.g. from the NASCENT project). Studies have concentrated on one particular vent situated in a pasture where clover is the dominant plant. The vent:

1) Is spatially well-defined and isolated from other gas vents;
2) Has CO_2 concentrations ranging from 2 to 100% without the presence of other conflicting gases (such as H_2S, which only occurs in the central core of the vent)

In order to understand the effect of CO_2 leakage on such an ecosystem, the partners have been characterising a 50 m transect across the vent and have undertaken a variety of botanical, microbiological, geochemical, mineralogical and gas analyses. These were carried out in September 2005 and June 2006 in order to assess seasonal variations. Results are currently being compiled and interpreted and will be available in March 2007.

A generic system model is also being developed which is initially using Latera field information (see West et al., in press). The model can then be applied to both natural analogue sites and geological storage sites using software developed by Quintessa (UK). It is planned that the system-level model will have sub-models for the deep geosphere, near-surface regions, and representative ecosystems. Although the model structure is simple, a large number of chemical, biological and microbiological processes will need to be considered in representing the transfers between the different parts of the sub-system.

The overall ambition for the Latera system-level model is to:

- Reproduce realistic fluxes to the surface and to near-surface aquifers;
- Provide an overall mass balance for the system;
- Calculate the effect on groundwater acidity;
- Calculate soil gas concentrations for different assumptions about key near-surface processes;
- Calculate the contribution of vented CO_2 to atmospheric concentrations; and
- Calculate potential impacts to flora/fauna and humans from calculated environmental concentrations

It is planned to complete illustrative calculations for this site by the end of 2006.

5.2 BIOMONITORING

A poster was presented at the Greenhouse Gas Control Technologies conference (GHGT8) by Tarkowski et al (in press), which detailed efforts by two Polish groups (Mineral and Energy Economy Research Institute of the Polish Academy of Sciences and the Agriculture University of Cracow) to isolate soil microorganisms that could be used to monitor CO_2 leakage. This appears to be preliminary work but was the only paper presented on the topic at GHGT8.

5.3 ASGARD

In 2005, Profs. Mike Stevens and Jeremy Colls of the University of Nottingham established a field site to study impacts of CO_2 leakage on agricultural crops funded via a large university capital grant and the UK Carbon Capture and Storage Consortium, see http://www.co2storage.org.uk/. The ASGARD site consists of 30 plots measuring 2.5m x 2.5m which are arrayed in a rectangular grid pattern (5 x 6 plots) with pathways (~50 cm) between each plot. A CO_2 injection system has been developed allowing injection of CO_2 at variable flux rates, at a depth of approximately 60cm below each plot.

In the spring of 2006, 16 plots were planted with two crop plants, barley and linseed, 10 were to remain covered in grassland pasture vegetation with the remaining 4 plots being available for other uses e.g. testing equipment. Additionally, two areas were selected to the East and West of the grid to act as control plots. CO_2 injection began in early summer 2006 and is planned to continue until the end of the predominant growing season in September 2006. Plant responses will be studied by the university, including assessing changes to spectral responses to further develop monitoring using hyperspectral remote sensing techniques.

The British Geological Survey is collaborating with the University, via the CO_2GeoNet programme, as the ASGARD site has the potential to become one of the few European Test Facilities for studying impacts of carbon dioxide leakage on terrestrial ecosystems and for testing onshore monitoring techniques. Specifically, it could be the only Test Facility in Europe where controlled direct injection of CO_2 could be undertaken and could thus be a major hub of research for Carbon Capture and Storage (CCS) for European organisations – principally those who have been involved in the European Network of Excellence CO2GeoNet. In addition to geological site characterisation, BGS is assessing impacts to soil microbes and invertebrates, pasture vegetation, soil geochemistry and mineralogy. BGS is also testing new soil gas monitoring equipment at the site.

5.4 OHIO RIVER VALLEY

Shidara et al. (in press) recently presented an EIA case study for the Ohio River Valley region of the USA. Here, they developed an impacts assessment methodology to assess the potential impacts of an upwards migration of CO_2 on groundwaters. This involved three steps: evaluating CO_2 behaviour during migration, evaluating the nature of trace elements and an environmental impact for groundwaters. Upwards migration was modelled using the TOUGH2 code and the authors report that more detailed reservoir modelling is underway at Battelle Memorial Institute. Two cases were modelled, a baseline case based on field and laboratory data and a second case where sealing capabilities are hypothetically poor. The Mitsubishi Heavy Industries pilot test plant was used to evaluate the concentrations of trace elements (As, B, Se and Hg) remaining in the CO_2 stream following recovery by chemical absorption. All concentrations were found to be below detection limits i.e. at parts per billion levels. The potential for CO_2 to mobilise trace elements during migration through the shale, sandstone and limestone overburden indicated that some elements, notably As and B, could be mobilised during CO_2 migration through shales. However, concentrations of these elements remained below Japanese water quality thresholds.

5.5 DEPARTMENT OF ECOLOGY AND EVOLUTION, UPPSALA UNIVERSITY, SWEDEN

Professor Lars Tranvik at the Uppsala University has been studying natural CO_2 supersaturation of lake waters, which is a result of bacterial mineralization, and consequent export of CO_2 to the atmosphere (Algesten et al; 2003; Sobek et al, 2005). Such studies will have some relevance to evaluating terrestrial impacts – particularly in terms of long-term exposure of organisms to high concentrations of CO_2 in shallow lakes. However, Prof. Tranvik is not aware of any specific studies connected to CO_2 storage. Work following on from the Lake Nyos event is not relevant to these studies (deep lake, different geological setting, etc).

5.6 THE ZERT PROJECT

A collaborative project, called the Zero-Emission Research and Technology Center, involving DoE National Labs and universities has recently been launched. Organisations involved include Montana State Univeristy, Los Alamos, Pacific Northwest, Lawrence Berkeley and Lawrence Livermore national laboratories, West Virginia University and the National Energy Technology Laboratory. As part of this project a new test facility is being developed on Montana State University grounds to test monitoring technologies and improve groundwater-vadose zone atmospheric dispersion models (http://www.montana.edu/zert/home.php). The site will comprise of a horizontal perforated injection pipe, approximately 100 m in length, at a depth of 2.8 m, that will allow controlled release of CO_2 into the soil environment. A series of monitoring wells will be placed around the injection pipe to monitor CO_2 movement in the vadose zone. A range of atmospheric monitoring equipment will also enable atmospheric dispersion of CO_2 as it leaves the soil surface, to be monitored.

Preliminary feasibility vertical injection tests were performed in the summer of 2006 with injection rates of 2.3 kg/day. A range of monitoring techniques were deployed to monitor CO_2 movement and include soil gas techniques , atmospheric monitoring (eddy covariance), remote sensing techniques (hyperspectral and LIDAR), geophysical (resistivity) and geochemical techniques (isotopic analyses of gases and water, tracers).

An overview was presented by Prof. Lee Spangler of Montana State University at the IEAGHG International Monitoring Network meeting in Melbourne, Australia in November 2006 (see www.co2captureandstorage.info for more details).

5.7 REFERENCES

ALGESETEN, G, SOBEK, S, BERGSTROM, A-J, AGREN,A, TRANVIK L J AND JANSSON, M 2003 *Role of lakes for organic carbon cycling in the boreal zone*. Global Change Biology, 10, 141-147

BENSON, S. M., HEPPLE, R., APPS, J., TSANG, C. F. & LIPPMANN, M., 2002. *Lessons learned from natural and industrial analogues for storage of carbon dioxide in deep geological formations.* Report nr. LBNL-51170, Lawrence Berkeley National Laboratory, Berkeley, USA.

SARIPALLI, K. P., COOK, E. M. & MAHASENAN, N., 2002. *Risk and hazard assessment for projects involving the geological sequestration of CO_2*, *In*: GALE, J. & KAYA, Y. (Eds), 2002. Proceedings from 6th International Conference on Greenhouse Gas Technologies, Kyoto, October 2002.

SHIDAHARA T., GUPTA, N., IWASAKI S., SUENAGA H., ITO Y. (In press) *A case study on the environmental impact assessment on groundwater in Ohio River Valley region for CO_2 geological sequestration.* 8th International Conference on Greenhouse Gas Control Technologies. Trondheim, Norway, June 2006.

SOBEK, S, TRANVIK, L AND COLE, J J. 2005 *Temperature independence of carbon dioxide supersaturation in global lakes*. Global Biogeochemical Cycles 19 GB2003.

TARKOWSKI, R., KROLIK, W., ULIASZ-MISIAK, B. AND BARBASZ. W. (in press) *Biomonitoring as a tool to detect CO_2 leakage from underground storage*. 8th International Conference on Greenhouse Gas Control Technologies. Trondheim, Norway, June 2006.

WEST, J. M., PEARCE, J., BENTHAM, M., ROCHELLE, C. AND MAUL, P. (in press) *Environmental issues, and the geological storage of CO_2 – a European perspective.* 8th International Conference on Greenhouse Gas Control Technologies. Trondheim, Norway, June 2006.

6. GAPS IN CURRENT UNDERSTANDING

In this section, we discuss the areas where the potential impacts of a leak to the near-surface cannot, as yet, be fully described, due to a lack of knowledge or agreement between key stakeholders. This is not meant to imply disagreement exists between stakeholders, rather that issues have not been discussed, except on a project-specific basis and formal regulatory frameworks, if needed, have not been developed.

6.1 KEY KNOWLEDGE GAPS

A power company perspective: Eriksson et al. (2006), identified some priority gaps in knowledge within the terrestrial environment. It was recognised that existing information relates to studies performed at the organism level. These gaps are listed as follows:

- The subsurface impacts relating to increased CO_2 concentrations in soils and groundwaters
- The potential effects on birds has not been studied.
- Ecosystem responses are virtually unknown. Since organisms are part of an ecosystem, if one species is affected by increased CO_2 concentrations, this may have indirect consequences for other species.
- Little information is available on the effects of increased CO_2 concentrations on freshwater lakes and rivers. Most information relates to atmospheric increases in CO_2 concentration and climate change rather than leakage from depth.
- The effects of additional, potentially toxic, components that may be mobilised with CO_2 during leakage have so far received little attention.

Though Eriksson et al. do not list which species should be the focus for further research, these could include vegetation (including crops), invertebrates, microbes (especially in the soil environment), mammals and birds.

Most potential impacts and their inclusion in EIAs, seem to be based on expert opinion with little supporting data. However, we have identified that:

1. Although there are data on the effects of slightly increased CO_2 concentrations and on lethal concentrations on species, obtained during investigations into the impacts of climate change, there are no data on long term chronic exposure following a leak from a CO_2 storage reservoir, on either target species or total ecosystems.

2. For a robust EIA of a CO_2 storage project, it will be important to understand the local effects of a CO_2 leak from depth, in comparison to global increases on the environment and habitats. Elevated atmospheric CO_2 (say to 550ppm) could be several orders of magnitude below that from a leaking storage site. Much of the existing data are from studies of global atmospheric rises.

3. Acceptable limits or thresholds for CO_2 concentrations in a variety of near-surface ecosystems have yet to be established. These are likely to vary depending on the environment, reflecting natural background variations in CO_2 concentration (see Table 1).

4. Currently, there is no strategy or research program for identifying key organisms or appropriate thresholds for specific ecosystems. This constrains the capabilities of risk assessments to accurately identify important risks and consequently the formulation of appropriate, cost-effective monitoring protocols and remediation plans.

5. Current best practice in environmental impact assessments defines the scope of assessments as the operational lifetime of the project and include legacy issues associated with infrastructure and site decommissioning. Timeframes of relevance to geological storage are not normally considered. Notably GJV makes some reference to the Gorgon CO_2 storage project in their EIS on the proposed Barrow Island gas processing facility (See section 3.3.2) but does not refer to timescales.

The following are specific areas that may require further investigation to enable EIAs to include consideration of the long-term impacts of potential leaks from CO_2 storage projects in the terrestrial environment:

1. 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.

2. No data on total ecosystem responses to a CO_2 leak and their recovery times is available.

3. No specific data is 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 has been generated, with the exception of literature reviews performed within the Nascent project.

4. Co-injected species have received little attention so far but could include O_2, H_2O, SO_2, NO, H_2S, CO, Ar, N_2, Hg, Cd, and NH_3. Hg and Cd are likely to be at ppb levels. Many of these co-injected gases 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. While the CO_2GeoNet research at Latera provides information on the impacts of H_2S leaks from depth in the near-surface environment, the preliminary data obtained so far would suggest concentrations of soil H_2S are far in excess of those likely to arise from a leaking storage project (possibly with the exception of catastrophic well failure).

5. Little data exists on impacts from high concentrations of CO_2 emerging from depth on the soil environment.

6. There is currently a lack of integration between considerations of potential impacts of CO_2 leaks on terrestrial ecosystems and performance assessments. 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, clearly CO_2 storage projects present new challenges due to the very long timescales that need to be considered after the injection project has finished.

As recommended by Zakkour (2006), the EIA process, including formal public consultation, may be a suitable approach for an operator to develop its monitoring and remediation plans, and formulate appropriate evidence that future (residual) risks are as low as reasonably practicable. It may also provide regulators with an appropriate and familiar methodology for assessing a project's safety case. To date, there has been little discussion of how to successfully incorporate an EIA into the assessment of a site's future performance. Reasons for this could include:

- A lack of a clear regulatory framework, including appropriate safety/performance criteria. Such criteria may be defined by current relevant legislation developed in other areas, supported by relevant data to plug gaps identified here.
- Current and near-term CO_2 projects are closely associated with oil and gas production operations and are licensed within this regime, where long-term storage issues do not appear to be normally considered.
- As CO_2 storage moves increasingly from concept to demonstration, with new projects being initiated, consideration of potential impacts is also now receiving more attention.

6.2 EIA AND PERFORMANCE ASSESSMENT

It is currently unclear if specific safety/performance criteria for long-term CO_2 storage projects should be added to those already defined through other HSE legislation. If performance criteria were considered appropriate, several questions may be identified:

- Should they be generic or site-specific?
- How relevant could generic safety criteria be? Will generic criteria reflect issues related to global emissions?
- What form would they take?

If such performance criteria are not considered a requirement of an EIA or performance assessment, three issues should be addressed:

- How can operators and regulators judge site performance and what aspects of ecosystems to monitor?
- How do operators and regulators know when to intervene, what to remediate, how to remediate?
- How do the operators and regulators address public concerns about long-term safety of the site?

Within many stakeholder groups it is assumed that a leak from a CO_2 storage facility is unacceptable and to be avoided, but no real evidence of the impact of such a leak is clearly presented. For both operators and regulators, this may be a difficult position to defend. A better argument may be:

- We have designed the best possible project, including site selection, site characterisation and geological model, infrastructure design, project plan etc…
- We have baseline data against which to compare future performance, including variations in near-surface environment
- Our predictions indicate the chances of a leak occurring are as low as possible
- We will monitor to spot deviations from these predictions
- If such deviations occur, this may lead to interventions to prevent CO_2 reaching the surface
- However if a leak did occur…
  - We have identified susceptible receptors
  - It would require a leak of a specified magnitude to cause unacceptable harm
    - Criteria may be: water or air quality, biodiversity, loss of habitat, etc…
    - These criteria will be defined by existing regulations (e.g. EC directives etc) or by new regulations
  - Such a leak is (very) unlikely
    - Based on performance assessment

- We could detect the leak (and attribute this to project CO_2) and its impacts on indicator species
- The impacts are *known* for key species (microbe, plant, invertebrate, reptile, mammal, bird, human…)
- The indirect impacts (changes to habitat, biodiversity, etc) on the ecosystem are *known*
- We have developed an appropriate remediation plan
- Recovery times are known

6.3 A PROPOSED RESEARCH PLAN

Here we propose a generic workflow for identifying impacts and their relative significance, monitoring and remediation:

1. *Scenario definition:*

   Define various relevant scenarios, including leakage pathways, fluxes and anticipated CO_2 plus other contaminants in receptor environments. This would be achieved through FEP analyses and initial scoping modelling, thereby identifying gaps in knowledge for specific scenarios. The scenarios would reflect the storage context (geographical location, local environment, land use, etc)

2. *Characterisation:*

   Define surface and subsurface ecosystems in terms of flora and fauna. Identify key indicator species (most susceptible, those showing biggest change).

3. *Impacts:*

   Identify impacts of CO_2 on indicator species and total ecosystem.

   Define appropriate thresholds and safety criteria.

   Identify recovery rates.

   Scope impacts on groundwaters via modelling and experiments, if appropriate.

4. *Monitoring:*

Develop floral and faunal monitoring techniques

5. *Integration:*

   Improve system models by integrating key processes and indicators in an iterative manner.

Key outputs from such a research plan would be:

a) Identification of target species for monitoring and recommendations for appropriate, cost-effective monitoring techniques.

b) Development of appropriate, cost-effective remediation strategies

c) A monitoring protocol for near-surface ecosystem impacts.

d) Identification of recovery rates

e) Identification of appropriate thresholds, trigger events and safety criteria

Specific R&D activities

An integrated approach for all the activities described above is needed to develop a systematic, rigorous and coherent appraisal of potential impacts. This will promote greater acceptability by operators, regulators and other stakeholders. Here we outline specific activities that could be combined to meet the workflow described above. Indicative costs have been requested and have been given. These costs should be taken as very rough estimates and treated with appropriate caution. They are based purely on the authors' experiences of current research; for example within CO_2GeoNet. Costs will vary greatly depending on funding models, institutional costs and location.

a) Coordination and annual meeting of key researchers, internationally, from experimental, analogue and system modelling communities with key stakeholders (operators, regulators…). The objective would be to compare approaches, data and share experience, and achieve consensus on key issues with stakeholders.

€150k

b) Development of system models for scenarios.

€150k

c) Use of experimental sites for identifying processes, response times, impacts, recovery rates, indicator species for different ecosystems, land use and climate and development and testing of monitoring techniques. A number of experimental sites will be required to reflect variations in ecosystems for various onshore storage projects (temperate, arid, semi-arid, subtropical, tropical, various land uses (agricultural, wooded, urban, wilderness, lakes, rivers etc).

€2.5m per site

d) Where opportunities exist, natural near-surface and surface CO_2 seeps can provide very valuable information on long-term processes not readily available from experiments. They also enable models to be validated, providing confidence that models are able to realistically represent key processes for leakage and impacts for a specific scenario or range of scenarios.

Activities could include microbiological, invertebrate, botanical and biogeochemical assessments of impacts, identification of key processes and their rates of change, development and testing of monitoring techniques including remote sensing, atmospheric monitoring, floral and faunal monitoring.

€700k per site

7. CONCLUSIONS

1. Current demonstration projects are associated with commercial oil and gas operations and as such are regulated by existing oil and gas legislation. Regulators are now beginning to evaluate whether existing regulations are adequate to address the long-term issues arising in CO_2 storage. The potential for leakage, its impacts and remediation are key concerns for all stakeholders. One established approach to addressing these concerns, especially onshore, may be through environmental impact assessments (EIAs).

2. However, currently EIAs in many industries, including oil and gas, typically focus on the construction, operation and decommissioning stages of a project. Long-term legacy issues, including potential impacts from a leak far in the future, are not addressed, especially in the near-surface environment.

3. There is a considerable body of research on the effects of elevated *atmospheric* concentrations of CO_2 on ecosystems, especially on plants.

4. Information is lacking on long-term chronic and acute exposure to CO_2 in the soil environments.

5. Receptor ecosystems will be site-specific but, in general terms, can be categorised as groundwater, soil, freshwater and surface ecosystems. In specific cases, caverns may also be an important consideration. Flora of interest may include natural and crop vegetation. Fauna may include soil microbes, invertebrates, reptiles and mammals. The impacts of elevated CO_2 on humans during acute exposure have been documented, though largely for healthy adults. Acute and chronic exposure to other sections of populations has not been studied.

6. Possible impacts are wide-ranging and include influences on single species and on total ecosystems. Additionally, changes in groundwater quality as a result of (bio)geochemical processes may need to be considered.

7. Gaps in information are:

(i) 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.

(ii) No data on total ecosystem responses to a CO_2 leak and their recovery times is available.

(iii) No threshold values have been identified – again these are to some extent likely to be ecosystem- and even site-specific. It is not clear whether the use of threshold values is appropriate in the risk management of storage projects. The definition and application of threshold or trigger values requires very careful consideration to avoid overly burdensome constraints on projects and operators. However, such an approach may have benefits such as clear integration with monitoring regimes that enable specific actions to be defined following thresholds being reached; and the formulation of targeted and clear remediation plans.

(iv) No specific data is available on the potential impacts on groundwater or surface water quality. Though the potential for CO_2 to mobilise trace metals, other gases and hydrocarbons has long been recognised, little data has been generated, with the exception of limited research performed within the Nascent project.

(v) Little data exists on impacts of high concentrations of CO_2 migrating from depth into the soil environment.

8. There is currently a lack of integration between considerations of potential impacts of CO_2 leaks on terrestrial ecosystems and performance assessments.

9. Key components for a research programme to address current gaps are listed below and described in more detail in section 6.3. Key outputs from such a research plan would be:

   a. Identification of target species for monitoring and recommendations for appropriate, cost-effective monitoring techniques.

   b. Development of appropriate, cost-effective remediation strategies

c. A monitoring protocol for near-surface ecosystem impacts.
d. Identification of recovery rates
e. Identification of appropriate thresholds, trigger events and safety criteria

10. The overall approach should integrate research on impacts with risk assessments. An integrated approach for all the activities described above is needed to develop a systematic, rigorous and coherent appraisal of potential impacts. This will promote greater acceptability by operators, regulators and other stakeholders. Key components of a research programme:
    a. Scenario definition: to identify relevant scenarios including leakage pathways, fluxes and anticipated CO_2 plus other contaminants in receptor environments.
    b. Characterise surface and subsurface ecosystems in terms of flora and fauna. Identify key indicator species (most susceptible, those showing biggest change).
    c. Identify impacts of CO_2 on indicator species and total ecosystem. Define appropriate thresholds and safety criteria. Identify recovery rates. Scope impacts on groundwaters via modelling and experiments, if appropriate.
    d. Develop floral and faunal monitoring techniques
    e. Improve system models by integrating key processes and indicators in an iterative manner.