OVERVIEW OF LONG TERM FRAMEWORK FOR CO_2 CAPTURE AND STORAGE

Report Number PH4/35
November 2004

This document has been prepared for the Executive Committee of the Programme.
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Background to the Study

Capture and geological storage of CO_2 is a technically feasible mitigation option. Much of the technology required can be readily adapted from existing industries, such as the oil and gas production and chemical industries. However, despite the fact that there are several large scale demonstration projects underway or planned worldwide, CO_2 capture and storage has yet to gain international recognition as a safe and effective greenhouse gas emission abatement technology. In an attempt to understand the obstacles that stand in the way of wide scale deployment of CO_2 storage in depleted oil and gas fields, the IEA Greenhouse Gas R&D Programme (IEA GHG) undertook a study to assess what the potential barriers were and how these could be overcome[1]. The main barriers identified by the study were as follows:

1. The high costs of capturing, processing and transporting anthropogenic CO_2.
2. Incomplete understanding of reservoir processes and storage methods.
3. Monitoring, verification and environmental safety of CO_2 storage.
4. Lack of functioning emission trading system and storage regulations.
5. Commercial/organisational conflicts between CO_2 storage and production in EOR or natural gas recovery.

Work is underway to address several of these barriers but it is considered by IEA GHG that greater consideration may need to be given to the type of regulatory system that may be required. To begin to address this barrier IEA GHG has completed a study that has considered potential guidelines for CO_2 transmission and storage[2]. However, it could be argued that this addresses near term needs and may not encompass the whole range of regulatory issues that could be associated with storage of CO_2 in geological reservoirs for thousands of years.

The aim of the study reported here, therefore, is to focus on the long term framework for CO_2 capture and storage (CCS). The result will be a scoping paper that will be used to stimulate discussion on the key regulatory issues to be considered following, in particular, the closure of CO_2 storage sites; for this reason it was recognised that the study should explicitly take account of the likely timescales involved.

The study has been carried out by a consortium of companies which included: Monitor Scientific (USA), Massachusetts Institute of Technology (USA), University of Regina (Canada) and Ledingham Chalmers (UK).

Results and Discussion

The following aspects of a long-term framework are discussed in this report:

- Relevant timeframes,
- Liability and ownership issues,
- Regulatory framework requirements,
- Record keeping and accounting.

[1] IEA Greenhouse Gas R&D Programme Report No. PH3/22, Barriers to overcome in implementation of CO_2 capture and storage (1): Storage in depleted oil and gas fields, February 2000.
[2] IEA Greenhouse Gas R&D Programme Report No. PH4/23, Rules and standards for the transmission and storage of CO_2, August 2003.

Relevant timeframes

One of the key requirements for this study was to address the issue of timescales for CO_2 storage. Setting a timescale for CO_2 storage provides a structure around which the remainder of the study can be built. The timescale will help to determine many of the regulatory issues and how these would be treated under a regulatory system. In the opinion of the contractor, two major considerations will influence regulatory guidance and control; these can be summarised as:

1. The performance of the storage system (i.e. the effectiveness of the system to store CO_2 long term as a mitigation option for climate change)
2. The environmental impact of the storage system.

In considering the timescales relating to performance, consideration was given to the likely duration of fossil fuel use as a primary energy source[3]. In this context it was recommended by the consultant that a performance timescale of a 'few hundred years' (200 to 500 years) could be considered[4]. Such a range reflects the uncertainties about the longevity of fossil fuels resources and about the ability of new technology to effectively replace fossil fuels in the energy sector.

Whilst it was acknowledged that the environmental impact depends on the performance of the system, such impacts can be considered to be more local than global in nature; hence it can be envisaged that different timescales will be involved from those relevant to system performance. It was considered by the contractor to be difficult to assign a timescale for environmental impact because our knowledge of the storage system is currently limited[5]. Information available currently indicates that the pressure build-up in a reservoir will reach a maximum at the point when injection ends; then the CO_2 plume will gradually spread out and begin to dissolve, with complete dissolution taking place after 3000 or 4000 years. In the intervening period, if the plume reaches a spill point or a natural feature such as a fault, there is the potential for the CO_2 to leak out of the reservoir and hence for environmental impacts to occur. The timescale for post-injection regulatory control could, therefore, extend from the end of the operational phase until several thousand years afterwards. However, as our knowledge of the storage system increases, this timescale might well be reduced.

Liability and ownership issues

Three potential types of liability associated with CO_2 capture and storage can be considered which are:

- *Operational liability* – i.e. the liability associated with the engineered system (capture, transmission and injection of CO_2),
- *Climate liability* – this is the liability associated with leakage from a CO_2 storage reservoir and its effect on the global climate,
- *In situ liability* – the liability associated with leakage of CO_2 that could result in public health impacts and/or environmental ecosystem damage.

Of the three liability types, it is considered that operational liability is well understood and effectively managed by industry currently. Since the technology for CCS is merely a development of existing

[3] The discussion on fossil fuel potential did not consider new sources such as natural gas hydrates, which could extend the longevity of the fossil fuel based economy by 1000s of years (and the required storage timescale accordingly).
[4] The timescale proposed by the consultants is based on an analysis of available literature including the IPCC Third Assessment Report and the IPCC SRES scenarios. It assumes that oil and gas will run out by the end of this century and then coal will remain the dominant fossil fuel for the foreseeable future.
[5] Currently our knowledge of CO_2 storage systems is limited to a few examples worldwide, such as Sleipner and Weyburn, where CO_2 has been injected and monitored. In view of the limited data available it would be difficult to assume that these reservoirs are typical of all future storage reservoirs. As more projects come on-stream and as more monitoring data is gathered, the knowledge of storage system performance and the potential for leakage will increase.

chemical and oil/gas industry practice we can expect that this liability can also be effectively managed during the operational phase of any storage project. Climate liability is primarily an economic issue since it can be assumed that CO_2 emissions will be traded and credits gained for reducing emissions; this is discussed further in the section on record keeping and accounting. In situ liability, however, is considered to be the most important for any long term framework on CCS. In situ liability will last for as long as potential impacts are likely to arise which, as discussed earlier, could be several thousand years based on our current knowledge of the storage system. An effective site selection process is the best way to minimize the risk of in situ liability.

Legal standards of liability are typically assessed in terms of *negligence* and *strict liability*. Apart from any specific statutory authority governing liability, most modern accident law in the USA is addressed through negligence claims. Negligence is the failure of a person to exercise reasonable care. Lawsuits often hinge on the interpretation of "reasonable care". Firms which conduct activities associated with CO_2 storage would be considered professionals. In law, professionals must exercise the skill and knowledge normally possessed by members of their profession, otherwise they may be found negligent. In order to encourage the entity most able to control risk to internalise the relevant costs, "strict liability" was established. Under strict liability in the USA, a person (or corporation) is held liable for the harm that his or her activity caused, regardless of whether reasonable care was used. Although the ultimate finding of strict liability is made in a court, application of strict liability can be imposed by either the courts or the legislature. The concepts of strict liability and negligence/duty of care were considered by the consultant also to apply in general terms in the UK[6] and will apply, in the future, in the rest of the European Union[7].

Consideration of long-term liability is a key element in assessing the viability of geological storage of CO_2. The way in which liability is addressed may have a significant impact on costs and, indirectly, on public perceptions of geologic storage. The critical question is how the judiciary, legislatures, and regulatory authorities will treat geologic storage once it is accepted as a mitigation option. It is currently uncertain whether liability for geologic CO_2 storage will be treated more like the historic treatment of natural gas (which has imposed relatively low costs on operators), or more like hazardous waste (which has been much more burdensome to participants, and much more politicised). The answer will depend in part on a number of factors, *viz.* (i) the results of current research assessing the risks of this technology; (ii) the first projects that attempt to store CO_2 on a large scale explicitly for the purposes of reducing emissions of CO_2 to the atmosphere; (iii) the reaction of the public and interest groups to those risks and efforts; and (iv) actuarial and financial analyses of liability.

Liability could be dealt with on a variety of levels. For example, four levels can be recognised in the USA: federal (national) government, state (sub-national) government, industry, and individual corporations. These levels are non-exclusive, and approaches are likely to take place on multiple levels; for example, by combining national statutes with corporate-level strategies. In Europe, an international (EU) regulatory framework would provide an additional level, applicable to Member States of the European Union.

Another issue influencing liability is reservoir ownership. Ownership rights vary from locality to locality - in some cases it is the owner of the land above the reservoir who holds the rights, and in others it is the owner of the mineral rights. Therefore, ownership of the storage reservoir needs to be established at the project outset. The other issue is the need to determine what compensation, in terms of royalty payments, are necessary and to whom. If governments embrace CCS, there may well be new laws regarding the use of geological storage reservoirs so, if a government assumes some of the long term responsibility for integrity they may also assume ownership of the reservoirs, if they do not own them already

[6] This interpretation is based on a landmark ruling in UK law under a case known as Rylands and Fletcher. Details of the implications of this ruling are discussed in the text of the main report.

[7] A new EC directive was proposed on environmental liability in January 2002, which is expected to be adopted in 2004. Member states would then have until 2007 to implement this directive

Regulatory framework requirements

Within the regulatory framework for long term storage of CO_2 a number of key components will be required. These key components will cover the following:

- Site selection and characterisation,
- Safety assessments,
- Leakage from abandoned wells
- Performance monitoring.

Effective site selection and characterisation prior to injection will be a critical factor that can reduce potential liability and help in gaining public acceptance for CO_2 storage. There are, however, potential operational and economic penalties associated with this component that must be taken into account when any regulatory framework is developed. If the initial guidelines for site selection and characterisation are too restrictive, it could have a major impact on project costs and set a precedent which may be unattractive to future project developers. Such an economic penalty could therefore adversely affect the application of the technology. However, if the initial guidelines are too loose, it opens up the possibility of having projects that perform poorly i.e. they leak. If leakage occurs, this could adversely affect public opinion on CCS which would again adversely affect the application of the technology.

Within the regulatory process a safety and environmental assessment framework will be necessary in order to assure the authorities that all important aspects of CO_2 storage have been considered and covered appropriately prior to project implementation[8]. However, currently, the safety assessment frameworks routinely used by industry do not cover the timescales being discussed in this report for CCS (i.e. hundreds to thousands of years). Typically, these frameworks cover industrial plant operating lifetimes of 25 to 50 years. Safety and environmental assessment frameworks that cover the appropriate timescales will therefore need to be developed, most probably by adaptation of existing frameworks currently in use within industry.

Well bores have been identified by risk assessment studies as one of the principal potential escape routes to the surface for CO_2 stored in the subsurface[9] in the post operational or abandonment phase of any project. The issues relating to wells and their treatment under a regulatory system are not new. However, a more rigorous treatment of abandoned wells will undoubtedly be required in any long term framework for CCS, because of the much longer time frames over which the CO_2 will need to be effectively stored. Currently our knowledge of the long term sealing potential of well bore cements exposed to a CO_2 rich environment is extremely limited.

From a regulatory perspective, performance monitoring (i.e. monitoring to evaluate storage performance of the reservoir) will be an essential requirement. The main justifications for conducting monitoring, once CO_2 injection has been completed, are:

- To confirm that the reservoir integrity is maintained, by verifying the predictions of safety assessment calculations,
- To engender public confidence - this will principally involve monitoring the surface environment.

In any long term monitoring programme, it is important that the monitoring data should adequately reflect reservoir behaviour as well as being capable of being interpreted with minimal ambiguity.
In addition to in situ monitoring, a long term framework will also require a supporting detailed modelling capability. However, for such a modelling programme to be accepted by all stakeholders, it is essential that there is confidence in the underlying models and modelling tools being used. Currently

[8] With regard to human safety and environmental impacts, it will be important for operators of CCS projects to demonstrate to the authorities that all have been considered in the safety framework.
[9] IEA Greenhouse Gas R&D Programme Report No. PH4/31, Risk Assessment Workshop, July 2004.

confidence in the models and modelling results is somewhat limited because of the restricted amount of reference data available.

Record keeping and accounting

Records will be kept for two principal reasons which are:

- For economic reasons i.e. to gain royalties or credits for CO_2 storage,
- For safety reasons i.e. to avoid leakage occurring in the future from actions such as drilling into buried pipelines or to avoid inadvertent drilling into a storage reservoir.

In the first case, information to be recorded will include injection volumes and any subsequent leakage that has occurred over the royalty period. Of course, if positive economic benefits can be gained from storing CO_2 it is logical to assume that, if some of the CO_2 escapes from its storage reservoir, there will also likely be an economic penalty or liability. The extent of any such penalty needs to be quantified early in the project development. Quantification of any leakage will require monitoring to provide data and must be sensitive enough to enable quantitative estimates of leakage from the reservoir back to the surface (atmosphere)[10]. In the second case, key information to be recorded will include:

- Geographical location of each reservoir and all wells that puncture the reservoir (i.e. including operational, suspended and abandoned wells),
- Geological and geochemical data on the formation, the formation fluids and the bounding seal and overburden,
- Data on the well completion history of each well,
- Any licensing, permitting and safety assessment submissions relating to the project, which will need to be retained for possible later re-examination.

An appropriate non-political body needs to be established to oversee the archiving of relevant records. These records will be kept for up to a thousand years and their accessibility maintained over that period. Typical media used to archive information today include paper, microfilm, and magnetic and optical disks. Estimates of the durability of records is that paper records last up to 1000 years, and microfilm up to 200-400 years (with one regeneration). In contrast, the current lifetime of magnetic and optical media is estimated at around only 10 years. Despite their relatively limited lifetime, magnetic and optical media are more attractive in terms of physical storage volume and accessibility of information. In any case, storage methods are likely to be updated periodically in response to technological advances. As a tool for storing relevant information on long-term CO_2 storage sites, Geographic Information Systems (GIS) offer distinct advantages.

With regard to records retention it is conceivable that some records (such as the location of wells) will need to be retained for thousands of years. However, mankind's track record in retaining records is not good. Some historical records have been kept for centuries and longer, but the preservation is haphazard at best. Relatively good record keeping has occurred only over the last century or so, and, for the oil and gas industry, over the last 50 years approximately. Even here, the geographic distribution of full records is patchy. Record keeping in the public sector is inevitably more effective than in the private sector. Generally, public acceptance of record keeping for the public good results in more effective data collection and data availability, although there may be exceptions. Records are ultimately the basis of the taxation system and environmental protection, two of the responsibilities of government.

To minimise the effects of political change, a key qualification for any organisation entrusted with archiving should be that it is non-political. At the national level, a number of different types of organisation could assume such responsibility. For example, most countries have a geological survey responsible for compiling and storing geological, or earth science, information.

[10] Apart from well-bore monitoring, similar to that carried out during oil and gas injection and production activities, it is not clear that this level of sensitivity exists currently.

Expert Group Comments

The draft report on the study was sent to a panel of expert reviewers and to a number of IEA GHG's members who had expressed interest in reviewing it. Despite the interest expressed by many in reviewing the report, the number of comments received was limited. The report was generally well received by those reviewers that responded. The comments raised by the reviewers related principally to: points of clarification, suggestions on the report structure and contents to improve clarity, comments on technical issues and editorial/typographical points.

Major Conclusions

The intention of the study was to identify the key issues affecting the long term regulatory framework for CCS with the aim of promoting a discussion on this topic. The key issues have been successfully identified; however, in doing so, the study raises as many questions as it answers, which is not unexpected.

One of the main conclusions from the study is that we cannot currently estimate with any accuracy how long we need to store CO_2 for. The best that can be stated is that it must be stored for at least 'several hundred years' (200 to 500 years) but might need to be stored for 'several thousand years' (3000 to 4000 years). The uncertainty in the estimates reflects the underlying uncertainties in the assumptions that need to be made to allow any timescale to be framed. As our knowledge increases and confidence in the storage system grows, the range and length of this timescale might be reduced. However, for our knowledge to improve significantly, many more large scale demonstration projects are needed. In addition, it is essential that any new demonstration projects must be accompanied by detailed monitoring and modelling programmes.

The issue of uncertainty is a theme throughout the long term framework issue, which may have additional implications for future project development. For example, in the case of liability, we are not sure how the judiciary, etc. will treat CO_2 leakage. A test case may be needed, although it must be hoped that no significant leakage will occur from any storage reservoir in the near future as this could harm the reputation of the technology. Another example is the well bore, which is acknowledged as a potential leakage pathway but currently our knowledge of this route is limited and must be developed much more extensively. The issue of well bore leakage and the state of existing knowledge and further research needs should be explored in some depth. In the meantime there is a risk that well bores will be treated very strictly under any new regulations, which could have an impact on project costs as well as setting a standard that may be unacceptable to project developers. There are a number of related issues, including monitoring and site selection, which have similar implications.

Recommendations

Whilst many of the areas of uncertainty highlighted by this study are already the subject of ongoing research, there are areas where IEA GHG could contribute to the development of a knowledge base that would help reduce the level of uncertainty in relation to CCS. One key area is that of well bores. A review of the state of knowledge and current research work that is underway could be undertaken to assess whether the current research activity is adequate to address the key issues relating to this topic and identify further research needs. Another area where IEA GHG could contribute is in the development of a safety/environmental impact assessment process for CCS. Current methodologies are not directly applicable to CCS and the development of new techniques that are more appropriate to the longer timescales involved in this type of project is essential for building stakeholder confidence in CCS.

Regulatory Issues Associated with the Long-term Storage of CO_2

Discussion Document

Report MSCI-2308 v3

September, 2004

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Acknowledgements

We are grateful to IEA GHG for funding of this work. We also appreciate the helpful comments from several reviewers and hopefully, the amended text reflects their constructive comments.

1 Introduction

1.1 Background

As one option for reducing and controlling greenhouse gas concentrations in the atmosphere, capture and geological storage of CO_2 appears highly promising. Thus, a significant number of presentations at the GHGT-6 Conference in Kyoto were devoted to geological storage as a means of reducing or controlling CO_2 concentrations in the atmosphere. Similarly, the overriding view presented at recent NETL-sponsored Annual Conferences on Carbon Sequestration[1] was one of optimism - that geological storage of CO_2 was a viable option and technologically achievable. CO_2 Enhanced Oil Recovery (EOR)[2] projects, such as the International Energy Agency (IEA) Weyburn CO_2 Monitoring and Storage Project, at least testify to the possibility of storing CO_2 in an oilfield setting.

Many nations, particularly in North America, Europe and Japan, are researching technologies for the capture of CO_2 and other gases from fossil-fuel plant emissions, for subsequent storage in deep underground formations. The significant level of funding being allocated to this area of research and development (R&D) reflects the importance being placed on such technologies as a means of reducing greenhouse gas emissions. Initiatives, such as the Carbon Sequestration Leadership Forum and the IEA Greenhouse Gas R&D Programme (IEA GHG), help to encourage exchange of information between countries and to promote international collaboration.

1.2 Objective of Study

Given the situation in which carbon capture and storage (CCS) is technically feasible and that technologies are being explored in many countries, what is lacking at the current time is some form of regulatory guidance aimed specifically at long-term CO_2 storage. This situation is hardly surprising, given that geological storage of CO_2 is at an early stage of development with only a few demonstration projects underway. To complement studies on other aspects of geological storage of CO_2, the IEA Greenhouse Gas R&D Programme (IEA GHG) considered that the time was

[1] May, 2003-2004, Hilton Alexandria Mark Center, Alexandria; see website <http://www.carbonsq.com/>.
[2] In the type of EOR project referred to here, CO_2 is injected into the reservoir to mix with the oil, thereby reducing the oil's viscosity and increasing its mobility. See, for example: <http://www.ieagreen.org.uk/weyburn2.htm>

appropriate for greater consideration of the *type* of regulatory system that may be required for geological storage of CO_2.

Accordingly, IEA GHG has commissioned this study, to develop a discussion document that identifies, and elaborates on, the key regulatory issues associated with geological CO_2 storage[3]. The focus of this work is the long-term framework for CCS, the objective being to develop a scoping paper that can be used to stimulate discussion of key regulatory issues that should be considered following closure of CO_2 storage sites. In particular, the regulatory issues need to be considered in terms of the likely timeframes involved in the long-term framework.

Because the focus of the study was on issues rather than specific regulations, international conventions that might affect geological CO_2 storage were not treated in detail. Rather, the reader is referred to recent papers elsewhere on this topic [*e.g.*, Wilson *et al*., 2003, Ducroux, 2004].

1.3 Layout of Report

Chapter 2 addresses potential timeframes associated with a long-term framework, in order to provide the context in which to discuss regulatory issues. Thereafter, Chapter 3 contains a discussion of a number of key regulatory issues. Chapter 4 provides some relevant examples of ongoing regulatory and other activities associated with geological storage of CO_2. Finally, Chapter 5 provides a summary of the study combined with general conclusions.

[3] The term 'geological storage' of CO_2 is used throughout this report. 'Geological sequestration' is typically used in the USA in a similar context. In both cases, 'geological' is used to signify storage within the geosphere, typically at depths of several hundred metres.

2 Timescales of Relevance to Long-term CO_2 Storage

The issue of timescale, whether a few hundred years or over a few thousand years, will predetermine many of the regulatory issues to be discussed. More importantly, the timescale will provide the focus for how these issues could be treated within a regulatory system.

Two major considerations will influence regulatory guidance and control: *performance* and *environmental impact*. Performance relates to the effectiveness of the storage system to store CO_2 long-term, thereby resulting in greenhouse gas reduction by preventing CO_2 return to the atmosphere. ‘Long-term’ in this context can be considered as 100 years or more from storage start-up. In terms of *environmental impact*, CO_2 release to the environment may result in a variety of impacts (to humans as well as to animals and ecosystems) that need to be considered and assessed in order to justify or support the application of long-term CO_2 storage. Strictly, performance is also linked to environmental impact, since CO_2 release back to the atmosphere impacts global warming. The spatial scales are different, however, performance being *global* in nature, whereas the health and safety aspects of environmental impact described above are *local* in nature.

It seems reasonable that the timescales for consideration should relate to performance and environmental impact. The following sections address timescales in detail, but the importance of different timescales is further emphasised when discussing specific regulatory issues.

2.1 Timescale Associated with Performance

Fossil fuel combustion results in the release of stored carbon back to the earth’s atmosphere. The goal of long-term CO_2 storage is to remove/keep this greenhouse gas from the atmosphere, by reducing CO_2 emissions and maintaining atmospheric concentrations at, or below, a specified target, *e.g.* adherence to the principles of stabilisation under the United Nations Framework Convention on Climate Change (UNFCCC). In this way, CO_2 concentrations in the atmosphere are ‘proportionately’ reduced.

In this context, performance can be considered to be the ability of long-term storage to achieve and maintain a reduction in CO_2 emissions to the atmosphere. Note that a storage reservoir does *not* have to be leak-free. What is required is that if a reservoir leaks[4], the return of CO_2 to the atmosphere is sufficiently low over the 'performance timescale' that there is a negligible impact on atmospheric CO_2 concentrations. Any future leaks could also be offset by future reductions. This 'performance timescale', *i.e.* the time over which storage performance is necessary in the context of greenhouse gas reduction, is linked to the period of time over which fossil fuel consumption is likely to play a significant role in energy production. This time period is linked, in turn, to the complex interplay between fossil fuel depletion, the development of new technologies that will replace fossil fuels, as well as an increased use of renewables. Linking the timescale to fossil fuel depletion provides an *initial estimate* of performance timescale, but with the understanding that technology advancement may increase or decrease this estimate. For example, energy efficiency technology might increase the life of fossil fuels by decreasing annual utilisation rates. Non-fossil technology can reduce this performance time by replacing fossil fuels as our main energy source.

2.1.1 Fossil Fuel Depletion

Substantial time and effort have been devoted to estimating how long fossil fuel resources will last and to predicting how atmospheric CO_2 concentrations might respond to the depletion in these resources. It is beyond the scope of this project to improve upon existing estimates, but in an effort to provide some technical basis for timescale, some highlights are included below from the appropriate body of literature.

According to the IPCC 1992 scenarios [Leggett *et al*., 1992], conventional oil and gas reserves will be used up within the next century, leaving coal as the predominant long-term fossil fuel source. This situation is also implied by the information on fossil fuel resources/reserves shown in *Figure 1* [IPCC, 2001].

Sources for evaluating future CO_2 emissions include

- The Special Report on Emissions Scenarios (SRES) [IPCC, 2000], a report of the Intergovernmental Panel on Climate Change (IPCC), and
- The Third Assessment Report (TAR) of the IPCC, containing an evaluation of allowable emissions for a range of long-term atmospheric CO_2 stabilisation targets [Wigley *et al.*, 1996].

[4] We use 'leak' here to mean the vertical movement of CO_2, ultimately to the atmosphere, consistent with IPCC terminology. The IPCC uses the term 'migration' to refer to the movement within the zone of containment or into adjacent zones, and 'seepage' to refer to the slow loss to the atmosphere or other shallow zones.

The SRES provides a series of scenarios in groups or families, covering different driving forces for greenhouse gas emissions. Some scenarios, for example, take into account the likelihood that technological advances might rely on a strategy of replacement of fossil fuels over time with a combination of increased energy efficiency and renewable energy resources. No scenarios were included that explicitly assumed implementation of the United Nations Framework Convention on Climate Change (UNFCCC) or the emissions targets of the Kyoto Protocol. Furthermore, the IPCC acknowledged that there is no single most-likely, 'central' or 'best guess' scenario.

In terms of allowable emissions, the modelling predictions by Wigley *et al.* [1996] demonstrate the need for substantial control of emissions, relative to current emissions rates, beyond 2300 (a qualitative extrapolation suggests up to at least 2500).

Nakicenovic *et al*. [1998] examined six alternative energy futures (scenarios) and determined the different contributions to primary energy needs for these scenarios. Despite significant differences in findings among scenarios, the pattern of final energy use was consistent. Thus, *Figure 2* shows a continuing trend from energy used in its original form (*e.g*. coal) to more advanced systems of energy conversion.

In addition to the above considerations, information relevant to timescales is provided below from papers presented at the GHGT-6 Conference in Kyoto:

- Hawkins [2002] concluded that "…..*geologic storage systems must not leak more than trivial amounts over time spans of hundreds of years*".
- Hepple and Benson [2002] examined a range of scenarios for CO_2 storage, allowing for the gradual phase out of fossil fuels over a period of 300 years or less.

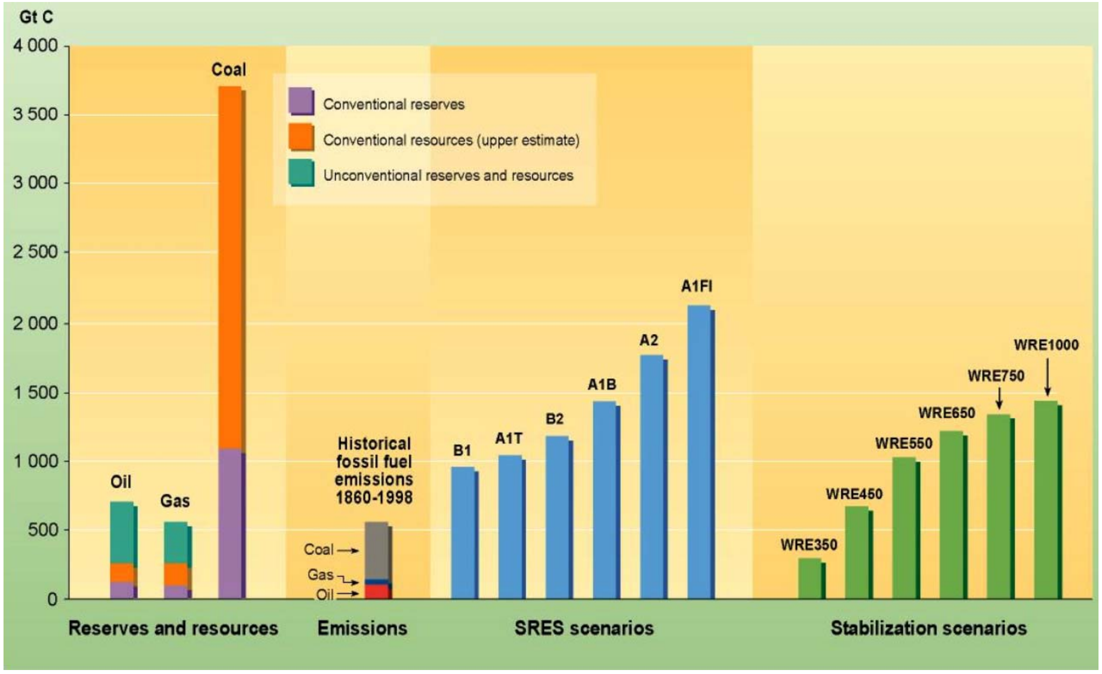

Figure 1: Comparison of carbon in oil, gas, and coal reserves and resources with historic fossil-fuel carbon emissions (1860–1998), and with cumulative carbon emissions from a range of SRES scenarios and TAR stabilisation scenarios until the year 2100 [IPCC, 2001].

NOTE: Data for current reserves and resources are shown in the left-hand columns. Unconventional oil and gas includes tar sands, shale oil, other heavy oil, coal bed methane, deep geo-pressured gas, gas in aquifers, etc. Gas hydrates (clathrates), amounting to an estimated 12,000 Gt C are not shown. The SRES scenarios (middle columns, labelled B1 to A1F1) are illustrative of the range of carbon emissions resulting from energy consumption according to different demographic, economic and technological driving forces. The right-hand columns (labelled WRE350 to WRE1000) show a variety of stabilisation scenarios or allowable emissions leading to a range of CO_2 concentrations. These CO_2 levels, in ppm, are given by the 3-digit numbers after 'WRE' in the right-hand columns. If by the year 2100, cumulative emissions associated with SRES scenarios are equal to or smaller than those for stabilisation scenarios, this does not imply that these scenarios equally lead to stabilisation [IPCC, 2001].

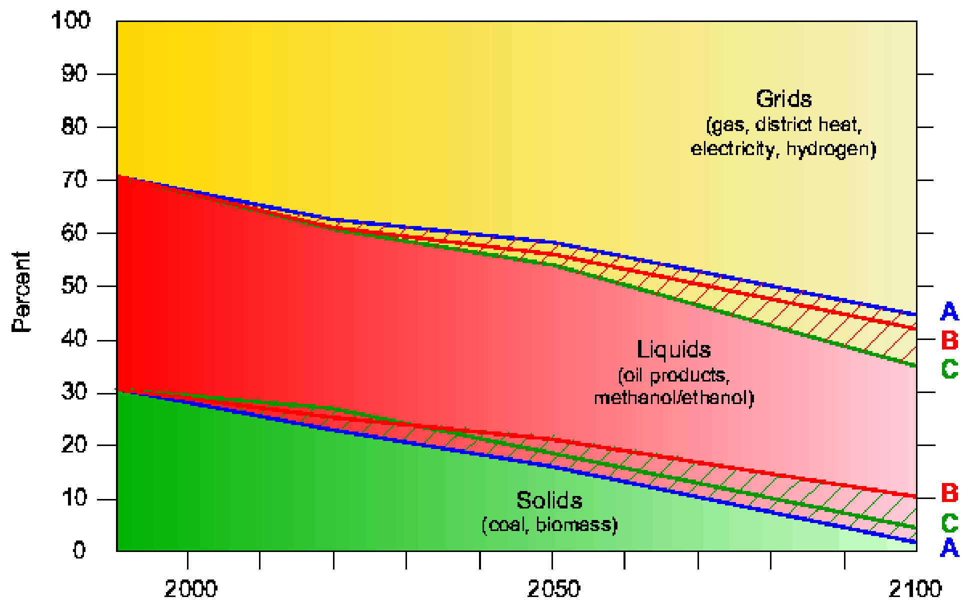

Figure 2: Percentage of total energy from different sources [Nakicenovic et al., 1998].

NOTE: Lines A, B, C represent small variations among different scenarios for alternative energy futures. Case A includes three high-growth scenarios; Case B incorporates more modest estimates of economic growth; and Case C is ecologically driven and assumes substantial international cooperation in the area of carbon emission reduction.

2.1.2 Conclusion on Performance Timescale

The above discussion focused on timescale for fossil fuel depletion as a means of providing an initial estimate of performance timescale. Clearly, the development of new technologies will alter our dependence on fossil fuels, but there are no guarantees on *when* new technologies will become available. New technologies and increased use of renewables will affect fossil fuel utilisation, but it will take a major technology leap such as fusion to replace fossil fuels and make them a minor part of the fuel mix. Thus, fossil fuels are likely to remain the major form of fuel for several hundred years at least.

Given the discussion in the preceding section, together with existing uncertainty over how long fossil fuel resources are expected to last, or be used to produce energy, we recommend that a 'few hundred years', *e.g.* in the range 200-500 years, be used as the time period over which storage performance or permanence is considered.

Note that the preceding discussion does not take into account the potential alternative fossil fuel sources such as hydrates. Current estimates of the worldwide natural gas potential of methane hydrates is ~ $4x10^{19}$ m^3, orders of magnitude greater than the world's currently known gas reserves.[5] Clearly, this fossil fuel source would provide 1000's of years of gas resources, extending the performance timescale correspondingly.

2.2 Timescale Associated with Local Environmental Impacts

Such a timescale is dictated by the period of time over which there *could* be human safety and environmental concerns associated with long-term CO_2 storage. This timescale is potentially much longer than that for climate change mitigation - periods of thousands of years have been discussed concerning such impacts [for example, Savage *et al*., 2003].

2.2.1 Relevant Input from Other Sources

Some lessons can be learned from the experience within the nuclear waste disposal industry, in terms of the philosophy as well as regulatory approaches to a long-term framework[6]. Before discussing specific lessons, it is worthwhile acknowledging the key difference between radioactive waste disposal and long-term CO_2 storage.

Radioactive waste comprises a wide range of hazardous materials that must be isolated from the environment for periods of hundreds to thousands of years to assure public safety. On the other hand, CO_2 is not normally considered a hazardous gas; safety concerns only arise if the CO_2 concentration becomes greater than 4% (*i.e.* about 100 times normal atmospheric concentrations)[7]. Indeed, the possibility exists that future generations may consider this gas a valuable resource – for example, by much more intense application of CO_2 EOR projects than currently exists.

In terms of lessons to be learned, the philosophy governing most countries' approach to radioactive waste disposal is that *no burden should be placed upon future generations from the actions of the current generation* (*cf.* the sustainability factor of

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[5] See, for example, < http://www.fossil.energy.gov/programs/oilgas/hydrates/>.

[6] In the course of much of the discussion in this report, reference is made to, or parallels drawn with, the final storage of nuclear waste. While being sensitive to the negative connotation of nuclear industry as a whole, and given that CO_2 is not a pollutant in the sense of radioactive components of radioactive waste, we feel that there are some valuable lessons to be drawn from this area of work. Thus, it would be foolish not to take advantage of lessons that can be drawn from the nuclear waste disposal industry - decades of policy development, in-depth scientific argument, and regulatory control. To this end, *Appendix A* is provided, reviewing key philosophical approaches to nuclear waste disposal, as well as discussing potential overlaps in approach.

[7] Material Safety Data Sheet for CO_2.

climate change discussions, in the context of greenhouse gas reduction). Thereafter, the general approach for safety concerning radioactive waste disposal, is to isolate the hazardous materials from the biosphere/environment for a period of time that is long enough for the potential hazard (risk of exposure to radioactivity) to become negligible. This reduction in hazard is caused principally by the loss by decay of harmful radiation over time. Clearly, this type of hazard is entirely different from exposure to CO_2 but the underlying objective, *i.e.* to ensure future safety, is the same.

There are two major types of disposal concept for radioactive waste: surface/near-surface storage, and deep (geological) storage. Although the latter is more relevant to most long-term CO_2 storage concepts, some lessons can be learned from the regulatory approach to the former, *i.e.* surface/near-surface storage.

Typically, a period of 200-300 years of institutional control is required for a surface, or near-surface[8], disposal facility. During this time, records of the site are retained in some central repository, and a combination of active and passive controls are used to prevent humans intruding onto the site. This period of time (200-300 years) reflects how long most of the radioactive material remains hazardous for a surface/near-surface site and, therefore, how long institutional control needs to be maintained. Implicitly, this is also the length of time considered realistic (*i.e.* achievable) in terms of record archiving and active institutional control. There are no obvious reasons why record archiving should be any different for CO_2 storage (see *Section 3.4*).

The timescale associated with *deep*[9] (geological) disposal of radioactive waste is of the order of hundreds of thousands of years, *cf.* 200-300 years for surface/near-surface disposal facility. In spite of these long timescales, the regulatory approach is that the *safety of the deep disposal site must be assured prior to closure*. Clearly, the long-term safety of a specific deep site can never be proven, but only stated with a high degree of confidence – *i.e.* assurance, supported by a broad range of technical justifications (modelling/calculations, scientific and societal arguments).

2.2.2 Specific Considerations for Long-term CO_2 Storage

Drawing a parallel with the requirements of the final storage of nuclear waste, the key factor regarding local environmental impacts is *when* a safe point is reached

[8] Near-surface' in this context is a depth of a few tens of metres [IAEA, 1994a].
[9] 'Deep' geological disposal applies to depths of a few hundred metres in order to isolate the disposal volume from potentially disruptive events. In terms of the potential for resource exploitation and human intrusion, additional guidelines for site selection exist in countries to avoid this possibility [IAEA, 1994b].

concerning any subsurface CO_2 storage project, *i.e.*, when the CO_2 can be considered not to present a potential human safety or environmental hazard. As long as reservoirs contain large volumes of CO_2, pressurised relative to ambient conditions, a driving force exists for leakage and potential release of CO_2 to the shallow subsurface and surface, thereby causing some detrimental effect within the environment accessible to humans and animals. Health and safety concerns aside, the performance of CO_2 storage reservoirs in terms of greenhouse gas reduction dictates that releases of CO_2 back to the atmosphere must be small. This, in turn, means that CO_2 storage reservoirs are likely to remain for thousands of years and, consequently, the potential for environmental impacts exists over this extended timeframe.

From one perspective, it seems logical that the longer the CO_2 remains in the subsurface, the greater the chance for CO_2 dissolution and other forms of storage (*e.g.* ionic and mineral trapping). These processes will help to reduce any potential hazard. Immediately after the operational phase of a CO_2 storage project, the reservoir will be pressurised at its maximum perturbation, when the driving force for substantial CO_2 migration is at a maximum. The buoyancy effect of pure CO_2 will also act as a driving force, encouraging vertical migration (upwards). The CO_2 will also begin to dissolve immediately in subsurface waters and this process will continue until completion or until the solubility limit for CO_2 is reached. The timescale for dissolution depends on a number of factors including salinity, contact area and water flow rate, and could extend to thousands of years. Once dissolved, however, particularly in subsurface waters in a basinal setting, the buoyancy effect is reversed and slow migration of CO_2 will occur over long distances.

Over time, any migration of CO_2 dissolved in subsurface waters will generate a plume that gradually spreads, decreasing its aqueous concentration. In this way, natural processes will help to dissipate the initial perturbation[10]. On the other hand, as migration of dissolved CO_2 occurs and the CO_2 'plume' spreads within the subsurface, the possibility exists of encountering some natural or man-made leakage pathway.

At this stage, there is a lack of substantial research or results relevant to a full understanding of these mechanisms. Thus, it is difficult to be definitive about the absolute timescale. It is possible that the appropriate timescale is 1000's of years, but as our understanding improves, it may also be in the 100's of years. Due to the

[10] Current modeling being carried out in the Weyburn Project indicates that the pressure transient for the Weyburn reservoir, lasts for several decades [Zhou *et al*., 2004].

heterogeneity of storage reservoirs, both timescales may be applicable, varying with different types of reservoirs. In this respect, while each reservoir may exhibit unique characteristics that could impact on storage potential and capacity, an understanding of the underlying key parameters will help to identify some common categories within which, hopefully, reasonable predictions (on storage capacity) can be made. In terms of future human actions (drilling, mining *etc.*), we assume that current practices and regulations will be in effect in the future and that this aspect of safety is still in place (blow-out preventers *etc.*).

Most environmental assessments address period of tens, or occasionally hundreds, of years. Longer timescales are well beyond those considered in typical engineering projects. One exception concerns radioactive waste disposal. Again, using the analogy from the radioactive waste disposal, although the timescale over which safety must be assured is long, the *assurance of safety* must be provided *prior* to a site being closed (reservoir being sealed). This assurance is also implicit in the EIA requirement for coal mining projects, but no specific timescale has been identified in the appropriate regulations (see for example, a discussion on post-closure maintenance in the USA in McElfish *et al.* [1996]).

Other exceptions to short-term periods for environmental assessments include:

- the 10,000-year 'no-migration' (of hazardous materials) requirement in Class I wells regulated under the United States Environmental Protection Agency's (USEPA) Safe Drinking Water Act (SDWA) and the Resource Conservation and Recovery Act (RCRA), and
- a timescale of 18,000 years associated with the storage of toxic waste in German deep coal mines.

2.2.3 Conclusion on Environmental Impacts Timescale

It is premature to narrow down the timescale associated with environmental impacts. The time period may be as long as 1000’s of years or much shorter – only a few hundred years.

If the timescale is 1000s of years, does this mean that a regulatory system must be in place for this period of time? Clearly, such a prospect is unrealistic. Nevertheless, until our understanding of long-term CO_2 storage projects improves with experience, a regulatory authority will expect to see that consideration has been given to the potential for environmental impacts well into the future, *i.e.* thousands of years - for as long as there is a significant safety risk. What can be done, however, and drawing a parallel with safety assessments carried out in the nuclear field, is for a regulatory agency to require the assurance of safety *prior* to sealing the storage reservoir, *i.e.* prior to abandonment (see below). Practically, this could be achieved by acknowledging two separate time periods [Wilson and Keith, 2002]

- *Pre-abandonment* period: A relatively short period of time following the conclusion of CO_2 injection and the period during which evidence is offered that the original set of predictions of safety *etc.* for storage does, in fact, hold.
- *Post-abandonment* period: Once the pre-abandonment period is complete, some form of abandonment certification can be issued and final abandonment occurs. While activity at the site may cease, liability would not.

3 Discussion of Regulatory Issues

3.1 Introduction

In an initial discussion among project team members of possible regulatory issues to address, the consensus was that all issues could largely be accommodated using as a template, the original issues defined by IEA GHG in its Call-for-Tender document. Thus the issues discussed in separate sub-sections below, are:

- Liability
- Economics
- Well-bore integrity
- Reservoir leakage,
- Monitoring, and
- Record keeping.

A few issues that did not fit comfortably into the above categories are discussed in a separate section (*Section 3.8*).

3.2 Liability

Liability issues associated with long-term CO_2 storage are discussed in detail by de Figueiredo *et al.* [2003], and the key points from their paper are presented in *Sections 3.2.1* to *3.2.3* below. Since these sections provide a U.S. perspective, *Sections 3.2.4* and *3.2.5* examine what international treaties and conventions may be relevant to this area in EC countries, with particular focus on the United Kingdom (UK)/England[11].

3.2.1 Introduction - Sources of Liability

De Figueiredo et al. [2003] divided the liability issues into 3 areas. The first is termed *operational liability*. This is the liability associated with CO_2 capture, compression, transportation and injection into the storage formation. The timeframe for these operations is decades. Environmental, health and safety risks associated with these processes are not new. Most known risks are associated with well or pipeline failures; for example, primarily regulated in the United States by the U.S. Office of Pipeline Safety [Heinrich *et al.* 2003]. The liability associated with these risks has been, and

[11] Note that where specific mention is made to England it is because the law in that particular topic area is different from that in Scotland.

continues to be, successfully managed in the oil and gas industry, including acid gas injection, enhanced oil recovery, natural gas storage, and CO_2 transport [Heinrich *et al.* 2003].

A second source of liability is associated with leakage of CO_2 from geologic storage reservoirs and its effect on climate change. Assuming that CO_2 emissions will be controlled under a regulatory regime in the future, there will be a liability associated with leakage. De Figueiredo *et al.* [2003] term this *climate liability*. For an effective storage time of thousands of years, climate liability would probably be negligible. On the other hand, if the effective storage time is only decades, CO_2 storage is probably not worth the effort because it is doubtful that the benefits of such a short storage time can justify the extra costs associated with storage. However, if the effective storage time is in between, questions arise as to how to account for this liability. Since *climate liability* is primarily an economic concern, being linked to economic benefits associated with CO_2 mitigation, it will be explored in much further detail in the following (economics) section (*Section 3.3.5*).

Once CO_2 exits the injection well and enters the geologic formation, its transport and fate are governed by *in situ* processes. The choice of appropriate sites is the best way to minimise any adverse effects related to CO_2 storage. However, there is a potential for leaks of CO_2 from the geologic formation to the surface, migration of CO_2 within, and away from, the formation, with associated impacts, *e.g.* induced seismicity [Heinrich *et al.* 2003][12]. Potential sources of liability include public health impacts, and environmental and ecosystem damage.

CO_2 is generally considered a safe, non-toxic gas at low concentrations, and does not directly affect human health. However, the gas is denser than air and may re-accumulate in low-lying, confined, or poorly ventilated spaces. At high enough concentrations, this can lead to fatal consequences resulting from asphyxiation [Benson 2002]. Health Canada [1989] quotes an "acceptable long-term exposure range (ALTER) for CO_2 in residential indoor air" of ≤ 3,500 parts per million (ppm; ≤ 0.35%). ALTER is defined as "*that concentration range to which it is believed from existing information that a person may be exposed over a lifetime without undue risk to health*". In making its recommendation, Health Canada attempted to take into account the sensitivity of particular groups of people, such as those with incomplete

[12] Induced seismicity refers to earthquakes that are related to human activities, normally associated with mining, large water reservoirs, or hydrocarbon extraction form oil and gas fields.

development (children), or deterioration of physiological processes. The particular vulnerability of children is recognised.

Significant leaks of CO_2 could also lead to environmental or ecosystem damage, such as soil acidification or suppression of respiration in the root zone [Benson 2002]. It is this third type of liability, which de Figueiredo *et al.* [2003] term *in situ liability*, that is the focus of this section.

3.2.2 Legal Standards of Liability

Negligence. Excluding specific statutory authority governing liability, most of modern accident law in the USA is addressed through negligence claims. Negligence is the failure of a person to exercise reasonable care [Restatement, Second, Torts §§ 282, 283, 284]. Lawsuits often hinge on the interpretation of "reasonable care". Firms which conduct activities associated with CO_2 storage would be considered professionals. Under negligence law, professionals must exercise the skill and knowledge normally possessed by members of the profession; otherwise they may be found negligent [Restatement, Second, Torts § 299A]. Industry customs or professional standards may bear on the determination of negligence [Restatement, Second, Torts § 295A]. A *prima facie* case of negligence would need to demonstrate that:

(1) the individual or firm had a duty to exercise reasonable care;

(2) there was a breach of that duty;

(3) the plaintiff suffered harm; and

(4) that the breach of duty caused that harm.

The natural gas transport and storage sector provides an example of negligence law as it is applied. The courts have found that natural gas transport and storage is not an abnormally dangerous activity, and that risks can be eliminated by exercising reasonable care and following federal and state regulations [*New Meadows v. Washington Water Power 1984*].

Strict Liability. In an effort to internalise costs with the entity most able to control risk, "strict liability" was established. Under strict liability in the USA (see *Section 3.2.4* for a discussion of corresponding experience in England), a person (or corporation) is held liable for the harm that his or her activity caused, regardless of whether reasonable care was used or precautionary measures were taken. Although the ultimate finding of strict liability is made in court, application of strict liability can be imposed by either the courts or the legislature. Strict liability laws are written and enforced at the state level, resulting in variability from state to state. Strict liability is imposed for abnormally dangerous activities, which ought not to apply to long-term CO_2 storage projects, at least those involving pure CO_2. Abnormally dangerous activities are characterised as involving:

- a high degree of risk;
- the potential for great harm;
- an inability to eliminate risk by reasonable care;
- uncommon activities;
- being inappropriate due to the location where it is carried out; and
- value to the community that is outweighed by their dangerous attributes [Restatement, Second, Torts § 520].

The above list of characteristics is not meant to be exhaustive. The courts ultimately must decide whether the risk created by the activity is so unusual that it warrants payments by a party for any harm caused, regardless of the measures taken to safeguard the activity. Thus, plaintiffs need to provide the court with a basis for concluding that an activity was abnormally dangerous, as a matter of law [*Dunphy v. Yankee Gas Services 1995*]. When courts or the legislature define an activity as abnormally dangerous, and therefore governed by strict liability, it has important policy implications. The cost of capital and the cost of insurance coverage may increase. Strict liability may lead firms to purchase insurance to cover potential catastrophic losses or may lead risk-averse firms to curtail activities.

In the context of long-term CO_2 storage, activities that will increase the hazardous nature include situations where the CO_2 stream is not pure, but contains toxic contaminants. Current transport regulations are in place to cover the movement of such a gas stream, but leakage of CO_2 with toxic contaminants (SO_2, H_2S) at some time in the future would represent a dangerous hazard, particularly if the gas is released into an enclosed volume (indoor air).

An example of the imposition of strict liability in the USA is the case of hazardous waste, governed by the Comprehensive Environmental Response, Compensation and Liability Act or CERCLA (commonly known as Superfund) [42 U.S.C. § 9601 *et seq*.]. Under CERCLA, even if the hazardous substance release problems were unforeseeable, the relevant parties acted in good faith and according to law at the time and exercised reasonable care, or even if state-of-the-art practices were used at the time the materials were disposed of, a party could still be held liable [United States Environmental Protection Agency, 2003]. Moreover, in CERCLA, the statute applies “joint and several liability”, meaning that if two or more defendants are held strictly liable, each may be liable for the full damages awarded regardless of fault [Restatement, Second, Torts § 875]. The application of joint and several liability in Superfund cases has led to many different entities, including contractors, transporters, insurers and intermediaries, being held liable [Theurer 2001].

Consideration of long-term liability is a key element in assessing the viability of geologic CO_2 storage. The way in which liability is addressed may have a significant impact on costs and indirectly on public perceptions of geologic storage. The critical question is how the judiciary, legislatures, and regulatory authorities will treat geologic storage once it is accepted as an option for a potentially important mitigation measure in the more controversial area of climate change policy. Whether liability for geologic CO_2 storage will be treated more like the historic treatment of natural gas which has imposed relatively low costs on operators, or more like hazardous waste which has been much more burdensome to participants (and much more politicised), is currently uncertain.

The answer will depend in part on:

- the results of current research assessing the risks of this technology,
- the first projects that attempt to store CO_2 on a large scale explicitly for the purposes of reducing emissions of $CO_2$to the atmosphere,
- the reaction of the public and interest groups to those risks and efforts, and
- actuarial and financial analyses of liability.

3.2.3 Addressing Liability

Liability could be dealt with on several levels; for example, on four levels as in the USA:

- National government,
- Sub-national government,
- Industry, and
- Individual corporations

The above levels are non-exclusive, and approaches are likely to take place on multiple levels; for example, combining national statutes with corporate-level strategies.

National Government

A national government may be able to take on some of the burdens that would otherwise be borne by industry. An example of this in the USA is the Price-Anderson Act of 1957, which establishes a framework for payments to the public in the case of a nuclear accident [42 U.S.C. § 2210 *et seq.*]. Under this act, nuclear plants are required to take on private insurance amounting to $200 million per plant. In addition, all nuclear plant operators contribute to an industry trust fund of $9.3 billion. The federal government assumes any liability above the combined $9.5 billion paid in by industry.

A "liability cap" may be a double-edged sword for CO_2 storage. On one hand, it would provide industry with some certainty as to the financial liability associated with any leakage. On the other hand, a liability cap could be detrimental to CO_2 storage from a public perception standpoint. Liability caps are quite rare and are generally reserved for areas of real catastrophic risk. They are also necessary for situations where no insurance company would be willing to bear the full damages of disaster.

Sub-national Government

A second means of addressing liability would be for responsibility at the regional level. For example, in the USA, the states bear liability, as in the case of low-level radioactive waste (LLW)[13]. LLW is governed by the Low Level Radioactive Waste Policy Act, as amended in 1985, which dictates that states are responsible for the disposal of LLW generated within their borders [42 U.S.C. §2021b *et seq*.]. The Act allows states to enter into compacts to control access to disposal facilities. The unintended effect of the Act has been that no new LLW disposal facilities have been built, largely because no state regulatory agency will approve a disposal facility within its borders [Murray *et al.* 2003]. The example of LLW shows that liability regimes may discourage CO_2 storage. It also raises questions of the efficacy of turning liability over to the states.

[13] Low-level radioactive waste (LLW) includes machine parts from nuclear reactors, clothing worn by workers in radioactive facilities, medical waste, and waste from university research laboratories

Industry

Industry as a whole may be able to bear liability for CO_2 storage. For example, in the case of the Price-Anderson Act in the USA, industry is required to undertake a joint insurance pool in which all plants must participate. In the event of a nuclear accident where the plant's $200 million insurance pool is used up, the joint insurance pool would be triggered, whereby each nuclear reactor must pay up to $88 million to cover damages. This insurance pool is only feasible because all operators are required to participate in it [Deutch and Moniz, 2003]. Such action also occurs within the oil and gas industry in Canada where sub-national governments (the regulators) impose a fee on the drilling of wells to build a fund to cover the costs of orphaned wells (*i.e.*, wells with no legal ownership that the state must take responsibility for abandonment).

Individual Corporations

Finally, there is the case of companies addressing potential liability on their own. In the USA, the EPA Underground Injection Control Program, under the authority of the Safe Drinking Water Act of 1974, administers a program requiring owners and operators of injection wells to demonstrate financial responsibility in case of accidents. Acceptable indicators include [USEPA 1990]:

- Surety bonds (guarantee by a surety company that a specified obligation will be fulfilled),
- Letters of credit (guarantee that a set amount of money will be available to a specified company under certain conditions),
- Trust funds (repositories of money set aside for a specific purpose), and
- Financial statements (audited information from a company's income statement and balance sheet demonstrating sufficient resources for specific obligations).

A recent United States General Accounting Office report, however, has noted that the above requirements may not assure that adequate resources are available in the event that a firm declares bankruptcy or ceases operations [United States General Accounting Office 2003]. Similar statutes are common in the mining sector in Canada where assurance of the capacity to effectively abandon mines is applied.

Moreover, assuming that the liability for CO_2 storage is adjudged low enough, some insurance companies may be willing to bear the risk. Insurance companies will gravitate to situations where risk categories can be pooled, or where the likelihood of accidents can be predicted. The availability of insurance will depend on assessments of the risk of CO_2 leakage from a geologic reservoir. Although research assessing the general environmental, health and safety risks of geologic CO_2 storage has already started [*e.g*., Benson 2002], risk assessments will be needed on a site-specific basis, *e.g.* Weyburn [Zhou *et al*., 2004]. Whether a firm can even be insurable for long-term liability will depend on the predictability of risk and the extent of potential damages.

3.2.4 Legal Standards of Liability in England

The principles set out in the sections on Negligence and Strict Liability in *Section 3.2.2* above would also apply in general terms to England. In fact, the law in the USA was based on the landmark ruling in the English case of *Rylands v Fletcher*. The approach in this case was to apply a two-part test, *viz.*

1. Whether the use of land is natural or 'non-natural'; and
2. Whether an escape occurred.

In this case the defender was found liable without further proof of fault. His liability was strict but not absolute.

However, a 1994 case (*Cambridge Water Company v Eastern Counties Leather*) varied this principle and now those claiming their land has been polluted must prove the contaminator knew it was causing the pollution.

The Rylands v Fletcher rule has been applied to the escape of many substances, provided that the use that caused the contamination was 'non-natural'. The term non-natural refers to the storing of substances not 'naturally' kept on land. Clearly, CO_2 could fall within this category of things that may escape from one place onto or into a third party's land if it was to migrate back to the surface from, for example, an onshore hydrocarbon reservoir.

In the *Cambridge* case, the House of Lords held that the lower court was wrong to find that it was not necessary to show that the defendant (a tannery) could have foreseen the possibility that ground water would be polluted at the time of the event that led to the pollution. So, foreseeability of harm was needed, not directness of consequences. The Lords held that foreseeability of damage was a prerequisite of liability in *Rylands*. Liability arose only if the defendant knew, or ought to have foreseen, that those things might, if they escaped, cause damage.

The *Rylands* rule still has a role as there are clearly instances where fault-based torts such as nuisance are able to co-exist with a strict liability-based tort such as *Rylands*. The 1994 judgement has, however, tightened the circumstances in which a 'contaminator' can be held strictly liable for the contamination of land. In most cases, it would now seem that a claimant has to prove likelihood or real possibility of escape and harm, previously thought unnecessary. It will be left in the hands of the legislators as to how relevant such case law will be in practice in the context of CO_2 storage as they will determine how comprehensive the necessary legislation will be to regulate such operations.

3.2.5 Addressing Liability in the UK

As with the structure set out in *Section 3.2.3* above, there are various levels at which liability could be dealt with in the UK:

- International framework,
- Domestic legislation,
- Industry, and
- Individual corporations.

Note that such a hierarchy applies also to other EC countries.

In this section, we examine:

(a) how liability in general is treated by the nuclear industry (as a surrogate for long-term CO_2 storage), both through the international framework, and how the UK in particular has implemented such international conventions; and

(b) the latest draft Directive from the European Commission on environmental liability.

<u>(A) Nuclear Industry</u>

International Framework

Civil liability for nuclear damage in the international arena is essentially governed by United Nations (UN) and Organisation for Economic Co-operation and Development (OECD) conventions. Before looking at these conventions it is worth mentioning the Euratom Treaty of 1957 (one of the three founding treaties of the European Community) which established the European Atomic Energy Community. Under this Treaty, the European Commission acquired the status of a Supranational Regulatory Authority in the area of radiation protection. The basis of the Treaty requires compliance with plans laid down to ensure no work results in the radioactive contamination of the water, soil or the atmosphere. It is relevant to the operation of all facilities handling radioactive substances, whether they are nuclear power plants, radioactive waste or storage/disposal facilities.

Under Article 37 of the Euratom Treaty, each member state "shall provide the Commission with such general data relating to any plan for the disposal of radioactive waste in whatever form as will make it possible to determine whether the implementation of such plan is liable to result in the radioactive contamination of the water, soil or earth base of another member state". The Treaty, which was drafted in the early 1950's, addresses the issues that were relevant at that time and does not specifically address the issue of liability.

Up until 1997, the international liability regime was embodied primarily in two instruments:

- The United Nations/International Atomic Energy Agency (UN/IAEA)-backed Vienna Convention on Civil Liability for Nuclear Damage of 1963, and
- The Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA)-backed Paris Convention of 1960 (as supplemented by the Brussels Supplementary Convention of 1963).

The Vienna and Paris Conventions were then linked by the Joint Protocol which was adopted in 1988 as a consequence of the Chernobyl disaster and the requirement to improve the basic conventions and establish a comprehensive liability regime. The Joint Protocol established a link between the Conventions combining them into one expanded liability regime. Parties to the Joint Protocol are treated as though they were Parties to both Conventions and a choice of law rule is provided to determine which of the two Conventions should apply to the exclusion of the other in respect of the same incident.

The Paris Convention ensures compensation for nuclear damage that crosses borders. It imposes an absolute no-fault liability for nuclear damage on a designated operator of the nuclear installation. The operator's liability under the Paris Convention is limited in time and amount. Under the Brussels Convention, the Contracting Parties undertake that compensation up to the amount of 300 million Special Drawing Rights (SDR) (approx. $450 million) per incident shall be provided. Such compensation shall be provided through a combination of insurance/financial security and contributions from the Contractor Parties, both individually and collectively.

In 1997 however the liability regime was further improved through the signing of the Protocol to Amend the Vienna Convention and the Convention on Supplementary

Compensation for Nuclear Damage. The 1997 Protocol recently entered into force on 4 October 2003 and sets the possible limit of the operator's liability at not less than 300 million SDR. It also addresses the concept of environmental damage and preventive measures, extends the geographical scope of the Vienna Convention and extends the period during which claims may be brought for loss of life and personal injury from 10 to 15 years. The 1997 Convention (which has not yet entered into force) defines additional amounts to be provided through contributions by Contracting Parties on the basis of relative nuclear capacity.

These Conventions are based on the civil law concept and share the following main principles:

- Liability is channelled exclusively to the operators of the nuclear installations.
- Liability of the operator is absolute.
- Liability is limited in amount.
- Liability is limited in time.
- The Operator must maintain insurance or other financial security for an amount corresponding to his liability; if such security is insufficient, the Installation State is obliged to make up the difference up to the limit of the operator's liability.

UK Domestic Legislation

Before turning to the substantive UK law that governs the area of liability it is prudent to set out briefly the relationship between international law and domestic law. In the UK, treaties only become part of the domestic law if an enabling act of the UK parliament has been passed.

In the UK, liability is imposed on operators of nuclear installations under the terms of the Nuclear Installations Act 1965. This Act essentially enacted the terms of the Paris and Brussels Conventions. If the limit of liability of the operator is exceeded, there is provision for claims to be made to the appropriate government authority instead of against the operator. The cap on liability was initially set at £5 million under the 1965 Act but this was then increased to £20 million in 1983 and is currently set at £140 million per incident under the Nuclear Installations Order 1994. There is also a time limitation of making a claim of 10 years from the date of the incident. There is a proposal under international law to increase the financial limit, which if enacted into

UK law would increase the current limit from £140 million to £430 million per incident.

In summary,

- Operators of nuclear plants are liable for any damage caused by them, regardless of fault - victims do not need to prove negligence. This is an example of the European based civil law concept of absolute liability being brought within the strict liability regime more prevalent under UK law.
- Liability is limited by both international conventions and by national legislation, so that beyond the limit (normally covered by insurance) the state can accept responsibility as insurer of last resort.

(B) Environmental Liability

The European Commission adopted a proposal for a Directive in January 2002 on environmental liability. A common position was reached in September 2003 and the Directive was adopted in April 21, 2004 and published in the Official Journal on April 30, 2004. Member states have until 2007 (3 years) to implement. The Directive is aimed at the prevention and remedying of environmental damage –specifically, damage to habitats and species protected by EC law, damage to water resources and land contamination which presents a threat to human health. It would only apply to damage from incidents after it comes into force. The proposal, which does not cover "traditional damage" (namely economic loss, personal injury and property damage), has the following characteristics:

- It is based on the "polluter pays" principle, *i.e.* polluters should bear the cost of remediating the damage they cause to the environment, or the cost of measures to prevent imminent threat of damage.
- It aims to create incentives for more responsible behaviour from organisations. To achieve this it is deemed desirable to develop a regime that promotes insurance cover.
- The regime should cover environmental damage caused by "dangerous activities". These are activities regulated by EC legislation on discharge or emission limits for hazardous substances, on other aspects of hazardous substances aimed at protecting the environment, integrated pollution prevention and control, major industrial accidents, waste handling and

disposal and the transport of dangerous substances. It is presumed that CO_2storage would fall within the ambit of “dangerous activities”.

- Strict liability would apply in respect of damage to land, water and biodiversity caused by “dangerous activities”. For bio-diversity damage caused by non-dangerous activities the liability will be fault based. There should be no defence that the activity was carried out in accordance with a permit. However, if the operator could prove that the damage was exclusively and entirely caused by something explicitly allowed by a permit, then there might be a case for making the permit-issuing authority contribute.
- Liability should be only for significant damage and the starting point for the level of liability should be the cost of restoration.
- The person who exercises control over an activity should be liable. Employees should not be liable and lenders not exercising operational control should not be liable.

EU Member States have a variety of domestic law regimes already in place in the field of environmental liability and the remediation of environmental damage. In the United Kingdom for example, common law rules cover a large part of the field, and there are a number of existing and proposed statutory regimes covering both “environmental damage” and damage to persons and property. Under these regimes, action is taken in the public interest by public authorities such as local authorities or the Environment Agency. They can require damage to be put right by those responsible for it, or put the damage right themselves and then recover the costs upwards from those responsible.

Example - Perspective of Swedish Nuclear Waste Authority (SKI)

The Swedish Nuclear Inspectorate (SKI), the regulatory body responsible for authorising the licensing of radioactive waste repositories in Sweden, is re-evaluating its specific responsibilities as Sweden approaches the go-ahead for the deep (geological) final storage of nuclear waste, as discussed by Wingefors [2003]. The introduction to his article begins:

> *"Is it really possible to stipulate that a final repository shall remain safe for thousands, or hundreds of thousands of years? Who is to see that everything is as it should be for such a long time? And who is to be held responsible if things go wrong?"*

The message of Wingefor’s article is that *responsibility must be assumed now*. In Sweden, similar to most countries, the nuclear industry is responsible for the disposal of nuclear waste, according to the Act on Nuclear Activities [SFS 1984:3]. This "responsibility remains until is has been finally discharged". Beyond this, no specific responsibility on the nuclear industry is laid out in the Act. Rather, recommendations that accompany the Act state that once the repository has been sealed in an acceptable manner, as overseen by the regulatory body (SKI), *the State assumes responsibility / liability*. The regulations in this area, therefore, are aimed at industry, and at ensuring that activities carried out during the construction, operation and closure phases of a disposal facility, render the site safe over long time periods. Ten thousand years is the minimum term necessary to assure safety in the Swedish regulations [SFS 1984:3].

3.3 Role of Economics in Regulatory System

3.3.1 Introduction

All the issues described in the other sections of this report will have an economic impact. In this section, we focus on the issues that potentially have the largest economic impact and, therefore, need to be addressed in a long-term regulatory framework.

CO_2 capture costs are well understood today, as commercial CO_2 capture plants are in operation. While adapting these plants for CO_2 capture associated with long-term CO_2 storage will require some design modifications and an increase in scale, this is not a long-term issue. The long-term regulatory issues are associated with long-term CO_2 storage. In this section, we address:

- Issues related to identifying and acquiring reservoirs that will make good CO_2 storage facilities, including the trade-off between up-front *site selection and characterisation costs* and long-term costs associated with liability, monitoring, and leakage.
- Issues relating to *ownership of the storage reservoir*, including royalty payments to that owner.
- Issues related to *monitoring*. In this section we limit the scope to the economic aspects of monitoring because other parts of this issue are contained in the monitoring section.
- The issue of *performance* (or permanence). Any CO_2 that is released back to the atmosphere over time may reduce the initial benefits associated with the original capture and storage. The economic impact of this release must be accounted for.

3.3.2 Site Selection and Characterisation Costs

Standard site screening and candidate evaluation methodologies have not yet been developed for CCS, although one of the key deliverables from the Saline Aquifer CO_2 Storage Project (SACS) is a Best Practice Manual for CO_2 injection into aquifers that discusses site characterisation needs [Holloway *et al*., 2003]. An interesting trade-off that should be addressed is the relationship between up-front site selection costs versus long-term liability exposure. Although investment is typically driven by regulation and/or best practice, it is conceivable that an increase in investment at the site selection stage could reduce the long-term liability associated with either direct issues of health, safety, and the environment, or with release of CO_2 into the atmosphere?

Another dimension of this issue is related to the permitting requirements. These will vary with jurisdiction, but they will set the minimum requirements for site evaluation. While the permitting process exists for analogous activities (*e.g*., acid gas injection, CO_2 injection for EOR), it is probable that the process will be modified for CO_2 capture and storage due to the larger volumes and/or longer timescales involved. How these permitting requirements might evolve could have a major impact on the economics of storage.

It is very important for new and somewhat controversial technologies like CCS to avoid major mishaps. Accidents on the scale of Three Mile Island or Chernobyl have had a major impact on public acceptance of nuclear power worldwide, and have almost killed the nuclear power industry in some countries. While accidents on this scale seem remote for CO_2 storage, bad experiences of a lesser type can still cause difficulties throughout the industry. Such bad experiences need to be avoided, especially in the early growth of the industry as it tries to establish a good track record. This would call for extra effort in site selection and characterisation for early projects. However*, one wants to avoid setting regulatory precedence for all future projects*, where, hopefully, the scope of the effort for site selection and characterisation can be lowered based on previous experience.

We speculate that the change in exploration costs over time should be very similar to analogous activities like oil & gas exploration. On the one hand, experience and improving technology will tend to drive down costs, while "depletion" (of the best storage sites) will tend to drive up costs.

In summary, a long-term regulatory framework needs to develop guidelines for site selection and characterisation. If the guidelines are too restrictive, it could have a major impact on project costs. If the guidelines are too loose, it opens up the possibility of poor performing projects. In developing these guidelines, one must take into account the relationship between site selection and characterisation with the issues of liability, monitoring, and leakage, as well as how the regulatory and permitting process will evolve over time.

3.3.3 Royalty Costs

In most economic analyses of CCS costs, the royalty issue is not discussed. The implied assumption has been that the storage reservoirs are royalty-free. However, someone owns the rights to these reservoirs and their approval must be obtained to inject CO_2 into these reservoirs. Since, as discussed in the previous section, there is the issue of liability to consider, it seems highly unlikely that the reservoir owner will not demand compensation

The first question is who owns the reservoir and its pore space? While we know of no systematic review of this issue in the CCS literature, informal discussions indicate that ownership rights vary for different localities. In some cases, it is the owner of the land above the reservoir; while in other cases, it is the owner of the mineral rights. A first step in developing a long-term framework will be to review *the legal definition of ownership for jurisdictions in those countries seriously considering CCS*.

The second part of this issue is to determine what compensation in terms of royalty fees will be required. At a minimum, owners need to be compensated for any costs or liability exposures that they are subject to from CO_2 storage. Beyond that, royalty fees will be set by negotiation and by market conditions. However, if governments embrace CCS as a major component of their climate policy, there may be new laws regarding the use of underground storage reservoirs for CO_2 storage. For instance, if the government assumes some of the long-term liability, they may also assume ownership of the reservoirs (or in many instances are already owners of the "resource" in which the CO_2 is stored).

In summary, a long-term regulatory framework should address the question of ownership of the storage reservoirs, both the current situation and possible changes in the law, and the question of royalty fees for these owners.

3.3.4 Monitoring Costs

Monitoring costs have been acknowledged in economic analyses in the CCS literature (for example, Bock *et al*. [2003]), but their treatment has been very superficial. In these studies, an assumption of some monitoring requirement (*e.g.*, seismic every 3 years) is made. When these millions of dollars are divided by the tens of millions of tonnes of CO_2 stored, one comes up with a monitoring cost less than \$1/tC. However, is such an estimate credible? The precise nature of such monitoring (seismic surveys) costs is a question that a long-term framework must address. Monitoring is discussed in detail in *Section 2.6*. Here, relevant aspects of monitoring relating to economics issues are identified.

The first question to be addressed is why conduct monitoring? There are at least two reasons. One reason is to protect health, safety, and the environment (HSE). As discussed previously, some monitoring for HSE reasons may be important to reduce costs associated with liability. The other reason is to verify credit received for reducing CO_2 emissions. Since the primary purpose of CO_2 storage is to keep the CO_2 out of the atmosphere, an economic penalty may be imposed if it leaks over time (see *Section 3.3.5*), requiring an *accounting of the leakage*.

A question to be addressed in a long-term framework is what type of monitoring system is required. Seismic monitoring, the state-of-the-art today, has poor resolution particularly for migration along vertical pathways. It is probably inadequate to use in an accounting system that needs to quantify leaks, since the accounting system will reflect only releases back to the atmosphere rather than leakage into other traps within the subsurface[14]. Yet, most monitoring costs estimates are based on seismic monitoring.

Another question to be addressed in a long-term framework is the timeframe for monitoring. Monitoring during injection and shortly after the injection has stopped is commonplace. However, monitoring for decades or centuries after the project completion is highly unusual. Will a regulatory system require long-term monitoring? If so, what are the mechanisms and costs to do this? Uncertainty over the length of time that monitoring will be required has the potential to negatively impact the economics of storage to the point that it becomes too uncertain to initiate activity.

[14] Note that we are concerned here only with CO_2 that escapes from the subsurface. Strictly, there are two different accounting systems possible. The first is the GHG accounting system that only relates to release back to the atmosphere; in this case, measurement may be very difficult with CO_2 fluxes across broad areas that may not be much above natural fluxes. The second system is the accounting that is based on regulations, however they look, about storage and discount rates; under these circumstances, CO_2 that does not reach surface may still be considered as discount on storage if it leaks into economic zones. It is this type of leakage that seismic may pick up – lateral increases in CO_2 concentration of a few percent over a 100 metres or so can be found. However, the exact mass of CO_2 lost may not be determined by seismic, only its presence.

In summary, since long-term monitoring requirements are uncertain, the costs of such an activity are uncertain. The economic impact will depend on the stringency of the requirements. Most studies in the CCS literature assume these costs will be small (<\$1/tC), but there is potential for significantly greater costs. Benson *et al.* [2004a] have provided cost figures for a range of monitoring techniques in their review.

3.3.5 Cost of Non-Permanence

It is clear that the reservoirs being considered as candidates for the storage of CO_2 are not hermetically sealed. In all probability, there will be some leakage back to the atmosphere over time. How much CO_2 escapes, and over what time period, will be very dependent on the specific characteristics of each individual reservoir. In this section, we discuss the issues related to the economic impact of the stored CO_2 making its way into the atmosphere.

The primary reason for CO_2 capture and storage is to keep the CO_2 emissions out of the atmosphere. In other words, there are positive economic benefits associated with this activity. Therefore, it is logical to assume that if some of the CO_2 escapes from its storage reservoir, there will be an economic penalty. The question then arises, how to quantify this economic penalty. This issue of permanence is not unique to CCS, but is currently being hotly debated as it applies to CO_2 sequestration in trees and soils [Marland *et al.*, 2001]. A review of a number of proposed approaches is presented by Noble *et al*. [2000].

Noble *et al*. [2000] refer to what, we feel, is the correct management approach for CCS as *treating removals and emissions as separate events*. The idea is that when one sequesters a ton of carbon, one receives the going price of carbon. When a ton of carbon is released back to the atmosphere, the owner of this carbon must then purchase a credit from elsewhere at the going price. The purchase will in turn lead to one less ton of net emissions elsewhere. A key element of this approach is that CO_2*, once stored, creates a permanent liability for the owner*. It also assumes that there is policy in place that creates a carbon price. This method is described in more detail in Herzog *et al.* [2003]. To examine how this approach may work in practice, we start by examining two limiting cases:

- If CO_2 starts returning to the atmosphere in a matter of years after it was stored, the price of carbon will not have changed significantly from when it was originally sequestered. In fact, there is a good chance that the carbon price (in real terms) may have increased. Under these circumstances, CCS makes no economic sense.

- The other extreme is to assume no leakage until after 1000 years of storage. At that time, the probability is very high that the climate change problem has long been resolved. Fossil fuels have been replaced with non- CO_2-emitting energy sources and the carbon price has fallen to zero. In this case, the economic liability is negligible.

The in-between timescales of decades to centuries are harder to analyse with any certainty. Will we have solved the climate change problem 200 years from now, implying a near-zero carbon price? Or will the situation be at a crisis stage, implying a very high carbon price? While highly uncertain, one must realise that there are always uncertainties associated with any long-lived investments (*e.g.*, the stock market). The investor must make an estimate of the likely price path of the good they are producing (in this case emissions reduction/ CO_2 storage) and compare the rate of return on that investment with other ways to invest the money. Any particular investor's expectations may prove to be wrong, affecting the amount of capital gains or capital losses.

While the above approach provides a nice theoretical context to deal with the non-permanence issue, it has some practical limitations. First, the firms that invest in CO_2 storage may not be around in a century or two. Therefore, who will pay for the carbon permits for the leaking reservoirs? Mechanisms must be put in place today to make sure that future liabilities associated with leaking reservoirs can be covered. For example, this can be done through various types of insurance or insurance pools, government guarantees, etc.

As an alternate approach, some argue that the since the Kyoto Protocol adopted Global Warming Potential indices (GWPs) based on 100-year time horizons, one can assume that storage of 100 years or more is permanent storage and that no liabilities exist beyond that horizon. For storage times less than 100 years, one can use a ton-year accounting approach [Noble *et al.*, 2000]. With this approach, the "discount" for non-permanent storage is based on the difference in the integrated atmospheric CO_2 over the 100 years, from a pulse of CO_2 removed from the atmosphere at time t=0 and re-emitted to the atmosphere at time t=T, based on a simulation of a carbon cycle model. This method certainly simplifies the implementation of an accounting method for leaks and would be highly favourable to the implementation of geologic storage. However, the 100-year time frame is arbitrary and probably undervalues the costs of a leaky reservoir. There is no connection to underlying economic conditions that would determine a carbon price, and no scientific basis has been provided for choosing 100 years or any other horizon length.

Several papers were presented at GHGT-6 discussing the issue of "allowable leak rates" from the perspective of CO_2 storage [Hepple and Benson, 2003; Lindeberg, 2003; Pacala, 2003; Dooley and Wise, 2003]. While these papers brought out some interesting points[15], the determination of acceptable leak rates is problematic and probably an unproductive exercise from a greenhouse gas reduction perspective. First, realistic leak rates are not a simple logistic function, as many of these analyses assume. Second, the value of any CO_2 emitted into the atmosphere from geologic storage will change over time as discussed above. The value will be determined in part by the response of the climate system (*e.g.*, what is the ultimate stabilisation level required?) and the development of technology (*e.g.*, what is the cost at a certain time to reduce CO_2 emissions?; how fast are CO_2-free energy technologies adopted?, *etc*.). Given that no one can predict with any accuracy how these factors will evolve over time and that the logistic functions of leakage rate *vs*. time are both complex and highly reservoir-dependent, it does not seem possible to say today what an acceptable leakage rate would be.[16]

In summary, there is an economic liability associated with stored CO_2 finding its way back into the atmosphere over time. To quantify this liability today is very difficult. We feel approaches that give simple answers (*e.g.*, anything over 100 years is permanent; leakage rates of less than 0.1% total volume stored per year are acceptable) lack sound scientific and economic bases. We favour treating the leakage of CO_2 from storage reservoirs as a separate event from the original injection. To have this become a workable scheme, one must put in place mechanisms to take care of the potential economic liabilities associated with potential future leakage.

[15] We should state that not all of these papers focussed exclusively on the question of determining allowable leakage rates and that our comments should not be interpreted as a wholesale criticism of these papers. All of these papers had interesting insights to add to this debate, particularly in the areas of potential environmental concerns and public acceptance, which is why we reference them here.

[16] One could argue based on this type of analysis that zero is the only acceptable leakage rate. In fact, we have seen this done in one presentation using results from the papers referenced above. We feel that zero is far too restrictive a number, but this shows the danger in this approach.

3.4 Well-bore Integrity

3.4.1 Introduction

The well-bore is one of the principal potential escape routes to surface for gases stored in the subsurface. In this context, it should be noted that unrecorded or poorly completed wells already represent an operational liability (preventing the pressurisation of the reservoir) and should be dealt with by the operator during the active period of injection. Our focus here is on longer-term integrity of well-bores.

Factors affecting well-bore integrity include the drilling and completion practices used, the technical competence of the operator and the quality of the materials used (quality assurance), history of the well including perforation practice, and age of the well. Each of these factors will have some bearing on how quickly well components will degrade. Clearly, the older the well, the more likely the degradation of its sealing and casing components. Moreover, for older abandoned wells, the abandonment process may not have been as rigorous as today's requirements (Monea, *pers. comm*. 2003). As noted above, even in the event of complete failure in the well-bore, the rate of CO_2 release is determined by the permeability of the reservoir in which it is stored to the various fluids in the reservoir. This field characteristic offers the possibility for remediation before large volumes of CO_2 have been released from the storage reservoir.

3.4.2 Factors Affecting Degradation

Completion process and cement and casing stability

Using Canada as an example, at a minimum, regulations in Saskatchewan and Alberta[17] call for the setting and cementing of surface casing in order to protect the quality of fresh groundwater (usually defined as less than 10,000 parts per million total dissolved solids, or TDS). The regulations also allow for the welding of a blow-out preventer to the top of the casing if the well is to be drilled in an area known to have potential for overpressure or in unknown areas (*i.e*. new, deeper *etc*., where there may be a risk from overpressured zones)[18].

Problems that can arise during completion include:

[17] The oil and gas regulations relating to wells can be found at <http:// www.ir.gov.sk.ca/ >,for Saskatchewan, and at <http://www.energy.gov.ab.ca/>.for Alberta.
[18] This factor also has implications for future drilling into CO_2 storage sites, as procedures are in place to prevent catastrophic releases of gas.

- Where the casing is set and cemented in unconsolidated sediment (Western Canada), the cement bond is unlikely to be sound along the length of the surface casing. Flaws in the cementing will result in access to the steel casing by near-surface waters. In other areas of the world, more consolidated surface sediments can provide improved surface casing cement bonding.
- Inefficient flushing of the annulus between casing and rock with drilling fluids, and/or inefficient injection of cement into the annulus. Inadequate cement bonding will lead to the potential for a migration pathway along the contact with either the rock or the steel casing, as well as the potential for incomplete cementing to the height above the producing horizon stipulated in the (local) regulations. A lack of bonding will result in conduits for fluid movement as well as conduits for saline waters to access, and further degrade, the cement or attack the steel of the production casing.
- Interaction of saline fluids with metal casing. Since the bulk of the casing is not cemented, casing steel is in contact with the fluids present in the various horizons from the top of the cemented zone to the base of the cemented surface casing. Most of these fluids are saline, leading to degradation of the casing over time. Anecdotal evidence suggests that casing over 20 years old is potentially too old to permit re-entries and such casing needs to be pressure tested regularly before being used for injection purposes. Older casing in abandoned wells is likely to have breaks that could provide leakage pathways for gases and other buoyant fluids.
- Additional problems arising from the perforation of wells. The perforation process involves lowering a gun packed with a number of explosive charges into the well, to the desired depth for perforating. The charges are set off, thereby punching a hole (series of holes) through the casing, the cement beyond the casing, and into the formation. The act of perforating can damage the cement and create a conduit downwards into the water zone. This fracturing could extend upwards, weakening the cement, and exposing the casing to corrosion and the cement to physical and chemical degradation by fluid infiltration.
- Emplacement of cement in horizontal wells, particularly the short radius style of well (multiple entries *etc*.), in which the completion is open-hole completion, *i.e*., the casing ends above, or just at the top of, the producing zone. Under such circumstances, the cement must be emplaced in the curved

section of the well, where gravity complications may occur during cementing of the production casing.

- Degradation of the cement by natural processes (attack by host rock fluids) as the cement ages, regardless of the effectiveness of the cementing process. The interfaces between cement/host rock and cement/steel casing are potential zones of weakness for fluid to attack the cement. The nature of the reactions with fluids in the host rock will increase or decrease the initially low permeability of the cement. Some reactions dissolve solid phases, thereby increasing porosity; others, such as the precipitation of calcite, decrease porosity. The quality of the cement will have a great deal of influence on the rate of geochemical reactions with host fluids. Uncertainty remains, however, concerning the specific reactions that will occur *in situ* as cement ages at reservoir depth, particularly in contact with supercritical CO_2, and whether these reactions will be beneficial or detrimental to long-term CO_2 storage.

Abandonment Procedures

Conventional abandonment procedures call for a cement squeeze to plug off the formation, followed by filling the casing with several metres of cement. The bulk of the casing is then filled with a fluid containing corrosion inhibitors. The top of the casing is cut off below ground level and a cap is welded on to secure the casing contents. The depth at which the top of the casing is cut is below the level typical of farming operations, to avoid damage to equipment.

3.4.3 Well Integrity Issues

The direct link between well-bore component degradation and well integrity has been discussed above. In the same context, and for the purposes of dealing with leakage within a regulatory system, a number of issues need to be evaluated, *viz.*

- *Number of wells* in the vicinity of the injected CO_2 (or mixture of acid gases). More wells will increase the chances of one being inadequate for complete containment within the injection zone.
- *Age of the wells*: This will take into consideration both the likely quality of the materials used initially and the length of time for various degradation processes to occur that might allow for some leakage.
- *Nature of the wells*: For example, perforating vertical wells may damage the cement to the point that slow leakage pathways for fluids are created. In oil

fields, the production wells are low-pressure zones so that hydrocarbons will preferentially move into the well rather than leak to a higher pressure zone – the path of least resistance.

- *Geochemical processes*: Is the chemical effect of the host fluid on the cement and steel likely to cause problems with those materials, thereby creating leakage pathways?
- *Where is fluid likely to go if leakage occurs*? Will the fluid migrate through the casing to the surface or will it migrate into other aquifers and be dissolved long before reaching the surface?
- *Post-injection processes*: What are the consequences if the reservoir fluids become more acidic with the addition of CO_2? What happens with the reactions with the cement and the steel casing? What is the pathway of the more buoyant fluid? Is a cement squeeze and the addition of cement in the lowest portion of the casing adequate to maintain a separation of the CO_2 and acid fluids from the cement in the annulus and in the casing and the steel itself?
- *Nature of CO_2 leakage via failed well-bores*: If the well-bore seals fail, will the release of CO_2 to the surface be catastrophic? Some preliminary results involving well-bore leakage indicate, at least in an oil field setting, that the porous nature and permeability of the reservoir control the rate of flow of CO_2 to the well-bore, and, consequently, that blow-out conditions do not occur [Zhou *et al.*, 2004].

In any discussion of safety considerations, or presentation of assessment calculations on a site-specific basis, the regulatory authorities will expect to see the above issues dealt with in an appropriate way, *e.g.* in the form of modelling results. None of the above questions or issues is necessarily new, however – they feature in any oil and gas production, or acid gas injection projects. However, the long-term framework of the safety assessment of CO_2 storage will be expected to impose a more rigorous treatment of these issues than has been carried out in the past.

3.4.4 Well-bore Integrity and Timescale

The key difference between a long-term CO_2 storage project and more conventional (oil and gas production, acid gas injection) projects is the extended time period over which assessments will be required to be conducted. Risk assessments addressing operational periods are limited to a few decades at most, whereas the potential hazards from deep CO_2 storage may last hundreds to thousands of years into the future, when the opportunity to react to well-bore leakage may not be an option.

Consideration of timescale leads to the following concerns that need to be addressed mainly on a case-by-case basis, via modelling or calculations, and supported, where possible, by field-testing:

- The rate at which an expanding CO_2 plume will encounter existing well-bores.
- The age(s) and (likely) condition of the wells that will be encountered.
- How long is required for pressure dissipation, *i.e*. reduction in any back-pressure, to occur.
- How long it takes for the dissolution of the CO_2 in reservoir fluids, and to what extent.
- The likely time of contact of CO_2 with well-bore components. Given the likelihood that the near well-bore area is dehydrated as a result of contact with supercritical CO_2, how long does it take for rehydration to occur - particularly in an aquifer environment?
- How long it takes for well-bore components (seals and casing) in different wells, to degrade to the point of breakthrough, and the resultant pathways for CO_2 migration to the surface.

In storage reservoirs penetrated by many well-bores, some form of probabilistic treatment will be necessary to accommodate the variable well-bore conditions, and to take into account the different ages of well-bores, in particular.

In reviewing the different stages of a deep CO_2 storage reservoir after the reservoir has been sealed, the time during which the reservoir is overpressured would appear to represent the greatest potential for short-term significant leakage. Current modelling calculations suggest that this time period is relatively short [Zhou *et al*., 2004] - a few decades. Thus, effective sealing at abandonment would decrease the chances of leakage during this transient period.

More effective means of sealing wells at abandonment might be anticipated for future projects. For example, polymer-type seals that make use of an asphalt emulsion are currently being assessed[19]. However, the likely existence of older abandoned wells in the vicinity, without enhanced sealing materials, should not be ignored.

3.5 Reservoir Leakage

3.5.1 Background – General Comments

Whether from a greenhouse gas reduction / carbon credit or safety perspective, a regulatory system will be expected to ensure that reservoir leakage has been addressed adequately within long-term CO_2 storage projects. Each of these perspectives is discussed in the sub-sections below.

A wide diversity of geological settings is available for CO_2 storage, implying the presence of natural (physico-chemical) barriers to migration from the geosphere to the biosphere. Gunter *et al.* [2001] have summarised the important characteristics of the structures of sedimentary basins in the context of long-term CO_2 storage. These authors identified the most secure types of CO_2 storage reservoirs as those involving hydrogeological trapping - in 'stratigraphic' and 'structural' traps in oil and gas reservoirs that have held oil and gas for millions of years. Other types of sedimentary basin were also recognised as being suitable for long-term CO_2 storage.

In some of the geological settings identified as being suitable, there is not necessarily a physical barrier to flow, *cf.* non-transmissive faults. Under such circumstances, lateral migration is possible, but, because of slow flow rates, the CO_2 is expected to remain in the subsurface for thousands to millions of years. This appears to be the case with the geological setting for EnCana's Weyburn field, for example. Thus, while lateral migration of CO_2 out of the reservoir is possible, it does not necessarily represent a problem in terms of human safety.

The key issues concerning reservoir leakage, therefore, are:

- Will the reservoir allow leakage of CO_2 back to the surface (atmosphere) and will this be a safety concern, *i.e.*, what rate of leakage is predicted?
- Will the reservoir allow migration of CO_2 away from the reservoir and is this important?

[19] FLEXSEAL System, proprietary process developed by Steelhead Reclamation Ltd., Alberta, Canada.

3.5.2 Safety Assessment Considerations for Long-term CO_2 Storage Projects

Several issues relevant to reservoir leakage need to be addressed within a safety assessment framework, in order to assure the authorities that the important aspects of CO_2 storage have been considered and covered appropriately:

- CO_2 migration processes,
- Potential pathways for CO_2 migration, and
- An evaluation of plausible ways in which the storage system might be perturbed in the future.

With regard to human safety and environmental impacts, it will be important for those responsible for CO_2 storage projects, to demonstrate to the authorities that the future evolution of the storage system has been assessed to the extent of examining what types of perturbed conditions are possible, *e.g.* fault reactivation. In this respect, certain sedimentary basins are known to be inappropriate for CO_2 storage–particularly those in the vicinity of active tectonic margins [Gunter *et. al*., 2004], and would not be expected to be the target of CO_2 storage projects.

CO_2 Migration Processes

One or more of a range of processes can bring about CO_2 migration; principally:

- Pressure-driven flow, during the initial period following CO_2 injection, when fluids flow in response to a pressure gradient, thereby dissipating the overpressure from CO_2 injection.
- Density-driven flow, whereby CO_2 dissolves in subsurface waters increasing the density of the waters, thereby causing downward movement.
- Buoyancy-driven flow, whereby the less-dense (supercritical) CO_2 phase exerts an upward driving force, thereby causing upward movement.
- CO_2 dissolution into the water and transport within the aqueous phase.
- Diffusion, and
- CO_2 movement under capillary forces; *e.g*., through the cap rock.

Where oil is present, additional dissolution of supercritical CO_2 in different oil components will occur.

Migration Pathways

A number of natural and man-made pathways are possible for CO_2 migration to the surface. The first, and most direct of these, is via well-bores, which are discussed in *Section 3.5*. In general, any human intervention into or through the injection zone provides a potential avenue to the surface, depending on the nature of the pathways (*i.e.* cracks or gaps in cement seals, or holes in the casing owing to metal degradation) and where they occur.

In natural systems, the principal migration pathways are likely to be transmissive faults and fractures. These may be opened by natural occurrences such as loading and unloading by ice (isostatic rebound), tectonic activity *etc.* However, human-induced enhancements of the natural system can also occur, *e.g.* from the reopening of faults and widening of fractures in overlying rocks, or from chemical changes to cap rock and other rocks that may increase permeability[20]. Similarly, 'working' of the reservoir and the aquifer, including depressuring and repressuring, as well as changes in temperature, could damage the cap rock where fractures do not currently exist.

Some of the routes identified above are relatively direct, in the case of well-bores, while others are more circuitous. In particular, as CO_2 ascends to the surface, either by natural or man-made pathways, it will have opportunities to dissolve in different formation waters and be transported in these waters. Evidence of such processes in the Utsira Formation at Sleipner (North Sea) has been obtained from 4-D, or time-lapse, seismic data [Arts *et al*., 2003]. In the case of degraded well-bore casings, CO_2 can escape through breaches in the casing into the surrounding formations as opposed to leaking on towards the surface.

It will be important, therefore, to demonstrate to a regulator, how much opportunity is available for CO_2 trapping, dissolution and reaction.

Processes that Could Affect Future Reservoir Integrity

<u>Pressuring-depressuring-repressuring of reservoir</u>

In an oil and gas field, the process of operating a reservoir for oil production results in major changes in pressure; in particular, moving from an initial reduction in pressure to subsequent repressuring with water or other fluids. Depending on the history and nature of ownership, this process may have occurred several times during the life of the reservoir.

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[20] Conversely, in appropriate circumstances, the permeability may actually decrease as a result of geochemical reactions between the host rock and the CO_2-modified fluids, due to mineral precipitation.

The injection of CO_2 into a saline aquifer results in an initial over pressuring of the reservoir. Although injection is designed to be carried out below the reservoir fracture pressure, local heterogeneities may cause over pressuring to occur in some locations. Over pressuring during CO_2 injection can also occur as a result of water displacement, particularly if there is some impediment to lateral displacement of the water. In Canada, for example, acid gas systems are regulated by setting upper reservoir pressure limits and monitoring these to avoid over pressurisation and hence leakage [Bachu, 2004].

Thermal effects

Owing to the significant difference in temperatures between a reservoir and the supercritical CO_2 being injected (with or without other fluids), thermal effects or impacts on *in situ* stress might be expected. The long-term geomechanical response to such changes in *in situ* stress has not yet been evaluated in detail. Similarly, the dessication effects in the vicinity of wells through which supercritical CO_2 is being injected, has the potential to generate fracture zones in the reservoir rock or cap rock [Jimenez and Chalaturnyk, 2003].

Future evolution of the natural system

Fracture zones and faults have been identified above as potential pathways for CO_2 migration. Even if faults are currently non-transmissive, there are a number of ways of reactivating faults. In ice-affected areas, where there is isostatic subsidence and rebound that can change the ambient stress field significantly, there may be the possibility of fault activation or re-activation. In tectonically-active areas the faults and fractures may be opened and activated. Injection of fluid can increase the pore pressure in faults and allow mobility due to better lubrication.

Chemical effects

The dissolution of CO_2 in subsurface waters has the potential to change the water chemistry significantly. Resultant geochemical changes can affect porosity and permeability of different formations, either negatively or positively or both, by the dissolution of minerals or by the precipitation or change of minerals. In non-transmissive faults and fractures, containing infill material, mineral dissolution could result in the creation of new pathways.

The process of moving an acidic fluid through a rock has the potential to dissolve material, thereby increasing the rock's porosity and permeability. This process could have a significant impact on cap rock integrity, although related processes such as the re-precipitation of dissolved material in places of reduced permeability, will counteract the effects of dissolution. Thus, permeability enhancement or reduction, or both, may occur.

In identifying potential chemical processes for removing CO_2 (trapping, dissolution, reaction) within the natural system, it will be important to estimate the timescale associated with these processes for comparison with the time for CO_2 to move through a horizon. Clearly, if the rates of chemical reactions necessary to trap CO_2 chemically are too large relative to the rate of subsurface water movement, efficient trapping of this nature will not occur.

<u>Heterogeneities in the properties of the natural system</u>

Heterogeneities are common in nature, but not always characterised quantitatively. In particular, what appears to be a good cap rock or bounding seal may not be laterally extensive. This situation becomes important if the CO_2 spills from the area in which it is injected, into other areas of the injection horizon that do not have as effective a capping system, *e.g.* the occurrence of silt horizons in a shale capping system[21], facies changes *etc.*

<u>Movement of CO_2 through the cap rock</u>

Diffusion can occur across the cap rock. Oil and gas reservoirs have long been considered dynamic systems in the context of geological time [Macgregor, 1996]. Over geological time, diffusion is a significant mechanism for CO_2 migration. Diffusion through the cap rock is not, however, expected to be a significant mechanism over the hundreds to thousands of years associated with long-term CO_2 storage projects. Nevertheless, the rate of diffusion of CO_2 through the cap rock should be quantified.

3.5.3 CO_2 Migration Within the Subsurface – Greenhouse Gas Reduction Accounting

The issue here is whether a regulator will accept only containment of CO_2 in the zone of injection. As stated earlier, CO_2 can migrate out of a storage reservoir laterally, without necessarily resulting in any impacts to safety, *i.e.* human health and the environment. A similar situation could occur if CO_2 leaks up well-bores, then, via openings in degraded casing, accesses and dissolves in formation waters, with subsequent transport away from the well-bores in the waters. These types of migration are referred to here as *subsurface migration*. It is assumed that there is no

[21] Shales provide a common capping system, though not the only type.

opportunity for the CO_2 to return to the surface, or near-surface, environment, and, therefore, no safety hazard associated with this CO_2 migration.

Such migration within the subsurface, depending on its extent, will remove CO_2 from the reservoir into which it was injected. How will this impact the accounting process for greenhouse gas reduction, or carbon credits? Since the fluid does not return to the surface, it will continue to contribute to greenhouse gas reduction, but accounting for its movement will be complex if not impossible. Clearly, long-term modelling predictions of the CO_2 distribution, both horizontally and vertically, will provide useful and necessary information to support regulators.

In particular, once long-term CO_2 storage projects are underway *en masse*, a situation that will be necessary in order to make a significant impact on atmospheric CO_2 concentrations, it is conceivable that storage reservoirs will be adjacent to each other. In this case, 'communication' in terms of CO_2 migration, may occur between reservoirs, increasing the importance for accounting for such CO_2 movement. For similar reasons applied to multiple CO_2 storage projects in the same basinal setting, accounting may only be feasible for long-term CO_2 storage on a basinal scale, rather than on individual projects.

Finally, in terms of timescale, if regulators require containment of CO_2 within the storage reservoir, over what period of time will this requirement (containment only in the injection zone) be valid?

3.6 Monitoring

A more detailed consideration of monitoring has been carried out independently for IEA as reported in Benson *et al.* [2004a]. Here we have tried to focus on considerations relevant to a regulatory regime.

In seeking a regulatory perspective on monitoring associated with long-term CO_2 storage, the key questions to address are:

- Why monitor – what are, or should be, the objectives?
- What types of monitoring might be carried out to meet the objectives?
- How long should, or can, monitoring be carried out?

Monitoring carried out during the site characterisation and operational phases (CO_2 injection) is not discussed here (but see Benson *et al.* [2004a]). Rather, monitoring is discussed in terms of the long-term framework - once the reservoir has been sealed, in accordance with the scope of project. However, one aspect of early monitoring that could affect the regulatory approach to long-term monitoring is the need to establish a baseline against which future monitoring data can be compared. Baseline monitoring activities should begin at the earliest possible stage of a CO_2 storage project, ideally at the site characterisation / pre-operational stage, and certainly before the perturbations caused by CO_2 injection start to develop.

3.6.1 Other Relevant Perspectives on Long-term Monitoring

In the context of long-term monitoring after sealing of the reservoir, similarities can be drawn with the closure of a nuclear waste repository. An important premise for the latter, applicable to all national radioactive waste disposal programmes, is that nuclear waste generated from past and present years should minimise the onus placed on future generations. Thus, there should be no *requirement* on future generations to assure the safety of nuclear waste repositories and, therefore, no deep repository should be sealed and closed *unless* long-term safety is assured. It therefore follows that *the need for post-closure monitoring, at least in the case of nuclear waste disposal, is not justified technically.*

By way of specific examples, with regard to a *deep* nuclear waste disposal facility in France, monitoring for even a few hundred years was *not* considered to be of significant use in ensuring repository performance owing to the long timescales over which safety should ideally need to be studied. On the other hand, post-closure monitoring is a regulatory requirement for the only certified deep disposal site in the USA (Waste Isolation Pilot Plant, or WIPP; located in New Mexico).

3.6.2 Objectives of Monitoring

In the case of nuclear waste disposal, and in spite of the conclusion that long-term monitoring at a deep nuclear repository is not necessary on a technical basis, two main justifications for conducting post-closure monitoring have been offered:

- as *confirmation*: to establish that integrity is maintained; by confirming at least some of the predictions of safety assessment calculations;
- to engender *public confidence*.

In considering long-term CO_2 storage, it is assumed here that, prior to sealing the reservoir[22], the regulatory authorities will have been assured that a specific storage reservoir is safe. This assurance will have been provided in the form of safety (or

[22] "sealing" is taken here to mean sealing well-bores as the conduits to the storage reservoir.

risk) assessment modelling calculations carried out in support of the project. Is there, therefore, any technical justification for long-term monitoring? Clearly, the above two proposed reasons could be applied equally to long-term CO_2 storage. Furthermore, because the CO_2 storage reservoir is not as well-characterised, or engineered[23], as a nuclear waste repository, there is probably a greater justification for 'confirmation' in the case of a CO_2 storage project.

A third reason for monitoring, specific to long-term CO_2 storage, is:

- to provide data in support of accounting for greenhouse gas reduction.

Confirmation of Predictions

In terms of confirmation, careful thought should be given to a long-term monitoring programme. In confirming the predictions of assessment calculations, at least for a short time after closure, those parameters which might, or could, be monitored may not necessarily relate *directly* to events which are predicted in an assessment. For example, during the initial (pressure transient) phase, while the reservoir is returning to 'ambient' conditions, monitoring might detect changes in *in situ* stress which *could* relate to changes in pressure. Confirmation is not guaranteed, however, and it is likely that a major interpretative effort would be required if a monitoring programme were established.

It should also be appreciated that any changes in reservoir behaviour would be small or extremely delayed relative to any monitoring period being considered. Thus, if the monitoring simply confirms predicted some 'large-scale' aspect of behaviour in the reservoir, such monitoring might only raise concerns about improved (more sensitive) monitoring techniques.

Where some form of confirmatory monitoring programme is contemplated, it will be prudent to have complementary plans for responding to unfavourable monitoring results. For example, under circumstances which indicated that CO_2 was migrating from a reservoir faster than predicted, some provision may need to be made for perhaps reversing the process, or at least addressing any safety implications of the faster-than-predicted migration[24]. Given such circumstances, long-term monitoring should be based on a clear, preconceived description of what constitutes a deviation

[23] We should note here that natural systems are often "well-engineered"; under such circumstances, we should minimise disruption of such systems and, where disruption is necessary, ensure that well-bore components of storage are well-engineered.

[24] Remediation options are outside the scope of this study, but the reader is referred to Benson *et al.* [2004b] for discussion on this topic.

from expected evolution of the reservoir, and what action should be taken in the event of such a deviation arising. It seems likely, therefore, that long-term monitoring would be appropriate only for the identification of gross failures of the reservoir that can be directly linked to specific remedial action.

Public Confidence

Possibly more important than any technical confirmation of assessment predictions, post-closure monitoring can have a non-technical objective, to provide confidence to the general public that the CO_2 remains in place.

The surface environment will be of immediate concern to the general public, and important parameters to measure for public confidence are likely to be levels of CO_2 in water and soil gas. Again, the need to establish baseline behaviour is essential to interpretation of future long-term monitoring in this area. In particular, in the case of levels of CO_2 in soil gas, such baseline information must include an understanding of the extent of seasonal variation in data.

Greenhouse Gas Reduction Accounting

At a minimum, the monitoring necessary in support of this aspect of long-term CO_2 storage must be sensitive enough to enable quantitative estimates of leakage from the reservoir back to the surface (atmosphere). Apart from well-bore monitoring, similar to that carried out during oil and gas injection and production activities, it is not clear that this level of sensitivity exists currently.

Thereafter, as discussed in the previous section on reservoir leakage, CO_2 migration away from the storage reservoir is not necessarily detrimental to long-term CO_2 storage and greenhouse gas reduction, particularly if the CO_2 dissolves in subsurface waters and remains trapped in a deep aquifer. However, lateral migration could impact CO_2 inventories in neighbouring reservoirs and, in this case, the ability of monitoring to keep track of migrating CO_2 on even a semi-quantitative basis appears problematical. For this reason, long-term modelling predictions addressing both horizontal and vertical CO_2 distributions, will be necessary to complement the monitoring programme.

3.6.3 Types of Monitoring

Monitoring could be carried out at several horizons, *viz.*

- at the surface,
- in the shallow subsurface,

- in the deep subsurface, and
- in the injection zone itself, and
- in and around the well-bore; this monitoring overlaps with the above horizons.

Monitoring methods associated with each of the above include both remote and direct measurement, as discussed below.

Surface Monitoring

The types of surface monitoring include a combination of direct and indirect measurements. Such monitoring might include [Benson *et al*., 2002]:

- *Pressure sampling* to avoid over pressuring the reservoir, monitoring of gas and gas pressure in the annulus. This type of monitoring would be part of the operational phase but could be extended beyond the CO_2 injection period.
- Monitoring of *ambient air conditions* for leakage in the surface area. This is particularly the case with impurities in the gas stream that may be more directly hazardous to human health (generally following industrial health and safety standards). Monitoring of production for gases coming back with the oil stream – mostly for control purposes, but does demonstrate preferential routes through the reservoir for the gas and capture within the reservoir itself. Again, these types of monitoring would be carried out routinely during the operational stage, but could be extended after CO_2 injection has stopped.
- Evaluation of *ground heave* for a response to over pressuring. This can be accomplished in a number of ways, but will be dependent on the climate and nature of the soils (*i.e.* frost heave and swelling clays in the soil that will be affected by changing moisture conditions).
- *Soil gas sampling* for evidence of leakage occurring. Soil gas can be sampled in the well-bore area, along known or expected fracture systems, or as a general flux from the ground surface as gas spreads in the vadose zone. Knowledge of the source of CO_2 based on its isotopic analysis is essential.
- *Ecosystem response* - analysis of vegetation and a look for changing soil conditions. Measurements can be undertaken at ground level, by aerial photography or by satellite. For example, hyperspectral imagery from planes and its analysis over time has been shown to be a useful technique.

- *Analysis of gas composition* for correct verification of amount of greenhouse gas entering the vadose zone.

Near-Surface Monitoring

Near-surface monitoring could include analysis of ground waters for chemical changes and for the presence of gas - in particular the mobilisation of heavy metals caused by changing acidity and the presence of CO_2 in potable waters.

Deep Subsurface Monitoring

Similar to near-surface monitoring, monitoring for chemical changes could be conducted in zones overlying the injection zone, aimed at detecting chemical changes, pressure changes and the presence of gas. In addition, above the injection zone, monitoring could include:

- *Seismic analysis* of shallower horizons for increasing gas saturation. Note that such analysis would require lateral migration of gas over several hundred metres to register on the survey. Vertical profiling or cross well might pick up more vertical migration paths although the sensitivity of such techniques is currently being assessed.
- *Penetration of the casing* might be possible, to sample the reservoir above the injection zone, as well as to evaluate the cement condition and possible migration through the annular cement or along the interface between the cement and the steel casing.
- *Pressure testing* of the well for well integrity. Similarly, *cement bond logging* will help determine the quality of the cement bond.

Injection Zone Monitoring

Monitoring that could be carried out in the injection zone includes:

- Direct monitoring from *fluid samples* from production wells or observation wells could be continued after CO_2 injection had stopped.
- *Tracer surveys*.
- *Seismic surveys* (still not sensitive enough to determine CO_2 saturation levels in the fluids).
- *Pressure fall-off* tests.

Well-Bore Monitoring

An obvious target for a monitoring programme can be found in well-bores drilled into, and in the vicinity of, the CO_2 storage reservoir. As discussed in *Section 3.6*, currently, the material used for well-bore seals is cement, which degrades with time, even in the absence of aggressive groundwater species. In addition, corrosion of metal casings will occur over time. Thus, long-term CO_2 migration via abandoned wells is a key issue concerning future release of CO_2 back to the atmosphere and/or surface environment[25]. It is also expected to be a primary focal point for public perception of the effectiveness of deep geological storage of CO_2. Thus, well-bore monitoring would address specific concerns that authorities and the public might have. It should be noted, however, that remediation is probably easiest in the well-bore where access is possible and location of the leak most easily pinpointed. The industry has extensive experience in the management of wells.

Offshore Monitoring

The previous discussion focussed on monitoring techniques against a background of onshore CO_2 storage, although in principle, most of the techniques discussed can be applied for onshore CO_2 storage. Soil gas surveys represent an obvious exception. Offshore projects will, however, place certain practical (and cost) restrictions on what monitoring can be performed.

Thus, seismic monitoring methods have been applied successfully in Statoil's CO_2 Injection Project in the North Sea (Sleipner Vest). In particular, time-lapse 3D seismic surveying was used to successfully monitor CO_2 movement [Arts *et al.*, 2003]. On the other hand, in common with onshore monitoring, the ability of seismic methods to detect and leakage of small amounts of CO_2 is a function of resolution [Myer *et al*. 2003].l

3.6.4 Monitoring Timeframe

Factors that influence the monitoring period include expectations on the lifetime of *in situ* monitoring equipment, combined with the idea of a minimal burden being placed on future generations.

In situ monitoring could be conducted via monitors or equipment placed permanently within or around well-bores, although care should be taken to ensure that

[25] Modelling of well-bore migration of CO_2 is one of the focuses of the long-term assessment being conducted for the IEA Weyburn CO_2 Monitoring and Storage Project (Stenhouse *et al.* 2003).

emplacement of this equipment does not create preferential pathways for CO_2 migration out of the reservoir.

The durability and reliability of the instrumentation will severely limit the temporal extent of some types of monitoring and the associated data that can be collected. The ability to ensure continued calibration of equipment should also be taken into consideration. In this context, it appears unrealistic to expect long-term *in situ* monitoring to be extended beyond a few decades, without having to update or renew monitoring tools. Monitoring from the surface could, however, be carried out for as long as society wished it.

3.6.5 Long-term Monitoring Issues

After the reservoir has been sealed, monitoring would continue as long as society considers it beneficial. In this context, consideration needs to be given to who will review and apply the monitoring data that will be obtained, and what specific parameters are to be monitored.

From a regulatory perspective, it is possible that some period of *in situ* monitoring will be requested/required after CO_2 has been injected, but prior to the reservoir being sealed, *e.g.* continued collection of hydrogeochemical data, which are proving useful at Weyburn, although interpretation is by no means straightforward.

If monitoring is required for performance confirmation after the reservoir has been sealed, any licensing authority would probably require technical data that indicate that the behaviour of the reservoir is in accordance with the quantitative predictions made before sealing. If the general public requires reassurance, they will want to see simple, easily understandable, illustrative data that demonstrate that the reservoir remains safe. Whatever the specific objectives of monitoring, if the data collected were to indicate either a failure to reach some required 'target', or that the storage system behaves in an unacceptable way, these conclusions would precipitate a need for corrective action. Plans for such corrective action should be drawn up prior to sealing the reservoir and there should be confidence in the ability to carry out such corrective action.

Whatever monitoring is proposed or required, it will be necessary to ensure two aspects of the monitoring programme:

- The ability to distinguish between 'acceptable' (*i.e.*, within predicted specifications) and 'unacceptable' behaviour (outside predicted specifications). This means that the limits of 'acceptable' behaviour must be clearly defined, justified by some safety-related, or greenhouse gas accreditation rationale.

- The specific action to be taken if evidence of unacceptable behaviour has been identified should also be defined.

In the case of performance monitoring, *i.e.* monitoring to evaluate storage performance of the reservoir, a relatively detailed modelling capability will be required, to support the evaluation of what corresponds to unacceptable behaviour and what to do about it. Associated with this requirement is the need to have confidence in the underlying models and modelling tools being used.

To the extent that specific failures can be anticipated, *e.g.* well-bore failure, some allowance should be incorporated in the long-term regulatory framework to ensure mitigation of the consequences of occurrence. In the case of "highly unlikely" events, it seems counter-intuitive for a regulatory system to plan for their eventuality. The overall implication is that monitoring should be limited to those targets for which a sensible response to results and their interpretation, can be demonstrated, in particular, monitoring in, and adjacent to, wells

3.6.6 Summary

Long-term monitoring, *i.e.* post-abandonment, should not be necessary to demonstrate long-term CO_2 storage safety. Its main technical role will be to support greenhouse gas reduction accreditation, but how easily monitoring will be able to deliver the quantitative aspect of this role is currently uncertain.

Thereafter, another role of long-term monitoring will be one of generating confidence with the public, in demonstrating that the CO_2 is stored safely in the deep geological environment and that it will remain so for the foreseeable future. In particular, surface monitoring may be carried out to provide assurance to the general public that the quality of the environment is maintained. However, long-term monitoring for thousands of years is impractical. Whatever monitoring techniques are incorporated in a long-term monitoring programme (decades at least; possibly hundreds of years), it is important that the monitoring data should: (a) adequately reflect reservoir behaviour; and (b) be capable of being interpreted with minimal ambiguity.

3.7 Record Keeping

3.7.1 Background - Historical Perspective

Historically, record keeping in the oil industry has been inefficient. As an extreme example, one of the earliest oil field discoveries in the world was at Boryslav in western Ukraine, where oil and gas leaks to surface now occur. The first wells were hand dug with wooden cribs to support the sides of the hole. Deeper wells were drilled later with iron casing, but no cement. In both cases, the materials of the wells have long since disappeared and there is no record of probably thousands of shallow oil wells in the area of the city. The lack of residual metal precludes the use of any techniques to identify the locations of the abandoned wells. Leakage of natural gas has caused problems because of a lack of knowledge of the routes to surface. As stated above, this example is an extreme case and the initial discoveries were based on surface seeps of oil, so leaks occurred naturally from oil stored mere metres below the surface. The lack of records, however, hampers the development of remedial action.

More recent development of oil and gas operations has come with a more rigorous system of recording the land location of the wells. In Saskatchewan and Alberta, Canada, for example, even the early drilling in the provinces, dating to the 1940s, has been recorded so that there is relatively accurate reporting and documentation of the wells drilled in the provinces.

3.7.2 Approach to Record Keeping within a Regulatory System

The main questions to be asked in connection with a regulatory system and record keeping are:

- What is the main purpose of record keeping?
- What type of information will be most useful and relevant to archive?
- In what format should the information be retained?
- What measures should be in place to ensure protection of this information and how long can the information realistically be maintained?
- What type of organisation might be involved in record keeping?
- What can be done to promote the communication and exchange of relevant information, including public access to such information?

These questions are addressed in the sub-sections below.

In an oil and gas producing area, a useful analogue for long-term CO_2 storage, the records are used for multiple purposes. These include:

- Assessment of royalties (or other forms of production taxes assessed against the production from the well or producing unit by the resource owner),
- Assessment of dues by other levels of government, for example property taxes for municipal government, and
- Determination of the ownership of the surface property and mineral rights in the event of freehold mineral rights.

In addition, records are kept regarding the location of pipelines and buried cable to prevent them being dug up during construction *etc*. From a safety perspective, the cut-off point for casing is sufficiently below the surface to prevent farm equipment interfering with the casing. Future construction is a different issue, and a permit would need to consider the location of wells. The practicality of this process will be complicated as cities encroach on areas once drilled, produced and abandoned.

The accurate locations of both the surface and subsurface locations of the well are used to ensure that regulated offsets from the edge of the licensed producing area are maintained. In oil producing areas, the edges of licenses are well defined and, to avoid problems with interference with producing wells on adjacent properties, effective offset distances are maintained. Regulators will reserve the right to check the location of the surface facilities to ensure that offsets are maintained. Within a license, spacing of wells is typically regulated, although dispensation can be obtained to change well locations to ensure effective drainage of the reservoir. This is particularly the case with EOR projects where effective reservoir access is essential.

In areas with multiple producing horizons or with different mineral deposits at different depths, it is again important that the record keeping is accurate to ensure that sensitive areas are avoided. In particular, this may involve avoiding abandoned wells or areas where production or drilling could create problems with mining operations (for example water influx to mines).

3.7.3 Nature of Information to be Archived

Key information associated with CO_2 storage projects, that should be stored or archived, will include primarily the geographical location of each storage site together with the locations of the (abandoned) wells associated on, and in the vicinity of, that site. Thereafter, any licensing and safety submissions in support of the performance and safety of the project, should be retained. Part of this submission may include modelling predictions of horizontal and vertical distributions of CO_2 within the reservoir, since knowledge of the geographical extent of the CO_2 reservoir will help avoid the possibility of future inadvertent drilling into this reservoir. Future inadvertent drilling into existing CO_2 reservoir is a key long-term concern.

The nature (type and location including depth and target formation) of the wells being drilled into the subsurface is key information. Typically, the types of wells include vertical wells, slant wells (often drilled from a pad or platform) and horizontal wells.

Vertical Wells

For the purpose of record keeping, the *vertical wells* are relatively straightforward in the sense that the surface location and depth will dictate the location of penetrations of different horizons at different depths. In Saskatchewan, for example, the well is located in the system of digital information by its bottom hole location, but the surface location also remains in the files.

Slant Wells

Slant wells are located by surface location, true vertical depth calculations and bottom hole location (the well name or identifier includes both the surface and bottom hole location even though the well is located by its bottom hole location only). The methodology for slant wells has been extended to horizontal wells with the true vertical depth, surface location and bottom hole location identified.

Horizontal Wells

The situation is more complicated for horizontal wells, at least in the Canadian provinces. Those horizontal wells with multiple legs are located by means of the bottom hole location of the individual legs. This type of location system leaves some potential problems depending on the type of well drilled. For sidetracked or short radius wells, the problem is eliminated in the sense that the distance from the vertical component of the well to the reservoir entry point is small. Penetration of overlying horizons can be considered as essentially the same location as the vertical component of the well. With long radius wells and long-reach horizontal wells, there needs to be more input to the official system to identify the geographic location of penetration of overlying horizons by the well[26]. The Saskatchewan digital system includes the location of the base of the intermediate casing, usually the kick-off point for long-

[26] This can be calculated by using the geological picks and the calculation of well location based on rate of build of the angle of the well.

radius wells. The other information, including proposal for drilling and any survey along the well, is held in paper form within the government, but is accessible to the public.

Saskatchewan and Alberta Experience

Saskatchewan and Alberta form a more advanced example of information collection than many other jurisdictions. An early recognition of the need for information resulted in the development of a comprehensive set of regulations for the collection of data. For the purpose of this report, the information of importance includes the collection of well cuttings from many wells, the information on drilling, and information on abandonment of the wells. Much of this information remains in non-digital form, but is housed with the responsible government agency. While this information is not key to understanding the location, it is potentially important for the understanding of the nature of the well and its integrity. This information is being actively collected for the IEA Weyburn CO_2 Monitoring and Storage Project to better understand the risks associated with ageing well-bores.

Where the subsurface contains multiple resources, again using the Western Canadian Sedimentary Basin as an example, the locations of all deeper forms of drilling are maintained. This will include wells drilled to determine the extent of resources that may be mineable such as coal, potash *etc.*

3.7.4 Format of Information to be Archived

Typical media used to archive information today include paper, microfilm, and magnetic and optical disks [Nordic Working Group, 1993]. Estimates of the durability of paper is up to 1000 years, and for microfilm 200-400 years (with one regeneration); in contrast, the current lifetime of magnetic and optical media is estimated at around 10 years [NEA, 1995]. Clearly, based on these estimates, paper and microfilm are most appropriate for archiving over periods of hundreds of years, yet magnetic and optical media are more attractive in terms of physical storage volume and accessibility of information.

In the case of wells, early recording techniques were standard paper techniques, with the wells logged into ledgers and also posted on maps. This has subsequently been digitised so that the well records have been converted to digital format for storage on computer systems. The back-up system then becomes critical to ensure safe storage of digital information. Back-up occurs through standard processes including storage of paper files, where they exist, and digital backup on a daily or monthly basis. The sale of data to independent operators that repackage, interpret and resell the data also provides an informal mechanism for the distribution and safekeeping of the data.

As a tool for storing relevant information on long-term CO_2 storage sites, on a national, or even international basis, Geographic Information Systems (GIS) offer distinct advantages. Again, the storage medium is in the form of digitised files on computer systems with the same time limitations and backup requirements as discussed above.

3.7.5 Protection of Information and Realistic Timescale for Archiving

Societal stability comes into play when addressing this question, and it is interesting to note the range of estimates provided by regulatory agencies for time periods of institutional control in the case of nuclear waste disposal facilities. Some regulatory agencies (*e.g.* Canada and Switzerland) state that there should be no reliance placed on a period of institutional control and that no credit should be taken for such a period [AECB, 1987; HSK, 1993]. In other cases, such as the USA, the regulation governing low-level waste (LLW) disposal [USNRC, 1982] specifies an institutional control period of 100 years. In France, a period of 300 years is accepted for institutional control (including record keeping) associated with surface or near-surface final storage facilities. Thus, there is no international consensus on this issue.

In other areas, the Office of Quarries in Paris, created by Louis XIV (second half of 17th century) to prevent disturbances to buildings constructed above quarries, is still in operation, suggesting that up to 400 years might be possible to maintain archival material. On the other hand, archived information on Paris was destroyed in a fire during the civil war of 1870. In addition, many buildings containing archived material were destroyed by bombing during the Second World War. For this reason, duplicate archives are recommended[27] and, preferably at the international level, to counter the possibility of national archives being destroyed by civil unrest, or even by major changes in government.

The use of, and effective timescale for, active markers to identify nuclear waste disposal sites, is discussed in *Appendix A*. This option may be less attractive for the large number of CO_2 storage sites expected on a country-by-country basis, *cf.* only a few (< 5) nuclear waste disposal facilities in any country.

[27] For example, the Mormons kept duplicate records on ancestry in underground granite vaults in Salt Lake City.

With regard to CO_2 storage projects, the locations of wells (together with depth and target formation) will need to be kept for extended periods of time. As noted above, historical records of some events have been kept for centuries and longer, but the preservation is haphazard at best. Relatively good record keeping has occurred only over the last century or so, and, for the oil and gas business, over the last 50 years approximately. Even here, the geographic distribution of full records is patchy.

Record keeping in the public sector is inevitably more effective than in the private sector. While there may be exceptions, generally public acceptance of record keeping for the public good results in more effective data collection and data availability. Records are ultimately the basis of the taxation system and environmental protection, two of the foundations of government. The recognition that records have value beyond the basics, is becoming more obvious with increasing archiving of information and the ability to cross-reference databases. The latter component will be a critical element for the future to ensure effective monitoring of potentially high-risk areas.

3.7.6 Type of Organisation Involved in Record Keeping

Given the need for information/data archival, an obvious consideration is what type of organisation might be entrusted with this responsibility. In the discussion below, we assume that archival should be carried out at least at the national level.

Given the vagaries of national politics, political stability cannot be assured over the timescales associated with archival. Thus, to minimise the effects of political change, the first requirement should be that any organisation entrusted with archival be apolitical.

At the national level, a number of different types of organisation could provide archival responsibility. Most countries have a geological survey responsible for compiling and storing geological, or earth science, type of information. In the UK, for example, the British Geological Survey (BGS), the national earth sciences agency, operates the National Geoscience Data Centre as the national collection of geo-scientific information. In addition, UK legislation requires all licensees in the UK Continental Shelf to store most data in perpetuity. To this end, a National Hydrocarbons Data Archive (NHDA) has recently been created, managed by the BGS. One of the objectives of this database is to retain records of exploration and development.

In support of the national database, and depending on the size of the country, smaller, regional organisations like state (USA) or provincial (Canada) geological surveys could play a useful intermediary role.

Other organisations that might be suitable include:

- In the USA, the Bureau of Land Management and the Department of Natural Resources, both of which operate at the federal and state level;
- In Canada, the National Resources of Canada; and
- In the UK, the Department of Trade and Industry which is responsible for issuing licenses for the UK Continental Shelf (UKCS).

Other initiatives are more directly relevant to CO_2 storage. The Midcontinent Interactive Digital Carbon Atlas and Relational DataBase (MIDCARB) comprises the State Geological Surveys of five US states. Funded by the USDOE, the combined database management system and geographic information system contains information enabling the analysis of spatial relationships and technical characteristics of large point sources of CO_2 together with geologic storage options. The key feature of this system is the *storage of information at the local (state) level*, but accessible via a single web portal. For this mid-US region at least, it appears that detailed information concerning CO_2 storage projects, including well bore locations, could be compiled in such a database.

Beyond the national level, a more top-level archival of information/data (e.g., identifying different projects, their locations and scale) could be provided by an internationally-recognised organisation like the IEA. Clearly, where different countries are submitting information on individual projects, the organisation involved would need the infrastructure necessary to archive, *and* allow access to, a large quantity of material. Such a task would be facilitated by some consistency in the formatting of records in different countries. In this respect, a web-based system appears attractive. Thus, expansion of a system like MIDCARB would provide archival at the national level, while also offering the opportunity for an international database.

Similar approaches are being evaluated in other countries. In Canada, for example, several information systems are being reviewed with a view to providing policy makers in Canada with recommendations for a unified information model (a Canadian Geoscience Data Model) [Holonics, 2000]. Such a system is intended to provide timely spatial and non-spatial information on natural resources, the objective being to create a common geo-scientific model allowing integration of data and information from a variety of sources. The ultimate goal is to be able to integrate, manage and access information through distributed web-centric information access. These objectives appropriately fit the requirements of record keeping relating to CO_2 storage projects.

Some of the guiding principles governing this holistic data model were [Holonics, 2000]:

- There should be a balance between an industry focus and a science focus.
- Easy location/finding and capture of information.
- Ease of updating and management, including tracking changes over time.
- Flexibility re integration of different and/or new information sources.
- The (information) model should be based on industry standards.

3.7.7 Communication and Exchange of Information

Since one of the reasons for archiving information is that future human activities can take account of the existence of CO_2 storage reservoirs, there needs to be an effective means of ensuring that this information is widely disseminated. Thus, at the very least, archived material must be readily available. The possibility of generating and distributing maps identifying the locations of storage sites and abandoned wells, should be considered.

For the future, there will be a need for records to be kept of the location of injected fluids, the extent of areas containing CO_2 and the location of all wells and other potential leakage pathways, if any. The databases will need to be cross-referenced, not only with oil and gas operations, but also with other mineral resources, recognising that resources that we currently see as non-economic may well have value in the future (particularly minerals dissolved in saline aquifers). Additional cross-referencing will need to be undertaken to ensure that health, safety and environmental regulations, as well as monitoring of these regulations, have access to the location and potential leakage paths of CO_2.

In terms of public access to information, more and more data are becoming available to a broad range of people and organisations. Widespread access and use of the Internet is an obvious example. With effective placement of CO_2 storage data in the public domain, in the same way that oil and gas data are rapidly moved into the public domain in Saskatchewan and Alberta, the need for international availability of data could be met. For international purposes, however, it is unlikely that records will need to go beyond the verification of the storage in a site that meets international standards for safe and effective storage of CO_2, for the purposes of national accounts and for the accreditation of international trades. Resource issues will be covered by the appropriate regulatory agencies within a national government or subsidiary level of government. Similarly health, safety and environmental issues will be covered by the appropriate national or sub-national government agencies.

3.8 Other Issues

In the course of discussions within this project, a number of related issues were identified. Such issues are not covered in detail in this report, but for completeness, are identified below.

3.8.1 Integration of Different Regulations / Regulatory Systems

Clearly, the regulatory system addressing long-term CO_2 storage will have different requirements from those existing regulations covering the operational (pre-injection and injection) period of oil & gas projects. The latter include specific requirements for air quality and injection well completion and abandonment, as well as groundwater quality. The main difference lies in the time period over which the regulations apply; decades for operational activities, and probably hundreds of years for long-term storage. Thus, once a storage reservoir has been sealed/abandoned, will problems arise over which regulations take precedence, particularly if the regulatory bodies are independent? For example, groundwater quality regulations are in place but will need to be extended into the future to accommodate the safety requirements of long-term CO_2 storage.

3.8.2 Future Development of Regulations

It is conceivable that governments could decide that regulations in-place today are adequate to address long-term CO_2 storage, with perhaps minimal modification. However, entirely new regulations might be developed in the future and these may need to be dealt with in a different way, possibly making requirements on projects that cannot be met readily, e.g. concerning monitoring. In addition, it is quite likely that groundwater regulations could change in a country, and this also could affect the impacts of long-term CO_2 storage.

Thus, even if the existing regulatory system is adopted for long-term CO_2 storage, provision still needs to be made for projecting regulations out into the future.

Drawing on an analogy with the nuclear waste disposal industry, for example, a license is issued at closure, but also at this time there needs to be a demonstration that regulations can be met into the future. In many cases, a specific period of monitoring is allowed in support of this demonstration.

In this context, there is a timely opportunity for the CO_2 storage industry to work towards a consensus in regulatory procedures, recognising where changes to existing regulations are necessary, and demonstrating a willingness to incorporate such changes.

3.8.3 How Future Exploitation Activities Might be Regulated to Avoid CO_2 Leakage

The scale and number of long-term CO_2 storage projects that will be necessary worldwide to make a significant impact on greenhouse gas reduction is massive. Accordingly, there is a strong likelihood of projects occurring in the same general vicinity, perhaps at different times in the future. Under such circumstances, it will be important to ensure that future projects do not impact previous ones in terms of CO_2 leakage. This concern is not limited to CO_2 storage projects but covers future resource exploration and exploitation in general. It could be argued that, for such future projects, the technology applied to exploration or site characterisation activities will be able to identify CO_2 storage reservoirs in advance of well-bore drilling. However, a more formal control is warranted, to ensure that future projects do not result in CO_2 leakage from existing storage reservoirs.

As one regulatory control mechanism, the Environmental Impact Assessment (EIA) process leading to the submission of an Environmental Impact Statement (EIS) in support of a planning application, seems to be one available option. The fact that the EIA process, or something equivalent, already exists in most countries for large-scale projects, is a benefit. Part of the EIA process would require a survey of CO_2 storage projects in the area, which would benefit from a national or regional database (see *Section 3.7.6*).

In Queensland, Australia, for example, all new mining projects need to apply for authorisation of mining activities under the Environmental Protection Act 1994. The Environmental Protection Agency (EPA) is the lead agency responsible for all key issues associated with the environmental management of mining activities. Similarly, in the Netherlands, according to the Environmental Management Act (concerning environmental impact assessment), there is a requirement to carry out an EIA with respect to deep drilling projects (which also covers creating underground storage) [CRUST LTF, 2001].

In the UK, as noted in *Section 3.7.6*, one of the objectives of the National Hydrocarbons Data Archive is to retain records of exploration and development in the UK continental shelf. A key objective of this database is that future exploration and development, or re-development activities for hydrocarbon, CO_2 storage, geothermal energy, or other geo-scientific or commercial activities, will be able to build on a summary of existing information. Such a database would facilitate a survey of CO_2 storage, or other relevant projects in the area.

3.8.4 Modification of Existing Regulations to Cover Long-term CO_2 Storage

The possibility of adapting existing regulations to cover long-term CO_2 storage is attractive. Currently in the USA, for example, a range of fluids[28] are injected into deep aquifers, regulated under the Underground Injection Control (UIC) Programme (40CFR Part 146) which is authorised under the Safe Drinking Water Act (SDWA) of 1974. The SDWA is specific in requiring EPA to provide safeguards to ensure that underground injection wells do not endanger groundwater sources. The UIC was amended in 1988 in response to the Resources Conservation and Recovery Act's Land Ban and created specific requirements for the deep injection of hazardous wastes - Class I wells. By virtue of the 1988 amendment, operators of Class I hazardous injection wells must demonstrate to USEPA, through the use of computer models, that hazardous wastes will not migrate out of the injection zone for at least 10,000 years. This demonstration can be based on either flow modelling or the modelling of waste transformation within the injection zone.

Tsang *et al.* [2001] reviewed the UIC programme in the context of geological CO_2 storage in saline aquifers. Notably, in their concluding remarks, these authors state that “some degree of leakage can be allowed and incorporated into regulatory approach”.

In general, the UIC regulations for Class I wells (covering the injection of municipal or industrial waste including hazardous waste below the deepest underground sources of drinking water) establish siting, construction, operating, testing, monitoring, and reporting requirements. Detailed geological and hydrogeological information must be

[28] defined in the USA as liquids, gases and slurries.

submitted in support of an application for a Class I well. There are also strict requirements on well construction.

It is interesting to note that separate monitoring wells are not required under current UIC regulations for Class I wells. The underlying technical argument is that the most likely leakage occurs in, or around, the injection well. Miller *et al.* [1986] argue that the driving force for leakage decreases with distance from the well and, under this circumstance, does not generate significant leakage away from the well.

3.8.5 Harmonisation of Regulations

There is a need to consider the harmonisation of regulations concerned with the storage of CO_2 as the existing regulations (noted below) might evolve into storage regulations. The regulations would include storage in saline aquifers, enhanced oil and gas recovery and enhanced coal bed methane recovery. Balancing the storage aspect will be important.

3.8.6 Evolution of Regulatory System

On a similar theme, the concept of a regulatory system governing long-term CO_2 storage, that evolves as our knowledge base improves, appears favourable. Under such circumstances, it will be important for early projects to result in a gain in knowledge, for both the regulator and society, so that evolving regulations can develop effectively. This approach is inherently contradictory to the norm, where information collection is usually a result of regulation, for example in the case of acid gas injection in Saskatchewan and Alberta. Interestingly, in these two Canadian provinces, this information collection has resulted in well-characterised sites.

The early projects discussed above could be state-supported to ensure that regulations are effectively developed.

3.8.7 Classification of Types of Reservoir Involved in CO_2 Storage

Essentially 3 regimes can be recognised:

- Reservoirs that exhibit significant leakage; such reservoirs are unlikely to be used (we believe that sites that result in non-trivial leaks would be a major political problem for proponents of storage).
- Reservoirs that are 'tight'; for these, no obvious regulatory issues should need to be considered other than the need to demonstrate that the CO_2 remains in place, for accounting purposes. Such reservoirs would still have to be characterised in detail prior to CO_2 injection, which begs the question what

amount of characterisation is necessary to establish that a reservoir is, indeed, 'tight'? In reality, it is unlikely that any reservoir could be characterised to the point where it is accepted as being 'tight', particularly by the general public.

- Reservoirs that result in slow leaks over time. Such reservoirs should be the main focus in terms of key regulatory issues.

3.8.8 CO_2 Release Rates

In terms of release rates that have appeared in the public domain (conference proceedings, papers), we are concerned that values are being set rather arbitrarily, *i.e.*, without a solid technical basis. Consequently, there is a real danger that the industry is held accountable to some of these values, presumably the more restrictive ones. Thus, realistic work needs to be carried out in this area.

3.8.9 Management or Control of CO_2 Leakage Rates

In terms of well-bores, one argument offered is that well-bore leakage can be mitigated (although management control of this option is likely to decrease with time – particularly over hundreds of years). On the other hand, reservoir leakage would be a difficult, and in most cases an impossible, problem to mitigate. To support regulatory guidance on this issue, then, what data are necessary to characterise a reservoir as having acceptable leakage rates?

3.8.10 Co-storage of CO_2 with Other Gases

Given that acid gas injection already occurs in certain countries, *e.g.* Canada, it does not appear unreasonable that other gases, *e.g.*, H_2S, could be injected into a formation with CO_2. However, additional complications are likely to arise in the long-term as a result of this option, particularly the inclusion of toxic contaminants. This issue is important both from a safety/environmental protection standpoint and, more importantly, from a public perception standpoint.

Thus, as new capture technologies are being developed, we anticipate the need for some specification concerning the quality of gas stream, *i.e.*, CO_2 purity level, in order to guide the efforts of R&D teams. At this stage, however, it is not clear that sufficient knowledge and understanding of the effects of impurities on long-term CO_2 storage exists, as a basis for specifying a minimum acceptable CO_2 purity level.

4 Ongoing Regulatory Projects and Activities

4.1 Case Study – Legal Aspects Concerning Underground Storage of CO_2 in the Netherlands

Since the focus of this report is on regulatory issues associated with deep (geological) storage of CO_2, it is appropriate to provide a specific example where legal aspects concerning CO_2 storage have been discussed in depth and published in the public domain. We emphasise that the example provided below is not intended as a global recommendation on how to approach CO_2 storage. Rather, it represents the considerations relevant to one particular country – the Netherlands, but the report is one of the few studies published on the topic of regulations governing CO_2 storage.

The specific project in the Netherlands is referred to as CRUST – CO2 Reuse through Underground Storage, the outcome of a request by government ministries to develop an approach for implementing a CO_2 'buffer'. In this context, 'buffer' is defined as "*underground CO_2 storage facilities that have been designed so that sufficient account is taken of the desire to recover and reuse*[29] *CO_2 in the future*" [Dijk and Stollwerk, 2002]. The CRUST Project is being implemented in several phases and one of the first tasks has been a legal analysis of legislation and regulations relating to the CRUST Project by a Legal Task Force [CRUST LTF, 2001]. Relevant information summarised below has been taken from this latter report

The Mining Act[30] (hereafter called the Act) in the Netherlands regulates, among other issues, the activity of 'storing substances', which, therefore, covers CO_2 storage. This Act also applies to the territorial waters and the Dutch part of the Continental Shelf, so is not limited to onshore storage. Under the Act, the storage of substances is defined as:

> "*Placing or keeping substances at a depth of more than 100 metres below the surface of the earth or the retrieval of these substances other than placing or keeping underground or retrieving substances with the aim of extracting geothermal energy from the underground (article 1 paragraph i)*"

[29] Note that this emphasis on CO_2 reuse in the Netherlands is not explicitly stated in other countries; in the Netherlands, CO_2 is seen as being beneficial for greenhouses.
[30] "Rules relating to the exploration for and extraction of minerals and relating to mining-related activities"

According to the Act, CO_2 storage will require a storage licence permit - a “licence to store substances”. Generally, such a licence identifies who the licensee is, and for which substances; for how long the licence is valid, for which area, and whether it relates to permanent or temporary storage. Exclusivity exists with such a licence, *i.e.*, it is not possible to obtain a storage licence if one for the same area, or even an exploration or extraction licence, has already been issued to another licensee.

With regard to ownership rights, specific attention is given to the ‘cavity’ in which the gas or other substances are stored - the landowner is also the owner of the cavity. The landowner must permit mining activities (including storage of substances) provided they take place at a depth of more than 100 metres “*without prejudice to the entitlement to compensation for any loss or damage that is caused by these activities*”. The Act stipulates that the party who stores the substances must have all necessary authorisations, including storage licence and environmental permit.

A 2001 Amendment to the Act addresses ‘*duty of care’* with regard to ‘*the proper execution of activities’*, including in this case CO_2 storage. The licensee must ensure to a reasonable extent, that activities under the licence do not:

- *“cause deleterious effects on the environment;*
- *cause damage through movement of soil,*
- *jeopardise safety, or*
- *harm the interests of systematic management of accumulations of minerals or geothermal energy”.*

In the context of possible damage from soil movement, the operator of a storage project is liable for loss or damage as a result of soil movements caused by underground storage, even in the event there is no fault. This is referred to as ‘strict liability’ (strict liability is also discussed in *Sections 3.2.2* and *3.2.4*). The Minister of Economic Affairs is authorised to provide financial guarantees to cover the liability for the loss or damage caused by such movement.

In discussing environmental aspects of underground storage, the Task Force reviewed the relevant implications of environmental laws, noting the close relationship between national and European legislation. In particular, key issues that were discussed in the application of environmental laws to a project such as CRUST included:

- *Is CO_2 a waste*? The Task Force concluded, based on a variety of considerations including national and European definitions of 'waste', that CO_2 can be classified as a waste in the context of underground storage.
- *Is CO_2 a hazardous or non-hazardous waste*? According to the Designation of Hazardous Wastes Decree for both Dutch and European descriptions, CO_2 is classified as a non-hazardous waste.
- *Legal implications of CO_2 being classified as a waste*: The section of the Environmental Management Act, which contains specific rules for waste removal, is applicable.
- *Environmental Impact Assessment needs*: According to the Environmental Management Act, an EIA is required for the activity of "*setting up an installation intended for the placement deep underground of non-hazardous waste*…" Here, "installation" refers to both the above ground and the underground parts of the facility. The Minister of Economic Affairs is the competent authority in the Netherlands for granting an environmental permit. This authority applies to coastal waters up to 12 miles. Note that in the appraisal procedure specified under the Environmental Management Act, it is possible for the Minister of Economic Affairs to judge that an EIA does *not* need to be prepared, in which case this decision is published in the public domain.

4.2 Other Relevant Activities

4.2.1 Interstate Oil and Gas Compact Commission Activities - USA

The oil & gas industry in the USA is being proactive in considering the possible regulatory control of long-term CO_2 storage projects. The Interstate Oil and Gas Compact Commission (IOGCC) representing the governors of oil- and gas-producing states, met in 2002 to discuss the development of guidance documents and possible state regulations that might deal with geological CO_2 storage. One outcome of this 2002 meeting was a stated interest on the part of state participants in developing regulatory guidelines in this area, and a recommendation that the IOGCC take a lead role in this process.

On the other hand, it should be appreciated that IOGCC guidelines have no legal bearing. Thus, the important role of IOGCC is in providing the benefit of years of experience with technical and regulatory issues relating to oil and gas production and

EOR. Ultimately, the public and environmental groups will look to government agencies with responsibility for managing environmental risk and legal obligations to ensure protection.

4.2.2 Regulatory Oversight of Coal bed Methane in Alberta

In Alberta, Canada, coal bed methane (CBM) is recognised in the province as a substantial source of energy. Currently, the Alberta Energy and Utilities Board (EUB) is responsible for regulations in this area and CBM is subject to the same EUB drilling, production, and operational rules and regulations as other natural gas projects. Alberta Environment and Alberta Sustainable Resource Development also have a regulatory role in the development of CBM, and CBM issues are handled in the same way as for other natural gas. Here is an example of a relatively new industry regulated in the same way as an existing one.

4.2.3 UIC Programme in the USA

The USEPA is entrusted with the responsibility for protecting underground drinking water sources. In order to comply with the SDWA, EPA established requirements for the safe siting, construction and operation of injection wells. Unless explicitly exempted from the programme by SDWA, injection of any liquid, gas or slurry is included in the programme, regardless of the nature of the substance. USEPA has been taking an active interest in CO_2 storage projects and is evaluating the need for oversight in this area. Because CO_2 injection for the purpose of climate mitigation, *i.e.*, geological storage, had not been anticipated when the UIC regulations were written, wells drilled for current CO_2 storage RD&D projects in the USA have been permitted as experimental (Class V) wells. The existing regulatory framework within the UIC Programme is being reviewed to see how it could be adapted for the regulation of CO_2 storage projects.

5 Summary and Conclusions

A number of regulatory issues have been discussed in the previous sections and the key points from discussion of these issues are summarised in *Table 1*.

In discussing these issues, a key underlying consideration was the type of regulatory system that might be necessary for long-term CO_2 storage. We are aware that, in North America at least, existing regulations governing the oil & gas industry and acid well injection cover a large part of what will constitute the deep (geological) CO_2 storage industry- specifically, pre-injection, injection, and abandonment. In addition, the possible modification of the USEPA's UIC Programme to cover geological CO_2 storage has been discussed in *Section 4.2*. Thus, rather than develop a whole new regulatory system, a more logical approach would be to add to, or modify, those existing regulations in the areas that are necessary.

It seems preferable that regulation*s* governing long-term CO_2 storage be developed within an existing regulatory scheme. Although the regulatory regimes in North America and Europe are different, we do not see any barriers specific to one geographic location that would prevent this approach. At the May 2003 NETL Second International Conference on Carbon Sequestration, during discussions by a regulatory panel, there appeared to be a consensus that existing regulations already cover, or at worst, can be adapted to cover, most of the activities associated with CO_2 storage. This approach (of adapting existing regulations) also has the benefit of allowing the learning process to continue, thereby taking advantage of new knowledge gained, consistent with the argument presented in the previous section.

We noted in *Section 3.8.2*, and reemphasise here, that there is a timely opportunity for the CO_2 storage 'industry' to work towards a consensus in regulatory procedures, recognising where changes to existing regulations are necessary, and demonstrating a willingness to incorporate such changes.

Where there is a need to adapt current regulations to regulate the geological storage of CO_2, consideration should be given to the issue of uncertainty in the modification of regulations. The timeframe following completion of injection and acceptance of the safety of the (geological) storage ‘container’ should be well-defined. Uncertainty about the transference of liability to the public sector could significantly impact the economics of storage in a negative fashion.

The philosophy underlying this approach is "as we learn more, we continue to become smarter". The logical question that follows concerns what information/data we need to become smarter. For example, in terms of monitoring and leakage, is the existing monitoring capability able to identify and characterise reservoir leakage?

Questions such as this are more important than focusing on the regulations themselves. Consequently, it is important to ensure that the data flow operates to achieve the goal of increasing knowledge. The ultimate, which we should strive to avoid, is government intervention to ensure effective data collection, without predetermining regulations.

Regulatory issues guiding environmental safety are relatively well established – only the timeframe of hundreds of years differs from typical operational guidance, with some exceptions. On the other hand, the regulatory issues governing greenhouse gas reduction accreditation are more complex. For example, for accounting purposes, a key issue surrounding long-term CO_2 storage is whether the regulatory system will require that the CO_2 remains in the reservoir, *i.e.* without any CO_2 migration, or whether there will be some provision for dispersion within the geosphere. How to account for such CO_2 migration within the geosphere is one of the challenges facing CCS.

Table 1: Long-term CO_2 storage: summary of key regulatory issues in the context of timescale.

Topic	Issues	Timescale of relevance	Comment
Timescale		Performance - few hundred years (200-500 years) Environmental impacts – several thousand years.	Uncertainty due to influence of developing technologies on fossil fuel consumption Regulatory system can address such a long timescale up front, *i.e*. pre-abandonment.
Liability		Strictly, as long as environmental impacts are likely	Potentially thousands of years; therefore necessary for transfer of responsibility from private to public sector.
Economics		Thousands of years (environmental impacts) Hundreds of years (performance) Hundreds of years (performance)	Significant uncertainties associated with long-term framework, particularly in estimating costs of monitoring.
Well-bore integrity		Performance (hundreds of years) and environmental impacts (thousands of years).	Degradation processes mean degraded seal behaviour after a few decades to a hundred years. Conceivably, new abandoned wells with superior casings and sealing materials could meet short-term (hundreds of years) requirements, but future remediation probably a necessity.
Reservoir leakage		Performance (hundreds of years) and environmental impacts (thousands of years).	Leakage within geosphere should not be an issue, but accounting for this type of migration will be problematic. Initial projects should focus on how much characterisation is necessary to allow adequate prediction of CO_2 behaviour in storage reservoir.

Table 1 (continued): Long-term CO_2 storage: summary of key regulatory issues in the context of timescale.

Topic	Issues	Timescale of relevance	Comment
Monitoring	Principal reasons for monitoring are confirmation of predictions, greenhouse gas accreditation accounting and public confidence.	Relevant to both performance and environmental impacts	Variety of techniques available, both surface and subsurface, as well as *in situ* well-bore monitoring. Calibration and accuracy likely to restrict timescale for *in situ* monitoring to decades. Intense monitoring activity in short-term (decades) – pre-abandonment stage; surface monitoring for hundreds of years is possible for public confidence, but post-abandonment monitoring should not be necessary if the assessment work prior to abandonment is carried out adequately.
Record keeping	Information retained principally storage site and abandoned well locations; also characteristics of wells. Archives for greenhouse gas reduction credit accounting AND future environmental impacts.	Hundreds of years (performance) Thousands of years (environmental impacts).	Realistic timescale for maintaining archives is probably a few hundred years; hence information relevant to environmental impacts (abandoned wells) will eventually be lost. However, transient phase of storage reservoirs will be covered.
Other	Integration of different regulatory systems – operational phase (pre-injection, injection and pre-abandonment) and post-abandonment. Future development / modification / integration of regulations, *e.g.* concerning groundwater – may impact future liability. Technical basis for justifying values for acceptable leakage rates.	Overlap occurs at abandonment; post-abandonment needs to cover future performance and environmental impacts. Primarily environmental impacts but could also be performance. Relevant to both performance and environmental impacts.	

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Appendix A: Relevant Considerations from the Nuclear Waste Disposal Industry

A1 Introduction

The basis for this Appendix is the premise that consideration of long-term effects from CO_2 storage has elements in common with the field of nuclear waste disposal, as well as elements that differ. Considerable attention has been placed on the final storage of nuclear waste over the past several decades, and there are now well-established concepts and approaches for dealing with consideration of geological systems engineered to function over long time frames. As a result, we feel it is useful to review here some of the basic concepts derived from nuclear waste disposal research and application, and to explore the extent to which those concepts could be applicable to geological storage of CO_2.

Topical areas in which the two fields are likely to have the greatest overlap are:

- Ethical considerations related to inter-generational equity,
- Basic considerations that should be part of a regulatory system designed to ensure that ethical constraints are met,
- Considerations of long-term record keeping and site markers, and
- A systems-level approach to evaluate safety of the facility in the future, including appropriate consideration of uncertainties that arise from projections into the long-term future.

Topical areas in which the two fields have the greatest differences are:

- Legal and regulatory structures for the two will be substantially different,
- Time periods of concern for nuclear waste are usually much longer than the time periods of concern for geological storage of CO_2, and
- The physico-chemical behaviour of CO_2 in the subsurface is different from that of radioactive elements, requiring the use of significantly different modelling approaches.
- Public acceptance of the nuclear industry and the perception of risks are at least an order of magnitude greater than that for the hydrocarbon or coal industry.
- Subsurface facilities for nuclear waste storage are fully engineered, whereas CO_2 storage generally makes use of existing natural structures (voids).

The areas of similarity are therefore seen to be the general concepts and approaches, whereas the areas of difference are the specific considerations and approaches needed to evaluate the system. These topics are discussed in the following sections.

A2 Storage Facility Life Cycle

As with nuclear waste storage, a CO_2 storage site will be developed in a staged manner. At each stage of its lifetime, it is necessary to demonstrate that the storage site will be safe as proposed. It is useful to begin by defining stages in the lifetime of the storage site, to provide a common basis for further discussion. The stages of a long-term CO_2 storage / sequestration site are likely to be:

1. Site Selection and Characterisation
2. Design
3. Operation
4. Closure
5. Post-closure or abandonment.

These stages are discussed in more detail in the following sections.

A2.1 Site Selection and Characterisation

The goal of a siting process is to identify a suitable site in the areas of:

- Availability of storage volume in host rock in relation to CO_2 supply,
- Long-term safety,
- Safety in the operational period (short-term safety),
- Technical feasibility,
- Social acceptance,
- Environmental considerations,
- Cost.

All except the first factor above, are discussed in terms of nuclear waste storage by Savage [1995].

From a purely technical perspective, it is necessary to consider all of these goals, to optimise the site selection to achieve all of them simultaneously, and to an acceptable standard. While technical considerations play a necessary role in site selection, political considerations have become far more important in siting controversial facilities in recent years. Consequently, sites currently are often chosen based significantly on acceptance by the local population. With this additional constraint, it is necessary to ensure that site characteristics are adequate for the purpose of long-term CO_2 storage.

A2.2 Design Stage

As with nuclear waste storage, the design of the long-term CO_2 storage project should minimise the need for active maintenance after site closure, and should complement the natural characteristics of the deep (geological) site to reduce any environmental impact. The design should take into account operational requirements, closure plan and other factors contributing to stability of long-term CO_2 storage, such as protection from external events.

The design of any monitoring program should not compromise the long-term performance of the disposal system. Similarly, the potential for degradation/failure of closed and sealed operational wells over the long term needs to be taken into account, to provide assurance that the integrity of the (overall) system is acceptable.

The construction stage can generally only start after regulatory authorisation has been issued. In the case of nuclear waste, this requires that safety assessment documentation has been reviewed, that the detailed facility design has been approved, that the respective licensing procedures have been completed, and that an appropriate quality assurance program has been established.

A2.3 Operational Stage

For nuclear waste disposal, the operational phase usually comprises the following activities:

- Commissioning,
- Waste receipt, and
- Emplacement.

The operational stage is sometimes also considered to include operational monitoring and surveillance, and any emergency activities [IAEA, 2003]. However, these are often considered to be separate from the operational phase, and to require a separate licence.

The licence to operate the site may be subject to conditions imposed by the regulator to ensure that the operations are consistent with the applicable regulations. In addition to the post-closure and industrial safety requirements for these activities, there may be requirements for physical security, fire protection and other safety related matters [IAEA, 2002].

During the operation of a repository, the operator must be able to demonstrate that the site is performing as designed with respect to its impact on workers, members of the public and the environment, as well as being in compliance with the conditions of the licence.

Given that the operational stage of a CO_2 storage project is similar to that of an oil&gas project, the requirements for the operational stage are expected to be met without difficulty.

A2.4 Closure Stage

Closure refers to technical and administrative actions taken at the end of the operational period to put the site in its final state, ensuring long-term safety. In the case of CO_2, closure takes place after storage operations have been completed. Engineered barriers, such as well seals, are intended to ensure the integrity of the storage site, to minimise the migration/leakage of CO_2, and to reduce the likelihood of disturbance by human activities. Closure should be conducted in accordance with a closure plan that includes an updated safety assessment and a description of the institutional controls intended for the post-closure phase [IAEA, 2002].

A2.5 Post-Closure or Abandonment Stage

As with nuclear waste storage, the post-closure period of the life-cycle refers to the time in which the CO_2 storage site is developed to its final state, and is performing its function of isolating CO_2 from humans and the environment. The post-closure period is often further subdivided into periods of *active* institutional control and *passive* institutional control.

In the case of nuclear waste disposal, some form of institutional control may be assumed to remain in place for a period of around 100-300 years after the site has been sealed [IAEA, 1999]. Institutional control will preclude any inadvertent human intrusion into the disposal site, and disruptive natural events are not expected to occur over this time period. Institutions designated for post-closure control of near-surface sites can be instrumental in providing scientific and technical support for safety in the following ways [IAEA, 2002]:

1. Consequence reduction. If a situation giving rise to a potential release is identified (for example, a leaking well), the institution can evaluate a range of options intended to reduce the impact. This is usually referred to as remediation or intervention.
2. Reduction of the likelihood of the consequence arising. Institutional control measures, such as the construction and maintenance of fences and other physical security measures, markers, land use controls and archives, can all be seen as means to reduce the likelihood of the site being disturbed. It is important to reduce the likelihood of system integrity being impaired.
3. Monitoring of sites. Post-closure monitoring can serve several functions. It can provide an early warning of system malfunctions that might lead to unacceptable impacts on individuals and the environment. It can also help in verifying the intended overall performance of the disposal system.

At each stage of the life cycle of the disposal facility, it is necessary to maintain the safety assessment, to ensure that safety will be maintained throughout. This means that the safety assessment needs periodic revision and updating to incorporate the most up-to-date information. As the understanding of the facility and its environs grows, the safety assessment may need to be updated as well. Such updates may be established in law, requiring a periodic review, or they may be requested by the regulatory authority to ensure that the safety case remains relevant to current practices and understanding at the site.

A3 Ethical Principles in Waste Management

A3.1 IAEA Fundamental Principles of Nuclear Waste Management

The ethical basis for nuclear waste management has received considerable attention in the literature. As such, it provides a useful template for establishing the general principles that should apply to long-term CO_2 storage. In this section, therefore, the principles of nuclear waste management are identified, and specific discussions are provided on how these principles should be applied to CO_2 storage.

Clearly, CO_2 is not a waste in the context of the long-term storage of this gas. Indeed, CO_2 is a beneficial material in, for example, an enhanced oil recovery (EOR) flood, or, as foreseen in the CRUST project (see *Section 4.1* of main text), in greenhouses. However, the primary goal of CO_2 storage is the removal of excess gas from the atmosphere, regardless of other potential beneficial consequences of the action. Consequently, for the purposes of this discussion, 'CO_2 removal' can be equated to 'waste' in the text below.

The International Atomic Energy Agency (IAEA) formulated nine basic principles that reflect the ethical basis for nuclear waste disposal [IAEA, 1995][31]:

1. *Protection of human health*: Waste shall be managed in such a way as to provide an acceptable level of protection for human health.
2. *Protection of the environment*: Waste shall be managed in such a way as to secure an acceptable level of protection for the environment.
3. *Protection beyond national borders*: Waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.
4. *Protection of future generations*: Waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.
5. *Burdens on future generations*: Waste shall be managed in such a way that will not impose undue burdens on future generations.
6. *National legal framework*: Waste shall be managed within and appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.
7. *Control of waste generation*: Generation of waste shall be kept to the minimum practicable.
8. *Waste generation and management interdependencies*: Interdependencies among all steps in waste generation and management shall be appropriately taken into account.
9. *Safety of facilities*: The safety of facilities for waste management shall be appropriately assured during their lifetime.

The application of these principles imposes unique constraints on waste disposal facilities. Their safety must be assured over unprecedented timescales (hundreds to hundreds of thousands of years), and must be capable of functioning in these far distant times without human intervention (Principles 4 and 5). These unique constraints must be kept in mind when considering options for waste disposal.

IAEA [1995] established these nine fundamental principles to guide responsible management of nuclear waste. These principles form the basis for all nuclear waste management activities, and form the fundamental basis for the Joint Convention on the Safety of Spent Fuel and Radioactive Waste Management. Consequently, these principles have become codified in international treaty, and are obligatory upon signatory nations. The equivalent basis in both national and international law is

[31] The original language of these principles is posed in terms of radioactive waste. The reference to radioactivity has here been dropped, on the premise that these principles ought to apply to all wastes.

considerably different for long-term storage of CO_2 than for the final storage of nuclear waste. Nevertheless, the nine principles provide a useful template for considering what should be included in national legislation and international treaty.

A3.1.1 Principle 1: Protection of Human Health

Waste shall be managed in such a way as to secure an acceptable level of protection for human health.

The assessed impact of a long-term storage of CO_2 project must ensure that human health will be protected at all phases of the project. Consequently, there must be adequate protections in place for both workers and the public during the operational phases of the project, as well as adequate protection for members of the public after the termination of operations.

Protection of human health during the operational period may be ensured using standard industrial approaches existing for handling large volumes of CO_2 for EOR projects. There is long-standing experience in such operations, and a good public safety record. In this respect, there is overlap between Principle 1 and Principle 9.

On the other hand, protection of human health during the post-operational phase is less well studied to date, and is the focus of much of the current research on CO_2 storage. Human health will be shown to be protected if airborne concentrations at the ground surface remain below a threshold value. Two threshold values are envisioned:

1. A value associated with asphyxiation, in the event of a sudden release of CO_2 to the surface, and
2. A more moderate value to limit potential health effects associated with chronic exposure to moderately elevated levels of CO_2.

For completeness, note that this principle can also be applied to *global* environmental effects, *i.e.*, climate change. In this respect, this principle is fundamentally important as the main driving force for most CO_2 capture and long-term storage projects.

A3.1.2 Principle 2: Protection of the Environment

Waste shall be managed in such a way as to provide an acceptable level of protection of the environment.

Protection of the environment may be formulated in terms of three principles:

1. Protection of natural resources,
2. Protection of non-human biota, and
3. Protection of cultural resources.

Protection of Natural Resources

Protection of natural resources refers to groundwater, soil, and mineral resources. In the context of CO_2storage, protection of natural resources may be the most important aspect of protection of the environment. Existing legal requirements for protection of aquifers can be used to establish quantitative criteria. The primary concerns for groundwater resources are the potential for acidification and for liberation of toxic heavy metals associated with that acidification.

Protection of Non-human Biota

Protection of non-human biota relates to the potential for kills of livestock or wildlife, and potential kills of plant life associated with releases of CO_2 to the biosphere. It is anticipated that levels of CO_2 sufficient to kill animals would also be of concern for human health. As a consequence, levels of protection for humans are likely to also be protective of animals. Protection of animals is therefore considered to be subsumed by requirements for the protection of humans. The sole possible exception would be legal requirements for the protection of endangered species, if any exist at the site. Requirements (or lack thereof) for protection of endangered species need to be determined on a site-specific and species-specific basis.

Protection of non-human biota may also be interpreted to mean protection of plant life. Releases of CO_2 have the potential to result in damage to local flora, although low-concentration leakage is unlikely to result in a negative impact. In general, non-endangered flora are protected not on an individual plant basis, but rather on a species-wide basis. Plant kills would therefore not generally be considered to impose relevant considerations on a CO_2 storage project, unless endangered species were involved.

Protection of Cultural Resources

An additional consideration that may play a role in development of a project is the potential impact of site selection on cultural resources. This principle plays a particular role in developing public consensus for environmental projects, particularly when Native American lands are used. The applicability of this principle to a CO_2 storage project must be determined on a site-specific basis, accounting for local political considerations.

A3.1.3 Principle 3: Protection Beyond National Borders

Waste shall be managed in such a way as to ensure that possible effects on human health and the environment beyond national borders will be taken into account.

This principle is derived from an ethical concern for human health and the environment in other countries. IAEA [1995] states that a country should not allow impacts in other countries more detrimental than those judged acceptable in its own country.

This principle is of minimal concern in North America, where borders are few and countries are large. It could be expected to play a more significant role for CO_2 storage projects in Europe.

A3.1.4 Principle 4: Protection of Future Generations

Waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

This principle is derived from an ethical concern for the health of future generations. In the establishment of acceptable levels of protection, the latest recommendations of international organisations, for example the International Commission on Radiological Protection (ICRP) and the IAEA, are typically taken into account.

The international nuclear waste management community has developed a consistent philosophy about the necessity to account for potential effects of waste disposal on future generations [ICRP, 1997]. The fundamental intent of this philosophy is to extend to future generations the same levels of protection that are considered appropriate today [IAEA, 1996]. Consideration of such long-term, intergenerational ethical considerations has been unique to the management of nuclear waste [Okrent, 1994]. Fundamentally, disposal of nuclear waste is perceived to be a particularly difficult problem because stronger technical requirements are imposed than on other activities of similarly hazardous nature [KASAM, 1988]. For instance, heavy metal wastes, which are toxic forever, are managed less stringently than nuclear wastes. Hazardous wastes are managed in a way that is intended to limit releases to the environment for a few tens of years, and potential risks at longer times are not evaluated [Kozak, 1996]. As discussed by KASAM [1988], potential intergenerational considerations should ethically be taken into account when planning all technological activities, but generally they are not. Indeed, in most technical activities, long-term risks are discounted in similar manner that accountants discount future costs [Portney and Weyant, 1999].

A3.1.5 Principle 5: Burdens on Future Generations

Waste shall be managed in such a way that will not impose undue burdens on future generations.

The basis for this principle is given by IAEA [1995] as fulfilling an ethical obligation on the current generation not to transfer burdens associated with wastes to future generations. Since the current generation enjoys the benefits of activities that generate the waste (*e.g.* electrical power), it is ethically responsible for the current generation to bear its burdens (*e.g.* the cost of disposal.) The responsibilities to the future generation include [IAEA, 1995]:

- Developing technology,
- Constructing and operating facilities,
- Providing a funding system,
- Providing an adequate system of controls and plans, and
- Establishing and financing an institution to handle waste management in the future.

This principle was understood to represent an argument that we should make rapid progress toward designing, siting, constructing, and operating disposal facilities. That is, since the current generation enjoys the benefit of the waste-generating activities, we should bear full responsibility for the costs and difficulties in disposing of the wastes.

Regarding financial obligations, the idea is that sufficient financial resources need to be ensured today so that near-future generations (say, 50-100 years hence) will have enough funds to close and monitor the facility for appropriate period of time. Some have suggested that financial resources should be sufficient to accommodate the possibility that intervention may be needed in the future to remediate a facility that has failed. However, this is not a typical provision of national financial requirements for disposal facilities.

A second facet of this principle is that safety of the disposal facility should not, to the extent possible, relay on institutional control or actions.

An interesting difference between ordinary waste management activities and long-term storage of CO_2 is that future generations are viewed as the primary beneficiaries of the activities, through the avoidance of greenhouse gas production. This difference is viewed as representing a significant shift in the in the ethical balance on burdens to future generations.

A3.1.6 Principle 6: National Legal Framework

Waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.

A national legal framework is necessary providing laws, regulations and guidelines for management of CO_2 storage projects. The responsibilities of each party or organisation involved should be clearly allocated for all waste management activities that take place in a country. As part of this responsibility, it is necessary to allocate sufficient financial resources to each organisation with responsibility for nuclear waste [IAEA, 2000a].

The discussion of this principle by IAEA [1995] emphasises the establishment of an independent regulatory function. Long practice in a number of countries has demonstrated that if the regulatory function is not independent of the operator, safety suffers. Independence is necessary at all levels of the organisation, typically up to the national governmental (*e.g.* ministerial) level or equivalent. Independence at a high level reduces the likelihood that political pressure will be used to influence staff decisions about safety.

Similarly, at the staff level, it is necessary to maintain independent technical expertise in both the operator and regulator organisations. Many of the technical requirements for regulation of nuclear waste are very specific and require a high level of skill. Operating organisations frequently have the ability to maintain a high level of technical expertise, because they are involved in the actual technical work. The need for competent technical staff in the regulatory authority is equally important, since their responsibility is to identify problems with the operator's activities. The regulatory function works best when supported by highly qualified, trained, and experienced technical staff.

Enforcement functions are particularly identified as a key element in effective regulatory control of a waste management practice. That is, it is necessary for a regulator to be able to levy penalties on the operator for non-compliance with regulatory requirements. The regulatory function can only be effective if effective regulatory enforcement is established.

A3.1.7 Principle 7: Control of Waste Generation

Generation of waste shall be kept to the minimum practicable.

In the context of a long-term storage project, this principle is not directly applicable, since it refers to processes leading to the production of CO_2, which cannot be controlled by the project. However, this principle could be applied in terms of a philosophy to make optimal use of storage reservoirs, or even to store pure CO_2 rather than flue gases.

A3.1.8 Principle 8: Waste Generation and Management Interdependencies

Interdependencies among all steps in waste generation and management shall be appropriately taken into account.

Use of this principle implies that the overall system of long-term CO_2 storage needs to be considered rather than looking at particular aspects in isolation. There are many examples of problems that may occur if due consideration is not taken of the overall waste management system. Decisions taken in one waste management operation may reduce or eliminate options later.

A3.1.9 Principle 9: Safety of Facilities

The safety of facilities for waste management shall be appropriately assured during their lifetime.

This principle, which is partly redundant with other principles, focuses on safety in a broad context and is intended to address all periods in the facility life cycle.

IAEA [1995] notes that safety considerations need to be considered in siting, design, construction, operation, modification, decommissioning, and closure of a facility. Safety considerations in these different stages of the life cycle of the facility will differ, and need to be considered in the overall management system.

In North America, safety culture for the operational period of industrial projects in general is well established and regulated by existing agencies, such as OSHA. Consequently, this principle is addressed satisfactorily for North American projects. We believe that this situation also applies in Europe; for example, the Health and Safety Commission (HSC) and Health and Safety Executive (HSE) in the United Kingdom.

A3.2 NAPA Principles on Rights and Interests of Future Generations

The National Academy of Public Administration (NAPA), at the request of the U.S. Department of Energy (USDOE), studied how public administrations could take the rights and interests of future generations into account when making decisions [NAPA, 1997]. While the study for USDOE was clearly intended to be used for issues related to nuclear waste management and remediation, the principles are more broadly applicable to other environmental topics, as well as broader areas of public policy.

NAPA [1997] proposed an approach based on four principles:

1. *The Trustee Principle*: Every generation has obligations as trustee to protect the interests of future generations.
2. *The Sustainability Principle*: No generation should deprive future generations of the opportunity for a quality of life comparable to its own.
3. *The Chain of Obligation Principle*: Each generation's primary obligation is to provide for the needs of the living and succeeding generations. Near-term concrete hazards have priority over long-term hypothetical hazards.
4. *The Precautionary Principle*: Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is some countervailing need to benefit either current or future generations.

NAPA [1997] recognised that each of these principles has limits, and that they may be contradictory in some circumstances. Responsible decision making therefore requires the decision maker to achieve a balance between them.

Derived implications for long-term CO_2 storage associated with these principles are [NEA, 2001]:

- The generation producing the increased atmospheric concentrations of CO_2 is responsible for its safe management and the associated costs.
- There is an obligation to protect individuals and the environment both now and in the future.
- No moral basis exists for economic discounting of future health and risks of environmental damage.
- Our descendants should not be exposed to risks that we would not accept today. Individuals should be protected at least as well as they are today.
- The safety and security of storage sites should not be based on the presumption of a stable social structure for the indefinite future or on a presumption of technological progress.

- CO_2 storage should be carried out in such a way as not to be a burden for future generations.

A4 Basic Principles for Regulatory Structure

The assumption of a legal and regulatory structure consistent with the discussion in *Sections A1-A3* of this Appendix allows consideration of certain basic principles that might form part of a regulatory structure. The focus of this section is on the post-closure or abandonment period.

A4.1 Protection of Human Health

The first principle to be embodied in the regulatory structure is protection of human health. Such protection has two aspects:

1. Protection against potential low probability, but sudden large releases, which may lead to the potential for asphyxiation, and
2. Protection against higher probability releases at very low levels of CO_2, which lead to low levels of non-lethal health effects.

Legal precedents exist to omit consideration of extremely low probability events and processes that may lead to deleterious behaviour of the storage site. For example, in 10 CFR Part 63, the regulation for high-level radioactive waste destined for Yucca Mountain, a requirement is in place that only events and processes need to be evaluated that are expected to occur with a likelihood of occurrence greater than 1 in 10,000 over 10,000 years. This equates to an annual probability of occurrence of one in 10^8, assuming the probability to be time independent.

In 40 CFR Part 191, the EPA regulatory standard for high-level waste, additional probability-based criteria are introduced. The concept of this approach is to explicitly acknowledge the regulatory acceptability of higher consequences if they occur with lower probability.

Hence, a precedent exists for the development of a graduated scale of consequence, in which a small probability may exist for high-consequence events and processes. Under such circumstances, the conditions leading to potential health and safety concerns need to be more carefully defined in the long-term future. These conditions are:

- Protection at all times,
- Standardised receptor assumptions, and

- Reasonable assurance.

A4.1. 1 Protection at All Times

Health standards appropriate today should be used as the basis for health standards applied in the future. There is no basis for discounting human health of environmental standards at future times. By implication, therefore, the regulatory requirements should apply standards acceptable today to all times in the future. That is, there should be no change in health standards applied at times in the future. It is anticipated that the technical goal of geological storage (atmospheric CO_2 reduction) will be complete after a few hundred years, but the potential exists for releases of importance for human health to continue well after that time period. As discussed below (*Section A4.3*), it is possible that technical arguments can be made that releases will decrease in time (*e.g.* from geochemical reactions of CO_2 in the subsurface).

A4.1.2 Standardised Receptor Assumptions

Given the long time periods of concern, standard human behaviour assumptions should be made. This approach is consistent with current international guidance [BIOMASS, 2003]. This feature of the regulatory structure would take the form of specific sets of assumptions about human behaviour to be used in comparing with the standard. Indeed, this approach can be used in principle to derive health-based leakage rate limits.

A4.1.3 Reasonable Assurance

Regulations dealing with projection of storage site behaviour into the future explicitly call for reasonable assurance of compliance. Reasonable assurance is explicitly invoked in recognition that the future is unpredictable. Reasonable assurance is an approach contrasted with absolute assurance, which is recognised to be impossible to achieve [EPA, 2002].

A4.2 Protection of the Environment

For the purposes of geological CO_2 storage, environmental protection can be defined solely in terms of fresh water resource protection. In the USA, existing regulations for the protection of drinking water have been expanded by EPA and many States to encompass protection of groundwater resources[32] to the same level as drinking water. This approach introduces a number of technical difficulties that may be difficult to

[32] For more widespread application, 'fresh water resources' and 'groundwater resources' are used interchangeably here.

address on a generic basis. Foremost among these technical issues is to define a representative volume of water for which the concentration-based standards apply. It is anticipated that there may be a desire by regulatory agencies to apply the drinking water standards to groundwater in this way.

A4.3 Time Frames

A number of time frames appear naturally when evaluating long-term CO_2 storage. The first consideration is the time frame over which it is necessary to store / sequester CO_2 in order to have an impact on potential greenhouse gas warming. As discussed in *Section 2.1* of the main text, this is on the order of hundreds of years.

The second consideration is the time frame for protection of human health which, as discussed in *Section 2.2* could only be necessary for hundreds of years but needs to be considered over thousands of years. There is no *a priori* justification for a time cut-off at any time. There may be technical arguments related to the restoration of equilibrium conditions following the CO_2 flood that could be used as the basis for a time cut-off, but further technical analyses and understanding are needed to justify any value.

A third consideration is the time frame for groundwater protection. In 40 CFR 197, EPA specified that the groundwater protection clause applies over the same time period as the human health provisions. It is likely that this precedent would continue to apply to regulatory requirements for other types of disposal or long-term storage.

A5 Record Keeping and Markers

A considerable body of literature on site markers and record keeping has been developed over several decades, with the goal of determining the extent to which records and markers can be relied upon to deter inadvertent human intrusion at nuclear waste disposal facilities. Some aspects of this literature are pertinent to geological storage projects, and some are not pertinent. In this section, a discussion is presented of how the two areas are similar and how they differ.

Site markers are warning signs at the facility, put in place to identify that hazardous activities have taken place at the site in the past. They are intended to provide a direct warning to people that might encounter the site in the future. Site markers rely primarily on the durability and visibility of the marker to accomplish their task. By contrast, record keeping refers to maintenance of off-site records that would limit the potential for people in the future to engage in risky behaviour associated with the disposal facility. The intent is to retain knowledge of the site, and to limit future access to the site. Deed restrictions, restrictions on mineral rights, and government land ownership are all possible mechanisms for keeping records associated with a repository project.

A5.1 Site Markers

Trauth *et al*. [1992] evaluated the likely effectiveness of markers for the Waste Isolation Pilot Plant (WIPP) facility. They convened expert groups to form a collective opinion about the markers, comprising panellists from diverse backgrounds. The effectiveness of past marker systems with intended longevity was discussed, such as the Egyptian pyramids. A number of issues associated with markers were explored, including the possible defacement or misunderstanding of markers. The consensus of the group was that site markers may be effective for a few hundreds of years, but not longer, given the likely changes in language over the time period of concern for WIPP (10,000 years). This conclusion is consistent with the findings of other groups that have studied site markers associated with nuclear waste disposal facilities.

A5.2 Record Keeping

Record keeping and land control are considered key aspects of nuclear waste management strategies worldwide [IAEA, 1999, 2002]. Record keeping is regarded as a passive approach, using a variety of government recording mechanisms to retain knowledge that waste disposal activities have occurred at the site. It is accepted that as long as governmental institutions provide continuity, it is unlikely that such records will be lost or that unintended transfer of land would occur. Typical values of 100-300 years of institutional control are generally accepted for nuclear waste disposal facilities. Longer periods of time may be justified.

As in nuclear waste disposal, records are intended to retain knowledge of the practice for very long times. However, time frames for geological storage of CO_2 may be shorter than for nuclear waste disposal. This implies that greater reliance on record keeping may be appropriate for CO_2 storage.

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