



Role of Risk Assessment in Regulatory Framework for Geological Storage of CO₂

Feedback from Regulators and Implementers

Technical Study

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ROLE OF RISK ASSESSMENT IN REGULATORY FRAMEWORK FOR GEOLOGICAL STORAGE OF CO₂: FEEDBACK FROM REGULATORS AND IMPLEMENTERS

Background to the Study

One of the key issues that need to be resolved for wide scale implementation of CO₂ capture and storage (CCS) is that of security of storage. To gain general acceptance of the technology it will be necessary to prove that CCS is a safe and environmentally acceptable option. To resolve this issue it is considered that no single activity or action will satisfactorily answer the question alone. However, a number of different activities when taken together should be able to resolve it. These activities include:

- The development of a regulatory process for CCS that requires an operator to demonstrate “due diligence” in the selection of an appropriate site for CO₂ storage. The regulatory process would include: site characterisation, geological/geochemical modelling, development of a simulation tool for long term prediction of the fate of injected CO₂, an environmental impact assessment and also a risk assessment study. In addition, potential seepage/fugitive emission options will be identified as part of this exercise and remediation plans incorporated in the operational plans.
- The monitoring of CO₂ injection projects to determine actual seepage rates to the surface, if they occur. Knowledge of the flux to the surface will allow an estimate of both the local health and safety risks to be determined and the likely ecological consequences to be determined.

Taken together this work should help to build a reference manual of data on reservoir integrity/security and actual seepage of CO₂ that should build confidence that the CO₂ can be contained effectively in the geological formations into which it has been injected.

One issue that needs to be considered is the need for a risk assessment study. The use of Risk Assessment (RA) is common practise in many industries, such as the power sector and nuclear industries. The IEA Greenhouse Gas R&D Programme (IEA GHG) has established an international research network on RA, which has shown that the application of risk assessment tools and techniques to CCS is at an early stage and careful thought needs to be given to the results that this work is generating. RA studies will potentially be of significant interest to the regulatory bodies that will consider potential CCS projects. The RA network, therefore, identified a need to begin a dialogue with the regulatory bodies on what their needs and expectations are for risk assessment as part of a regulatory process for CCS¹. The aim of this study was to begin that dialogue process with the regulatory bodies. The study has been carried out by Monitor Scientific Inc. of the USA

Results and Discussion

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

- Study process,
- Briefing document on risk assessment status,
- Summary of regulatory and implementer feedback,
- Gaps and future research needs.

¹ IEA Greenhouse Gas R&D Programme, Launch Meeting of the Risk Assessment Network, Report No 2006/5, January 2006.



Study Process

The study involved first the development of a Briefing Document (BD) on RA for geological CO₂ storage projects. The BD reviewed the status of RA for CCS and served as a reference document for future actions. The BD was agreed with IEA GHG and was then sent to regulators² and implementers³ of CCS projects in different countries as a basis for dialogue concerning their individual roles in their respective CCS projects. In addition, to accompany the BD, a series of questions were posed to the regulators and implementers. The questionnaires were used as a means of determining the ability of existing or planned legislation in different countries, to enable the authorisation of CCS projects. The questions posed were somewhat different for regulators and for implementers; the reasoning for this is discussed in the main report.

Regulators and implementers from a total of ten countries were consulted and participated in the study. The countries concerned were; Australia, Canada⁴, France, Germany, Japan, Netherlands, New Zealand, Norway, U.K., and U.S.A. The countries selected were considered to give a comprehensive coverage of those countries currently most active in this area of CCS implementation

Briefing Document on Risk Assessment Status

This BD aimed to summarise the current status and role of RA in support of geological CCS projects, both now and in the near future. The BD is given in Annex 1 of the main report. In the BD the status of RA was evaluated under a number of headings, which were also used in the questionnaires to regulators and implementers as a means of grouping series of questions. A summary of the key points in the BD relating to RA as presented to the regulators and implementers involved in the study is set out below:

- RA is likely to be a key part of the regulatory regime for CCS projects as one method for demonstrating safety. However, RA should not be considered as the only means of demonstrating or assuring safety.
- RA is not new and already exists under a number of regulatory frameworks. Where RA for CCS differs from most industrial and engineering projects is in the long term timeframes associated with geological CO₂ storage. Therefore, there is a need to demonstrate confidence in long-term predictions.
- Two RA timeframes are relevant to CCS depending on the needs of the regulator, whether for greenhouse gas reduction/inventory control, or for HS&E impacts. The long term timeframe for RA is likely to be several thousand years.
- Seepage fluxes/rates of CO₂ are likely outputs from RA predictions and could then be used as a part of the regulatory requirement for CCS projects. However, any regulatory requirement for seepage rate/flux limits must be based on a good scientific understanding ultimately linked to specific hazards and their possible consequences. Currently the predictions from RA studies do not allow rates or fluxes to be determined with confidence.

² For the purposes of this study a Regulator refers to a person/position responsible either for developing the policy framework within which regulations are developed (In many jurisdictions, this person may be called the “policy maker”), or for ensuring that the relevant laws/regulations are followed.

³ For the purposes of the study an implementer as used in this report applies to the person who has responsibility for managing/carrying out a CO₂ storage project, and therefore, for ensuring that the project is conducted in a way that conforms to the regulations that are in place. For the purposes of this study, therefore, an implementer is *not* the person who implements regulatory policy.

⁴ Note that authorisation of CCS projects will occur at the sub-national level in North America (provincial level in Canada and state level in USA)



- More than one RA methodology exists that can be applied to CCS projects. Although there is no consensus yet on the merits and shortcomings of the different techniques, a number of groups are using the scenario and FEP⁵ approach. It must be noted that all the methodologies rely on expert opinion to varying degrees.
- There are many uncertainties in natural systems and a number of different techniques can be used to address these uncertainties. The adequacy of a RA study will depend to what extent the different types of uncertainty are addressed in the risk assessment calculations.
- To date, a fully-integrated RA, which links CO₂ leakage from the storage reservoir to an evaluation of end-points such as HS&E impacts, has not been carried out for CCS-related projects. Such a fully-integrated approach will help to increase confidence with stakeholders, including regulators and the general public, when it is available which may not be for several years yet.
- Natural Analogues (NA) serve a number of purposes linked to RA, the most useful being to validate predictive modelling results. In the absence of quantitative information, NA examples can be used to increase understanding, by identifying geological environments that are suitable for long-term CO₂ storage, and, on the other hand, by providing good reasons why bad sites leak. A key role of industrial analogues is to illustrate to stakeholders how fugitive CO₂ leaks can be managed and mitigated.
- Stakeholder acceptance, in particular public acceptance, is considered key to developing CCS projects in a timely manner. RA is considered to be a critical component of public acceptance. All indications suggest that science-based information is not sufficient to satisfy public concerns, and other avenues of communication, e.g., natural and industrial analogues, are needed to support the science-based approach, particularly when RA techniques are not easy to communicate.
- Monitoring will play a key role at all stages of CCS projects. A variety of monitoring techniques are available in support of RA, either for baseline measurements or to verify and validate modelling predictions. Which technique(s) to use will depend largely on detection limits, the need for minimal intrusion at storage reservoir depth, and on costs.

Summary of Regulatory and Implementer Feedback

The questionnaires and responses to the questionnaires by the regulators and implementers are summarised in the main report. Individual comments from regulators and implementers are also given in the main report for reference in Appendices 1 and 2 respectively. One observation that can be drawn from the responses of the two groups to the questions posed in this study is that there is no major disconnect between either of the groups which is heartening. Also, the same conclusion stands when comparing the corresponding responses of regulator and implementer(s) of the same country.

Both groups favour a regulatory framework that addresses CCS projects, with emphasis on the storage aspect which is regarded the more important issue for such projects. The establishment of some form of technical standard or protocol for addressing long-term safety in CCS projects was considered important by both groups. However, there were differing opinions concerning whether such a standard/protocol should be developed at the sub-national, national or international level. Current initiatives, such as the Framework for Risk Assessment and Management that is being developed under the London and OSPAR Conventions may help to provide a general basis for national legislation⁶.

⁵ Features, Events and Processes FEPs (FEPs - Features of the system, Processes that influence the evolution of the system, and the Events that can be viewed as processes that take place on comparatively short timescales).

⁶ Note: the emphasis from the London and OSPAR conventions will be on sub-seabed geological storage, but it is considered that most of the elements of the framework will be applicable to onshore geological storage as well.



The study has shown that implementers are looking for clear guidance from regulators in terms of what specific regulations or framework will address the long-term storage aspects of CO₂ storage projects. Specific regulations or a specific regulatory framework for CCS projects will take time to develop; 2007-2008 was the earliest anticipated in the countries covered in this study. It is therefore likely that in the near term CCS projects will need to be reviewed and authorised on a case-by-case basis.

Both groups view the assurance of long-term safety to be critical to the progress of CCS. In this regard, the responses from implementers indicate a desire for a rigorous methodology as a basis for assuring confidence in long-term predictions. In terms of storage and long-term safety, the timeframes considered by regulators to be appropriate for risk of leakage range from >~30 years to at least 1,000 years.

There was a broad range of opinions from regulators concerning CO₂ leakage rates/fluxes. It is likely, therefore, that the work currently being carried out on CCS-related projects, including RA results/predictions, will help to guide regulatory opinion on this topic.

Monitoring during the injection and post-injection phases of CCS projects will play a major role in regulatory acceptance of long-term safety. There was no consensus concerning the length of the post-injection stage, it is estimated to be ~10-20 years at least. Regulators considered that even after abandonment some form of monitoring will be required primarily for confirmation of modelling predictions and for verification purposes. The link between monitoring and verification of RA predictions was considered important by regulators.

Gaps and Future Research Needs

Both the regulators and implementers were asked to identify gaps and future research needs to assist the development of RA as a tool for CCS. Their responses are summarised in the table 1 overleaf.

The list of gaps/research needs indicate that there are both technical and non technical issues that need to be resolved. Both groups seem to acknowledge that the RA methodology and assessment models require further information/data to assist their development. From the implementer perspective there is again a requirement to develop a standard or protocol that gives them guidelines on RA methodology and its application, as well as a need for some criteria to enable them to assess the results against. Regulators are looking for guidance on monitoring requirements that might allow them to qualify seepage rates/fluxes and the impacts of such fluxes on the surface environment. Both groups focus on the need for some confidence in how wells are abandoned and their long term integrity. In addition, both groups feel that the storage pilot and demonstration projects will help to address many of the technical gaps that were identified.

IEA GHG considers that most of these gaps are covered by research that is currently underway either in pilot/demonstrations projects directly or are being addressed by activities such as the international research networks it has established on risk assessment, monitoring and well bore integrity. First impressions are that there do not appear to be any technical issues that will delay the process of developing a regulatory framework addressing geological CO₂ storage in all the countries covered in this study.



Table 1. Gaps and Future Research Needs Identified by Regulators and Project Implementers

Identified Gaps and Research Needs	Regulator	Implementer
Nature of long-term risks and associated institutional arrangements such as long term stewardship.	X	X
Agreed-upon RA methodology, preferably in terms of a Technical Standard/ Protocol.		X
Criteria against which assessment results should be compared.		X
Better definition/understanding of storage timeframe in the context of potential hazards and monitoring needs.	X	X
Monitoring requirements, particularly in the context of quantifying CO ₂ leakage/migration.	X	
Better understanding of what leakage is acceptable coupled with improved knowledge/understanding of specific environmental impacts, in particular groundwater, different ecosystems and offshore environmental impacts;	X	X
Well bore and cap rock integrity, including abandoned well integrity, in terms of reservoir performance;	X	X
Quantitative information/data from analogues.		X
Fluid movement response to CO ₂ injection, both regionally and locally.	X	
Quantification/verification of storage capacity estimates, preferably linked to local geology;	X	
Coupled models; in particular addressing the impact of geochemical interactions on geomechanical behaviour.		X
Effect of impurities, in particular H ₂ S, on thermodynamic (PVT) behaviour of CO ₂		X
Experimental data supporting thermodynamics and kinetics of CO ₂ reactions with different minerals.		X

Expert Group Comments

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

In general the report was well received at the network meeting and initiated considerable discussion. A number of constructive points were made that were taken on board and helped the overall content of the report. The responses from the expert reviewers were also constructive and generally helped to confirm specific issues relating to specific regional issues. In response to the expert reviewers comments the individual comments by the regulators and implementers were also included in the report for reference purposes.



Major Conclusions

The study is the first that IEA GHG has undertaken that has directly involved regulatory groups and CCS project implementers in a dialogue on RA needs. The issues related to and the results of this dialogue process have proved useful in a two way education exchange. As a result of the dialogue IEA GHG now feels that regulators, in particular, are better informed on the current status of RA when applied to CCS projects. Whilst RA is not a new tool, its application to CCS is new and requires considerable more development before we can be confident in the results that RA studies will produce.

The study has highlighted that there are a number of key areas that need to be addressed such as; the estimation of possible fluxes to the surface and their impact on the surface environment. In the flux case we need to correlate information from monitoring activities with geological/geochemical/hydrogeological modeling to allow us to gain confidence that predicted fluxes from RA's can be justified scientifically. On the issue of surface impacts IEA GHG has recently undertaken a study to assess what is known about the impacts of CO₂ leakage on shore, which should help to begin to clarify issues related to surface impacts.

The issue of storage time frames has been raised in this study. This issue was addressed in an earlier study by IEA GHG in an attempt to resolve this issue. Clearly this is not the case and our previous work may need to be revisited to see if we can bring further clarification on this fundamental issue.

Demonstration projects will undoubtedly be a significant source of information that can be drawn upon to help develop confidence in RA results. When developing demonstration projects we need to consider the developmental needs for RA as part of the activity to ensure that we do not leave any gaps that might result in the confidence of the scientific community and the general public in the predictions of RA to be undermined.

Demonstration projects will naturally take a time to produce the required results; in the mean time we should look to natural and industrial analogues as sources of information that can be used to generate confidence in geological storage of CO₂ as a safe and environmentally acceptable mitigation option.

Recommendations

This study was the first in a continuous process that needs to take place over the next 5-10 years as CCS projects and our knowledge on geological integrity increases. This activity should not be treated as a one off and the dialogue process on RA status should continue through the International research network on RA that has been established by IEA GHG.

Current and planned demonstration projects should be reviewed to ensure that all the gaps identified are covered and guidance is given to project developers on the type of information that is needed to develop our confidence in RA as a tool for CCS projects.

The development of a set of guidelines on RA could be the first step to developing a suitable standard or protocol. IEA GHG should consider setting up an activity to begin to develop RA guidelines and consider however the establishment of a set of criteria for RA quantification.

The issue of CCS timeframes needs to be revisited and further clarification given to the CCS community, if possible, by IEA GHG.

Role of Risk Assessment in Regulatory Framework for Geological Storage of CO₂

Feedback from Regulators and Implementers

Technical Report MSCI-2512v2 to IEA GHG

January 2007

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A project of this nature could not be completed successfully without the inputs from external participants. The material in the main body of the report plus Appendices A and B rely to a large extent on the feedbacks from the various regulatory and implementer participants and the conclusions are based on their inputs.

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1 Introduction

1.1 Initial Document Distribution

In February 2006, a Briefing Document (provided in *Annex 1*) on risk assessment for geological CO₂ storage projects, prepared during the first stage of this study, was sent to regulators and implementers of such projects in different countries as a basis for dialogue concerning their individual roles in carbon capture and storage (CCS) projects. In addition, to accompany the Briefing Document, a series of questions was posed to these regulators and implementers, as a means of determining the ability of existing or planned legislation in different countries, to enable the authorisation of CCS projects, in particular the longer-term storage aspect.

Regulators and implementers from a total of ten countries were consulted and agreed to participate in the study (these countries are the most active currently in this area):

- Australia, Canada¹, France, Germany, Japan, Netherlands, New Zealand, Norway, U.K., and U.S.A.¹

As discussed in the original Briefing Document, the primary focus of this IEA GHG study is on the regulator side and existing or planned regulatory frameworks for CCS projects. However, in terms of the approaches being used by implementers in the field of risk assessment (RA) associated with CCS projects, their input was considered highly relevant supplemental material to the project's primary focus.

Prior to finalising this report, some additional requests for feedback were made, resulting in additional responses that have been included in this final version.

1.2 Relevant Terminology

Certain terms used in this report require qualification. The Regulator refers to that person/position responsible either for developing the policy framework within which regulations are developed (In many jurisdictions, this person may be called the “policy maker”), or for ensuring that the relevant laws/regulations are followed. On the other hand, the implementer as used in this report applies to the person who has responsibility for managing/carrying out a CO₂ storage project, and therefore, for ensuring that the project is conducted in a way that conforms to the regulations that are in place. For the purposes of this study, therefore, an implementer is *not* the person who implements regulatory policy.

An implementer usually has an engineering / technical background, whereas the policy maker tends to take a more generic view of the situation and develops the framework within which regulations are developed. Importantly, this role involves a more comprehensive assessment of the economic, social, safety, and technical aspects of required regulations.

¹ Note that authorisation of CCS projects will occur at the sub-national level in North America (provincial level in Canada and state level in USA).



This report also has a defined terminology for injection, post-injection and abandonment phases, *viz.*

- The injection phase is that period of time during which CO₂ injection into the reservoir occurs.
- The post-injection (pre-abandonment phase *sens.* Keith and Wilson [2002]) is that period of time during which the regulator may require the wells to remain intact and monitoring to continue, prior to complete abandonment of the field and its injection wells.
- Abandonment is that period following the complete abandonment of the wells in the injection field. The process of well abandonment itself effectively means the permanent isolation of the injection zone from other formations in a manner stipulated by stipulated by local regulation.

The abandonment phase does not in any way determine responsibility for the field and its stored CO₂. In an oil- and gas-producing regime, this stage generally refers to the time at which the property is returned to the public domain. In such circumstances, regulations will determine the level of liability that resides with the producer of the resources in that field.

1.3 Questions / Responses

As will be seen in the subsequent sections, the questions posed to regulators and implementers were slightly different, but only to reflect the different roles that each party plays in CCS projects. Thus, for example, one key question for regulators is whether the existing framework or legislation in the respective country is able to authorise upcoming CCS projects. For implementers, the planned timeframe of upcoming projects in relation to existing or proposed regulations was significant.

A full set of responses were received from almost all of the above countries, sufficient to allow us to generate some overview comments on the status of regulatory frameworks for geological CO₂ storage, as well as on the role of RA in these regulatory frameworks. These overview comments are provided in the following sections.

Specific comments from regulators and implementers to individual questions provide valuable input to this study and are compiled in *Appendices A* and *B*, respectively. Although there was no requirement in the study specification for comments to be non-attributable, interaction with some (but not all) of the participants indicated that their preference was for comments to be non-attributable. Thus, in order to include as much feedback as possible, references to specific countries, organisations and individual projects have been removed in the comments contained in *Appendices A* and *B*. In addition, some of the wording has been edited to ensure as much uniformity as possible. However, the basic opinions expressed in the individual comments have not been changed.



2 Overview of Regulatory Responses

2.1 Summary of Responses to Specific Questions

Table 1 provides a summary of the brief (Yes/No) responses from regulators to the different questions. Clearly, there will be differences in interpretation of different questions because of uncertainty with the wording of some questions or even cultural differences between countries. However, there was a definite consensus in the nature of the responses on the need for a regulatory framework, *viz.*

- A framework for CCS projects is considered necessary.
- While some regulators responded “Yes” to CCS projects having been approved, the supporting comments that were provided indicated that these projects were not primarily storage projects but were linked to some form of energy-related (e.g., CO₂-EOR or natural gas production) or pilot-scale project.
- The same situation applied to responses to whether a regulatory framework for CCS projects already existed. The majority of regulators acknowledged that a specific regulatory framework was not yet in place, while for those that responded “Yes” to a regulatory framework being in place, the supporting comments indicated that only individual regulations could be used to cover the injection part of CCS projects in particular, but not a framework specifically for CCS.
- The earliest timing for any regulatory framework specific to CCS projects was anticipated to be 2007-2008, with responses in this category generally uncertain.

In terms of the role of RA in such a regulatory framework, the following consensus comments from regulators are relevant:

- The regulatory framework should address timeframes² and CO₂ leakage or release rates / fluxes, together with uncertainties.
- Regulators should not provide guidance on RA methodology, but should provide some guidance on modelling approaches. With regard to the latter, the regulators generally agreed that uncertainty should be addressed in the modelling.
- The framework should address monitoring and regulators would expect to see a link between risk assessment predictions and some forms of monitoring.
- An integrated assessment framework is preferred, whereby predictions of releases from the storage reservoir are linked directly, and processed through, to potential health, safety, and environmental (HS&E) impacts.

² This was typically taken to mean injection and post-injection phases, rather than one or more specific timeframes within the post-injection phase.



- Some form of RA protocol or technical standard was considered important as a means of providing clear guidance to individual projects.
- There is strong support for the use of analogues, both industrial and natural, as long as the analogues are relevant and ideally if they provide some quantitative information that can be used to support RA methods.
- Currently, specific gaps in technical knowledge are acknowledged, in particular wellbore and caprock integrity, as well as leakage quantification.

Those regulators consulted were essentially split about whether more than one modelling approach should be used, primarily because more experience is required in this area. With regard to risk communication, although not all regulators are involved in this task, those regulators who are directly involved regarded it as an important role of the regulator.

In the absence of a specific regulatory framework for CCS projects, regulators are approving CCS projects on a case-by-case basis. In addition, a number of regulators emphasised the site-specific nature of storage projects as being important when reviewing timeframes for RA predictions, as well as monitoring needs.

2.2 RA – Perceived Gaps/Needs

Based on the supporting comments provided by regulators, the following perceived gaps or research needs for RA were noted:

- Quantification/verification of storage capacity estimates, preferably linked to local geology;
- Nature of long-term risks and associated institutional arrangements;
- Improved knowledge/understanding of specific environmental impacts, in particular groundwater, different ecosystems and offshore environmental impacts;
- Wellbore and caprock integrity, including abandoned well integrity, in terms of reservoir performance;
- Monitoring, particularly in the context of quantifying CO₂ leakage/migration;
- Fluid movement response to CO₂ injection, both regionally and locally;
- Better understanding of timeframe in the context of potential hazards.

Clearly, many of the above concerns are linked to uncertainties in the modelling process and how these uncertainties are communicated to the various stakeholders.

Despite the perceived existence of gaps, the consensus among regulators appeared to be that the results from pilot projects, as well as full-scale storage projects, would help to improve understanding, although additional gaps in knowledge might also emerge. Overall, the benefits of experience with storage projects was seen as a positive step towards building confidence in the developing technology.



Table 1: Regulatory responses to questions on risk assessment, geological CO₂ storage, and regulatory frameworks

QUESTION	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
Is a regulatory framework necessary for CCS projects?	Yes	Yes	Yes	Yes	Yes	Yes	Under study	Yes	Yes	Yes	Yes	Yes
Have any CCS projects already been approved in your country?	No	Yes	Yes	No	Yes	No	Yes (EOR)	No	No	Yes	No	Yes
Do you currently have a regulatory framework for CCS projects?	No	No	Yes	No	No	Yes	No	No	Yes	No	No	No
If "No" to Q3, when do you expect a framework to be in place?	Open	2008	--	2008	??	--	??	5-10 years	--	Mid-2008	2007	??
Does/should the regulatory framework have one or more timeframes?	Yes	Yes	Yes	Yes	--	Yes	--	Yes	??	Yes	--	No
Does/should the regulatory framework address CO ₂ leakage rates/fluxes?	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes	Yes	Yes	Yes	Yes
Does/should the framework provide guidance on assessment methodology?	No	No	No	No	No	No	--	Yes	No	No	--	--
Does/should the framework provide guidance on modelling approaches?	Yes	Yes	Yes	No	Yes	Yes	--	Yes	No	No	Yes	No
Is there a need for more than one modelling approach?	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes	(Yes)	Yes	No	--
Does/should the framework address uncertainty and its requirements?	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes	Yes	Yes	No	No

Table 1 (continued): Regulatory responses to questions on risk assessment, geological CO₂ storage, and regulatory frameworks

QUESTION	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
Does/should the regulatory framework address any form of monitoring?	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes	Yes	Yes	Yes	Yes
Does/should the regulatory framework link any monitoring to RA results/ predictions?	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes	Yes	--	Yes	Yes
Does/should the regulatory framework require integrated assessments?	Yes	Yes	Yes	Yes	Yes	Yes	--	??	Yes	Yes	--	Yes
Does/should the regulatory framework address the use of natural or industrial analogues?	Yes	No	Yes	Yes	--	Yes	--	Yes	No	No	Yes	--
Are you involved in risk communication?	No	Yes	Yes	No	Yes	Yes	--	No	Yes	--	--	Yes
Is/should the regulator be involved in risk communication for CCS?	No	Yes	Yes	No	Maybe	Yes	--	Yes	Yes	No	Yes	Yes
Do you favour some form of risk assessment protocol or technical standard?	Yes	Yes	Yes	Yes	--	Yes	--	No	Yes	--	--	Yes
Are there specific gaps in terms of risk assessment for CCS projects?	Yes	Yes	Yes	Yes	--	No	--	Yes	Yes	--	No	Yes
Are there any specific gaps in the Briefing Document?	No	No	No	No	--	No	--	No	--	--	No	No

3 Overview of Implementer Responses

3.1 Summary of Responses to Specific Questions

Table 2 provides a summary of the brief responses from implementers to the different questions.

Based on these responses and supporting comments, the following key observations are relevant:

- There is a consensus within those consulted, not surprisingly, on the need for a regulatory framework specific to CCS projects.
- The regulatory framework should address timeframes as well as CO₂ leakage or release rates / fluxes.
- More than one modelling approach should be used, with uncertainties being treated. A broad range of modelling approaches was suggested by respondents, in line with those methods identified in the Briefing Document (Section I2.5).
- The majority of implementers plan to link some form of monitoring to RA predictions. It was recognised that monitoring techniques are still being developed and one respondent emphasised the important role of monitoring in supporting risk management.
- There is strong support for the use of analogues, both industrial and natural.
- The consensus from those consulted is that both the implementer and regulator should be involved in risk communication for CCS projects.
- There is strong support for some form of risk assessment protocol or technical standard.

3.2 RA - Perceived Gaps/Needs

Based on the supporting comments provided by implementers, the following perceived gaps or research needs for RA were noted:

- Quantitative information/data from analogues;
- As a basis for effective communication with the general public and other stakeholders, better definition/specification of what leakage is acceptable, what storage timeframe is required, and what is the regional containment zone;
- Effect of impurities, in particular H₂S, on thermodynamic (PVT) behaviour of CO₂;
- Coupled models; in particular addressing the impact of geochemical interactions on geomechanical behaviour;

Table 2: Implementer responses to questions on risk assessment, geological CO₂ storage, and regulatory frameworks.

QUESTION	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10
Is a regulatory framework necessary for CCS projects?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Have any CCS projects already been approved in your country?	No	No	Yes EOR	No	No	Yes	No	Yes	No	No
Is there a regulatory framework for CCS projects in your country?	No	Yes	No	No	No	Yes	No	No	Yes	No
Is your organization responsible for an upcoming CCS project?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Does/should the regulatory framework have one or more timeframes?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Does/should the regulatory framework address CO ₂ leakage rates/fluxes?	Yes PS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Do you favour a specific assessment methodology for CCS projects?	Yes	Yes	No	--	No	No	??	No	Yes	No
Do you use/favour a specific modelling approach(es)?	Yes	Yes	No	--	Yes	No	Yes	No	No	No
Should more than one modelling approach be used?	Yes	Yes	Yes	--	Yes	Yes	Yes	Yes	Yes	--

Table 2 (continued): Implementer responses to questions on risk assessment, geological CO₂ storage, and regulatory frameworks

QUESTION	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10
Do/will you address uncertainties for CCS projects?	Yes	Yes	Yes	--	Yes	Yes	Yes	Yes	Yes	Yes
In existing/planned CCS projects, are any forms of monitoring linked to RA results/predictions??	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes
Do/will you carry out an integrated risk assessment?	Yes	??	Yes	Yes	No	No	Yes	No	--	--
Do/will you make use of natural or industrial analogues?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes
Are you involved in risk communication?	No	Yes	Yes	Yes	No	Yes	Yes	Yes	--	No
Should the implementer +/- regulator be involved in risk communication for CCS?	Yes R I	Yes R I	Yes R I	Yes R I	Yes R	Yes R I	Yes R I	Yes R I	--	Yes R I
Do you favour some form of risk assessment protocol or technical standard?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	--	No
Are there specific gaps in terms of risk assessment for CCS projects?	Yes	Yes	Yes	--	No	Yes	Yes	Yes	--	Yes
Are there any specific gaps in the Briefing Document?	No	Yes	No	--	--	Y	No	Yes	--	--

- Experimental data supporting thermodynamics and kinetics of CO₂ reactions with different minerals;
- Agreed-upon RA methodology, preferably in terms of a Technical Standard/ Protocol;
- Environmental impacts on ecosystems;
- Criteria against which assessment results should be compared;
- Long-term borehole integrity;
- Duration of long-term monitoring;
- Long-term stewardship.

Some of the above gaps, *viz.* long-term borehole integrity, ecosystem impacts, and long-term stewardship, were also identified by regulators.



4 Rationalisation of CCS Project Authorisations Based on Regulator and Implementer Responses

4.1 General Agreement in Responses

Perhaps the most striking observation of the responses from regulators and implementers to the questions posed in this study is that there is no major disconnect between either of the groups. Furthermore, this conclusion stands when comparing the corresponding responses of regulator and implementer(s) of the same country.

Both regulators and implementers favour a regulatory framework that addresses CCS projects, the more important being the storage aspect of these projects. To some extent, this may be related to the choice of terms used to describe the relative responsibilities of the positions. To some extent, it may also be related to the fact that the implementer will always be dependent on the development of policy to create the framework within which regulations are set and enforced³. The responses certainly demonstrate the generally more technical nature of the implementer and the greater degree of comfort with the technical aspects of risk assessment and project policing.

4.2 Specific Projects

Table 3, intended as illustrative rather than comprehensive, contains a list of some recently underway and upcoming CCS projects, together with their dates of authorisation. The listing for Canada is a representative sampling of a number of projects (~50) that are classified as (i) acid gas injection/re-injection, but which include the storage of some CO₂ with the H₂S, (ii) CO₂-EOR (demonstration and commercial), (iii) enhanced coal bed methane (ECBM) recovery, and (iv) CO₂ storage [Legg and Campbell, 2006]. A similar situation applies to the USA. Table 3 also shows that authorisation for the first upcoming large-scale projects was being sought for 2006, and that no specific problems were anticipated at the authorisation stage. However, it is also likely that, because no specific frameworks are in place at this stage, the existing legislation will be used to authorise CO₂ injection only, with plans in most countries considered in this study to address the storage aspect at a later date.

For comparison with Table 3, Table 4, on the regulations side, identifies existing laws that are relevant to, *i.e.*, can be applied to, CCS projects.

In general terms the results of this survey are relatively predictable. The development of regulations concerning the long-term storage of CO₂ is absent globally. Regulations do exist for the use of solvents in EOR processes, but these are short-term regulations that do not account for long-term monitoring issues, *etc.*

³ An obvious exception to this generality applies to those countries where the oil and gas industry is self-regulating; in particular the USA.



Table 3: Primarily upcoming and new CCS-type projects.

Country	Project	Type	Planned start
Australia	Gorgon – 2H	Natural gas field	2006 (http://www.gorgon.com.au)
	Otway Basin Gippsland Basin (Monash Energy)	Pilot CCS Project Coal gasification	2007 Commissioning of demonstration project 2010; full commercial basis 2016.
Netherlands	K12B (North Sea)	Gas field	(Already underway 2004)
Norway	Snohvit Draugen/Heidrun	Gas field Gas field (power plant) + CO ₂ -EOR	2007 2011-2012
France	Paris Basin	CO ₂ storage pilot project	Authorisation requirement 2008
Canada	Apache Zama	Acid gas CO ₂ -EOR demonstration	(Already underway 2004)
	Swan Hills	CO ₂ -EOR	(Already underway 2004)
	PennWest Pembina	CO ₂ -EOR demonstration	(Already underway 2004)
	Drayton Valley	ECBM demonstration	2006
	Hayes-Enchant Arcs	CCS demonstration	(Already underway 2004)
	Apache Midale	CO ₂ -EOR	2006
	Glencoe Resources (Lacombe/Ponoka area)	CO ₂ -EOR	2006
Germany	Altmark Field??	Gas field (CO ₂ -EOR)	Potential field – being evaluated under CO ₂ STORE
	Ketzin - CO ₂ -SINK (EU)	Saline aquifer - pilot scale project	CO ₂ injection 2007
Japan	Nagaoka (experimental site)	Aquifer	Ongoing R&D project (2004- 2007)
U.K.	Miller field (DF1 Project) In Salah (Algeria)	Natural gas => H ₂ / CO ₂ (hydrogen-fuelled energy) Gas field	2010 (Already underway 2004)
U.S.A.	Claytonville, Texas Aneth Field, Utah	CO ₂ -EOR CO ₂ -EOR and aquifer sequestration	October, 2006 June 2006
	Carson (DF2) project	Petroleum coke => CO ₂	2011
	San Juan Basin DOE Regional Carbon Sequestration Partnership Program FutureGen	CO ₂ -ECBM pilot project CO ₂ storage field tests (~25 tests)	September 2006 2008=>
		Prototype emission-free electric and H ₂ production with CO ₂ sequestration	2008



Table 4: Relevant laws that are/could be applied to CCS projects.

Country	Existing Relevant Laws	Comment
Australia	Combination of petroleum, environmental and safety legislation	CCS legislation to be introduced in 2007. Currently, different legislations apply to different aspects of CO ₂ storage. CCS projects approved on a case-by-case basis until CCS legislation is available.
Canada <i>Saskatchewan</i>	CO ₂ EOR and Acid Gas injection	Specific framework 2008+ Use of mining law - understanding long-term implications.
<i>Alberta</i> <i>British Columbia</i>	CO ₂ -EOR and Acid-gas disposal Regulations exist for small-scale projects Environmental assessment	No regulations specifically for CCS. Working towards legislation for 2008.
France*	Mining Act, Water Law, at least for pilot projects	Laws applicable only if pure CO ₂ .
Germany*	Mining Law	Date "open" regarding legislation; possible modification of existing framework for underground storage (oil&gas).
Japan	None	2007 for sub-seabed CCS projects; Later for general framework (2020?)
Netherlands*	Mining Act Environmental Impact Assessment	Long-term aspect not yet covered; legislation expected by mid-2008.
Norway*	Petroleum Law (CO ₂ injection), Environment Protection Law (emissions)	Mostly covered by petroleum legislation.
U.K.*	Only covering CO ₂ -EOR (Petroleum Act, Pollution Control Act etc.)	No set date for CCS-specific legislation.
U.S.A.	Safe Drinking Water Act (established Underground Injection Control Program); Clean Air Act (federal legislation)	State legislation also relevant; for example, Groundwater Protection Act (some states). EPA currently assessing implications of adapting/modifying UIC; guidance for Regional Partnership pilot projects into saline formations indicates permitting under Class V rules.

* **NOTE:** The above European countries are also subject to EC legislation.



Projects are handled under existing regulations that are designed for short-term processes and do not allow for storage of substances over very long periods of time. The concept of storage can only currently be defined and approved on a case-by-case basis using existing regulations, often with over-ride clauses in regulations. Generally, risk management is not included within such regulations, nor is long-term monitoring for subsurface movement of fluids.

4.3 RA and The London Convention and OSPAR Convention Initiatives

The 1972 London Convention⁴ and its 1996 Protocol updating the original treaty are aimed at limiting discharges of wastes generated on land and disposed of at sea. The 1992 OSPAR Convention⁵ is the current instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic. The Contracting Parties in both the OSPAR and the London Conventions are addressing the development of a Framework for Risk Assessment and Management for the storage of CO₂ deep under the seabed (FRAM). (In fact, the London Convention has accepted a framework for RA). The primary objective of the FRAM is to enable the identification, implementation and verification of control measures that prevent the occurrence of effects in the marine environment. Such measures must comply with high-level acceptance criteria and lower level performance standards.

Since the initial draft of this report, technical meetings have been held under both Conventions, to establish clear protocols for risk management applied to CO₂ storage under the seabed, which will be used by individual nations in drafting their own legislation. While the objectives of both Conventions in addressing CO₂ storage under the seabed, are broader than RA alone, RA provides the major component of the risk management structure (see *Figure 1*). Thus, RA is designed and conducted to provide information to risk managers about the potential effects of different management decisions. In this sense, RA and risk management are strongly interrelated.

A Risk Assessment Framework was developed in a London Convention meeting held in London in April 2006. Following this meeting, an expert Workshop was held⁶ under the OSPAR Convention to discuss the technical and environmental aspects of sub-seabed CO₂ storage, with a view to obtain a consensus on the key elements of the risk management/RA framework. Output from the Workshop included [TNO, 2006]:

- FRAM components on RA and risk management – site characterization, exposure assessment, effects assessment, risk characterization and risk management (as shown in Figure 1);

⁴ Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter.

⁵ The Convention for the Protection of the Marine Environment of the North-East Atlantic; replacing the previous Oslo and Paris Conventions.

⁶ Department of Trade and Industry, London, October 25-27, 2006.



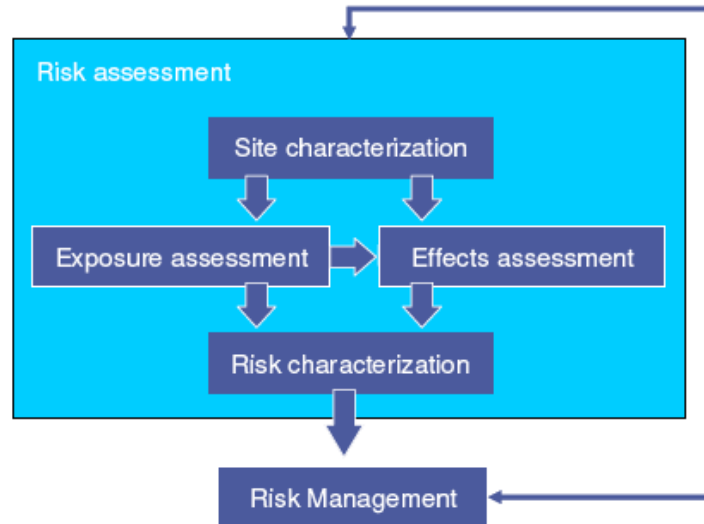


Figure 1: Framework for Risk Assessment and Management (FRAM) for the storage of CO₂ deep under the seabed [TNO, 2006].

- Description of component methods and tools;
- Relation to criteria and standards;
- Relation to the main phase of the CO₂ storage life cycle.

As such, the framework developed and the details therein provide a relatively comprehensive template for frameworks addressing CO₂ storage in onshore environments, and could therefore form a good basis for broad international acceptance.

4.4 Research Activities and Associated Timelines

In the context of perceived gaps/needs for RA identified by regulators and implementers, essentially no incompatibilities between the two groups were identified. This conclusion is *not* intended to imply that there are no outstanding issues associated with the regulatory approval of CCS projects. Clearly, the consensus is strongly in favour of a regulatory framework that addresses CCS, but there do not appear to be any technical issues that will delay the process of developing such a framework in all the countries covered in this study, *i.e.*, need to be resolved before regulations are in place.

Furthermore, based on the broad range of technical papers presented at the GHGT8 International Conference in Trondheim, Norway, ongoing research activities are addressing all of the gaps/problems identified in the comments received from regulators and implementers (summarised in Sections 2.2 and 3.2). The most important basis for an improved understanding of the processes associated with geological CO₂ storage, however, continues to be the experience gained from pilot-scale and large-scale CCS projects, building on the experience gained from large-scale projects such as Weyburn and Sleipner.



5 Conclusions from Study

The following conclusions from this study are provided as bullet points:

- Implementers need clear guidance from regulators in terms of what specific regulations or framework will address the long-term storage aspect of CO₂ storage projects. Until this happens, the economic climate is such that projects are likely to proceed relatively cautiously and only if there is a good economic incentive, *i.e.*, as part of EOR or ECMB projects.
- Given that specific regulations or a specific regulatory framework for CCS projects will take time to develop (2007-2008 was the earliest anticipated in the countries covered in this study), it is likely that CCS projects will need to be reviewed and authorised on a case-by-case basis.
- The implementers and regulators consulted view the assurance of long-term safety to be critical to the progress of CCS. In this regard, the responses from implementers indicate a desire for a rigorous methodology as a basis for assuring confidence in long-term predictions.
- In terms of storage and long-term safety, the timeframes considered by regulators to be appropriate for risk of leakage range from >~30 years to at least 1,000 years (Appendix A).
- There was a broad range of opinions from regulators concerning CO₂ leakage rates / fluxes. It is likely, therefore, that the work currently being carried out on CCS-related projects, including RA results/predictions, will help to guide regulatory opinion on this topic.
- Monitoring during the injection and post-injection phases of CCS projects will play a major role in regulatory acceptance of long-term safety. While no consensus was reached concerning the length of the post-injection stage, it is estimated to be ~10-20 years at least. Even after abandonment, some form of monitoring is considered by most of the regulators consulted to be necessary, primarily for confirmation of predictions and GHG control. Again, the link between monitoring and verification of RA predictions was considered important by regulators. Risk in the context of storage (*i.e.*, type of monitoring) was site dependent; there was no discussion of project size.
- Although some form of technical standard or protocol for addressing long-term safety in CCS projects was considered important by both regulators and implementers, there were differing opinions concerning whether such a standard / protocol should be developed at the sub-national, national or international level. Current initiatives, such as the Framework for Risk Assessment and Management being developed under the London and OSPAR Conventions, may help to provide a general basis for national legislation, at least governing sub-

seabed CO₂ storage. However, most of the elements of the framework are applicable to onshore CO₂ storage.

- There do not appear to be any technical issues that will delay the process of developing a regulatory framework addressing geological CO₂ storage in all the countries covered in this study.
- The most important basis for an improved understanding of the processes associated with geological CO₂ storage continues to be the experience gained from pilot-scale and large-scale CCS projects, building on the experience gained from large-scale projects such as Weyburn and Sleipner.

References

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Appendix A
Compilation of Regulators' Supporting Comments on
Specific Questions

Does a specific regulatory framework exist for CCS projects?

- A range of existing legislation, e.g. petroleum, environmental and safety legislation, will apply to many aspects of CCS activities, but technology-specific legislation does not exist.
- The framework is not specific to CCS, but existing framework/regulations are capable of handling CCS projects.
- XXX has regulations that have been adopted for small-scale projects that have been approved regionally, but does not have regulations specifically for CCS.
- A regulatory framework exists for CO₂-EOR, although not specific to CCS projects.

Given the absence of a specific regulatory framework, when is one likely to come into force?

- Depends on several aspects including;
 - Timeframe of pilot projects;
 - Site-specific nature of needs;
 - Whether several jurisdictions are involved.

Some aspects of CCS projects are covered under existing legislation/regulation. Storage projects are likely to be approved on a case-by-case basis in the short-term.
- Although there has been no discussion of a specific regulatory framework encompassing injection and storage, the perception might be to encourage such a framework and that might then become a goal.
- 2007 for sub-seabed CCS.
- Around mid-2008.
- It is likely that a framework will be developed as the number of projects being considered increases. Modification of the existing framework for the oil&gas industry is a possibility.

Does/should such a regulatory framework address timeframes?

- While acknowledging that the operational and post-injection phases have different sets of risks, the objective is to be as flexible as possible. Such a flexible approach may be re-evaluated once some projects have been authorised and are underway.
- Depends largely on site characteristics. Timeframes would be determined on a case-by-case basis at the time of approvals being granted.
- The key is to avoid captured and stored CO₂ escaping from the storage site, and in that respect scientific data and knowledge are crucial. IPCC and other organisations have defined timeframes. Without knowing what the “right numbers” should be, one has to set some limits as guidance to the RA.



- RA should be provided for the medium and long term (not specified).
- Besides the active injection phase, assessments should address the post-abandonment (10-30 years) and long-term (not defined yet, but > ~30 years) stages.
- Three timeframes are important from regulatory perspective:
 - Project operation: ~20-30 years;
 - GHG emission control: ~ 100 years;
 - Risk of leakage: at least 1,000 years.
- RA results that indicate that a project is safe are an essential precondition for approving any project.

Does/should such a regulatory framework address CO₂ leakage rates / fluxes?

- Unsure at this time.
- How leakages through wells, faults etc can arise is of course crucial for any safe storage estimates. This is important input to RA, but it has no meaning if one can't address how it can be measured or estimated properly. This again requires scientific understanding of the specific storage site.
- No assessment has yet been made as to what leakage rate/flux would be acceptable. However, the basis for establishing values will/should be based on meeting public health, safety and environmental objectives.
- No values could/should be prescribed except for pipeline leaks or well blow-outs. It depends on location and consequences. Leakage in a populated area is different from leakage at In Salah, for example!
- Leakage during the operational phase is expected to be measurable with acceptable accuracy. Leakage from underground reservoirs is difficult to quantify – especially if diffuse emissions affect a larger area or shallow aquifer. Therefore, large ranges of uncertainty are expected for any rate or flux determination. Thus, appropriate site selection, exploration, operation and monitoring measures should be assured to minimise any leakage risk and to prohibit storage in poorly explored sites, with inadequate technology or under cap-rocks of doubtful quality.
- To be confirmed.
- 0.1 to 0.001% would be a conservative value, based on the expected permeability of a cap-rock in a secure storage site.
- Not likely to impose a leakage/flux requirement on implementers. Rather, set a performance design for zero leakage, then establish design requirements to achieve this. Use RA to evaluate options and exposure pathways, i.e. to inform.

- In a strict sense, there is no technical basis for these values, but there must be some value as a basis for constructing a simulation model, and this value should be decided according to conservative assumptions.
- While CO₂ leakage/flux rates should be addressed, such detailed technical data are not normally considered a necessary part of the legislation, but more a link to more general (proscriptive) requirements of specific projects.

Does/should such a regulatory framework provide guidance on RA methodology?

- Only if a single methodology has been agreed upon as being better than others. Preference is for an objective-based regulatory framework.
- If possible, flexibility should be provided and prescriptive regulation should be avoided, including the RA, except where public safety issues are concerned. In that context, to the extent that two different RA methodologies both ensure safety, they should both be acceptable.
- Regulatory framework should require RA be performed, and assess results, but should not prescribe methodology, which is going to be highly variable depending on circumstances and data availability.
- More likely to set parameters, leakage rates *etc.* than the methodology itself.
- Methodology to provide standard procedure for conducting RA.
- Provide some guidance but essentially focus on meeting certain criteria. Methodology may evolve. Would not prescribe specific outputs.

Does/should such a regulatory framework provide guidance on modelling approaches?

- Overall requirements should be prescribed i.e. there should be a results-based approach, as long as there is a methodology that can be verified and is sufficiently reliable.
- What approach to choose is not important, as long as it's assumed to be appropriate for the particular situation. However, values of the key parameters and boundary conditions have to be specified. If these are not specified, different results can be obtained by varying the parameters. Carefully devised “benchmarking” is mentioned in the briefing document, and that is perhaps the path to chose.
- Guidance should be provided only to the extent that one type of modelling is shown to provide more reliable results than another specific situation (based on experience or other scientific evidence). However, flexibility should be provided and prescriptive regulations should be avoided, except where public safety issues are concerned.
- Regulatory framework should not prescribe modelling approach, which is likely to be highly variable depending on circumstances and data availability.



- Establish goals to be achieved. Models need to be good to convince stakeholders. Reviewers need to understand the modelling. Preferably off-the-shelf codes because there is only so much evaluation that one can do. Ultimately, the predictions are only as good as the input data.
- Possibly an impact assessment model based on simplified reservoir model.
- A detailed geological model of the reservoir, cap rock and overburden of a storage site should be compulsory. The geological model should be large enough to cover the surroundings of the storage site that could be affected by dissolved CO₂, increased pressure, or water displacement. Thereafter, we would expect to see, in an application or submission:
 - A fluid dynamical simulation to determine the expected extent of the area affected by CO₂ injection and long-term processes. Such models should be up-dated according to monitoring results obtained during progressive injection.
 - Other modelling approaches (geochemical models, compartment models, storage system models, etc.) used as appropriate for a specific case.
- The most important aspect is to establish the goals that need to be achieved. Thereafter, models need to be good to convince stakeholders, while reviewers need to understand the modelling. Off-the-shelf codes are preferred [for regulators] because there is only so much evaluation that a regulator can do, but ultimately, the predictions are only as good as the input data.
- In terms of component data of the model.
- No guidance if various approaches are possible.

Is there a need for more than one modelling approach?

- The preferred modelling approach should be decided on a case-by-case basis and based on available site-specific data.
- As the briefing states, consensus has not yet been reached on which modelling approach is preferable. Further, before specifying how the different approaches should be reviewed/compared, additional work must be done.
- The need for different approaches stems not from the need to compare them, but from different circumstances, data, capabilities, etc. However, various modelling approaches should all be accepted by the community. By way of comparison, there are various models for simulating fluid flow, and all are accepted after they have been validated.
- This issue needs more consideration. The approach taken must be adequately proved and must be suitable to the site. An objective-based regulatory framework should ensure this happens.
- Different storage options have specific risks, associated with particular physico-chemical processes, which require different modelling approaches.



- A range of modelling approaches is preferable, otherwise development is likely to be restricted.
- Based on the current level of technology, reservoir model tends to provide very rough assessment. To cover the shortcomings of this type of modelling, maybe a logic model approach, which does not provide quantitative impact assessment results but qualitative, would be acceptable.

Does/should such a regulatory framework address uncertainty and its requirements?

- The RA modelling needs to be verifiable to a level suitable for the potential risks identified as associated with the project. The regulatory framework may incorporate/refer to other regulations that require adoption of a precautionary approach (e.g. in environmentally-sensitive locations).
- Different techniques to deal with uncertainties (statistical, empirical, expert judgment etc) can be used. It's important that all possible uncertainties related to CCS are identified and addressed, but the preferred model is site dependent and should be based on the type of data available. However, well-bore locations and characteristics seem to be key elements here.
- The potential risk associated with certain types of uncertainty may be more readily reduced by different modelling approaches. Where such a situation is demonstrated to be the case, that type of modelling approach should be specified.
- Not sure at this stage, but fairly simple treatment whatever is decided.
- RA modelling should provide more likely scenario, confidence limits, and also extreme scenarios. Then the operator, regulatory agency and public can make decisions regarding whether to accept the risk or accept the cost of avoiding the risk.
- Parameter variations and sensitivity studies should be compulsory. Estimated or calculated ranges of uncertainty should be indicated for all numerical values, including mentioning of basic assumptions and critical parameters affecting values.
- Probabilistic models are useful. However they can be misleading because the simulated system is usually incomplete and simplified compared to the real system of non-linearly interacting processes. In addition, basic assumptions may be critical, but their probability is unknown (e.g. effective width of a fault plane), and probability distributions are often unknown.
- Uncertainty is the key issues ion this approach and thus needs to be carefully handled and explained.
- Probabilistic approach would be preferred. In addition, sensitive analysis should be conducted at the same time. Results of a probabilistic approach (Monte Carlo



simulation type) would vary depending on the selection of probability distribution function (PDF), which is often subject to subjective judgement. Also, setting covariance among parameters, which often is ignored, would influence results of probabilistic analyses.

- Uncertainty is addressed in regulations for other industrial sectors, so why not here?
- The regulator will expect uncertainty to be addressed automatically in specific projects.

Does/should such a regulatory framework address any form of monitoring?

- Besides proper site selection, this is possibly the most important issue with respect to CCS. It's not necessary to list the different monitoring technologies and their capabilities here, but a lot of good work has been published through IPCC, CCP, CSLF and other organisations as well. For how long the monitoring should continue is difficult to predict, and has to be considered on a case-by-case basis.
- The type and duration of monitoring will depend on the parameters and objectives of the regulatory framework, which have yet to be established. However, it is safe to say that some level of monitoring can be expected through at least the medium term.
- Monitoring will be conducted during the operational (injection) and post-abandonment (e.g. pressure, extent of plume fluids, offset wells, potential leakage) phases. Long-term monitoring for leakage should be conducted once the plume is no longer moving, to confirm its status.
- Monitoring should be required as long as there is evidence of fluid movement in the subsurface related to the CO₂ injection. Monitoring concepts will be site specific and should take into account differences in reservoir type, reservoir depth, environment (onshore/offshore), population density, rock type, storage volume, areal extent, and the number and nature of wells.
- The temporal application of monitoring depends on many factors, e.g. on the methods used, site-specific response times and the monitoring purpose/phase (whether baseline, operational, long-term). RA must not be concluded just because a permit is granted - it may be updated repeatedly (in the same way as licenses).
- Still at the research stage, but a combination of subsurface, near-surface and atmospheric monitoring is likely to be required. Monitoring will be expected for pre-injection, during injection and for some time post-injection.
- Monitoring should first be conducted for the most vulnerable leakage path, which is likely to be well-bore pathways. Other monitoring technology should be used on a site-specific basis. Generally, 4D seismic may be useful but is



costly. In addition, the degree of accuracy of seismic technology needs to be evaluated based on the latest-available scientific information. Monitoring should be conducted for the purpose of ensuring the effects of GHG control. Therefore, its duration should be about 100 years.

- Pressure at wells; leakage monitoring by seismic techniques as well as sampling.
- Any monitoring will be proposed and carried out by the implementer. The regulator's role is to accept or reject the implementer's proposal.

Does/should such a regulatory framework link any monitoring to RA results / predictions?

- Again, still at the research stage, but a combination of subsurface, near-surface and atmospheric monitoring may be required.
- The necessity and selection of monitoring techniques is site dependent. However, some techniques are expensive and, for that reason, must be submitted to cost-benefit analysis. During the injection period, it's important to have continuous or frequent monitoring, but after that period, it's more a question of what type of monitoring is necessary in order to be able to safely predict the storage sites capability to store the CO₂.
- In most cases the primary purpose of the monitoring is to confirm the RA results. Therefore, in order for any regulation to be effective, there must be a link between the RA results and the monitoring.
- Yes, the results should be used as a feedback loop in RA models to validate/modify/improve/update them.
- Weak points identified in risk assessment studies such as faults, wells, spill-points etc. should be monitored in order to verify, disprove, or constrain risks, or to identify leakage. Geological, reservoir and risk models should be updated according to the monitoring results. Monitoring methods and times will be site specific. Baseline monitoring should be started early and should be given sufficient time to yield information about pre-injection parameter variability that can be considered in RA prior to application for permits.
- Monitoring can detect leakage in/over an expected leakage pathway but cannot quantify the amount of leakage. Models should be used for leakage quantification at a specific location, which are based on RA. However, the latest modelling technology may not provide sufficient accuracy for leakage quantification. Therefore, a kind of conservative approximation should also be applied for RA combined with uncertainty analysis.
- Monitoring for a relatively long time until there is greater certainty, either with modelling predictions, or with an understanding of the fate of the injected CO₂.

- Background monitoring (if considered necessary for the nature of the storage site, e.g. monitoring of the marine environment for sub-seabed storage).
- Comparison will be expected with the criteria limits assumed in the RA.

Does/should such a regulatory framework require integrated assessments?

- Yes, to be able to react quickly in the case of leakage, and for public acceptance, though the risk might be small.
- Yes, in terms of developing an integrated standard. Perhaps there is a need for integration regarding aquifer injection, for example. The focus will be on groundwater, so it is essential to ensure that the CO₂ stays where it has been injected. Permits may evaluate individual risks and cover the range of risks. Global climate change does not require an integrated assessment.

Does/should such a regulatory framework address the use of natural or industrial analogues?

- Yes - for example, the hydrocarbon extraction industry operations.
- The lessons learned from analogues are important, but it should be underlined that only relevant analogues should be used. Hence, for storage of CO₂ in a depleted oilfield in the North Sea, for example, it's relevant to refer to caprocks in the same area and their sealing capability.
- Only if such analogues are available and if it is demonstrated that similar conditions apply. For example, the Sleipner experience is not relevant to onshore North America, while the Weyburn experience, or McElmo Dome, are not applicable to the North Sea.
- Natural analogues could provide information about slow long-term effective processes that cannot be modelled sufficiently in laboratory or by numerical experiments.
- Criteria (e.g. tolerable leakage rates) can be deduced from natural analogues. Monitoring or RA methods could be calibrated at natural analogue sites, and equipment could be tested. Technical analogues (e.g. natural gas storage) can be used to develop safety schemes.
- The use of analogues probably will be more important for scientific investigations and the development of a regulatory framework than for the site-specific application of RA.
- Yes - natural gas storage as industrial analogue; natural CO₂ emission sites as natural analogues.
- The broader framework of risk communication is more important.
- Long-term CO₂ behaviour in the storage reservoir.



Should the regulator be involved in risk communication involving CCS projects?

- The regulator should be involved with public education and safety and provide as much fact-based information as possible for the public to be aware and make a determination of all potential risks.
- The regulator cannot be a promoter of projects, its role is to ensure public safety, not to convince the public through a communications/marketing program. The project proponents, possibly including governments, may/should have a communications plan and strategy. The regulatory agencies have to maintain an unbiased position. The communications by the regulatory agency are made through decisions that become available to the public, including all the supporting material.
- Ensuring the project proponent/operator provides adequate information to the public. Different regulatory bodies have various amounts of public consultation depending on approvals being sought by proponents. Most regulators would require a site-specific operational plan to include public consultation as necessary.
- Yes, especially in connection with the OSPAR and London Convention activities on legalising CCS.
- Yes, probably on a project specific or area basis, through personal contact with impacted members of the public, open house forums, and community/industry working groups. In most cases RA would be conveyed on a qualitative basis, usually involving identification of the risks as well as strategies for mitigation (and how they are supported through policy, regulation and/or industry best practices). A comprehensive risk modelling approach may not be appropriate when interacting with the public.
- Maybe.
- The results of RA should be communicated via various media in a manner for people to understand easily.
- Yes, but we do not have a choice!
- Public announcement at the time of licence/permit issuance.
- Yes, for example, in case of a disaster during the operational phase.

Do you favour some form of RA protocol or technical standard?

- International standards/guidelines could be a good support/supplement to national laws and regulations on CCS projects. OSPAR, London Convention, CSLF or similar institutions are examples of organisations that could prepare such documents.
- Protocols are in the process of being developed. Although such protocols are likely to be established on a national and regional level, there is a need to try



and standardize protocols as much as possible on a national and international level to ensure industry is able to function efficiently.

- Preferably an existing protocol/standard if it satisfies requirements, otherwise one should be developed. Development should occur within the respective jurisdiction of authority (state/province or national, depending on country), but under no circumstances should be international.
- International (specific for CCS operations). The operator would be required to satisfy the regulator that the risk assessment met the requirements for the project and project site.
- There should be some basic standard addressing level of effort and the data required. This regulator's focus is on outputs, or end points, rather than on any detailed technical standard that achieves those end points.
- Yes, probably on a national basis, but taking into account a possible common framework internationally.

Are there any specific gaps in terms of risk assessment for CCS projects?

- How to deal with storage capacity estimations/verifications is important, and it could be a good idea to link it to local geological conditions. In that respect, we would appreciate a recognised methodology where a set of elements are addressed, and that those elements are relevant for further use in a local approach.
- Small-scale projects are useful for identifying where gaps exist. Approvals will continue to be limited until a comfort level is achieved that gaps have either been filled or do not exist.
- Long-term risks.
- Well-bore and caprock integrity, reservoir performance.
- Leakage quantification.
- Institutional arrangements to address possible long-term leakage.
- Various gaps:
 - Monitoring technologies, especially the ability to determine the extent of any leakage or migration;
 - Fluid movement – regional vs. localized displacement;
 - Abandoned wells;
 - Timeframe;
 - Specific impacts, especially concerning groundwater and ecosystems.
- The regulator will not have identified any gaps before authorising individual CCS projects. Some projects can be authorised and followed on a case-by-case basis using existing mechanisms, using the results obtained to further fill gaps in knowledge about CCS, then building conclusions into the regulatory regime.



- Datasets/information on which to base modelling, and therefore monitoring, of behaviour of the CO₂ in the subsurface. Currently, it is difficult to be prescriptive even in defining an acceptable level of risk.
- Offshore environmental impacts.
- The details of specific gaps have not been established, but are expected to be identified and addressed during specific projects.



Appendix B
Compilation of Implementers' Supporting Comments
on Specific Questions

Is a regulatory framework necessary for CCS projects?

- Some form of regulatory framework will be required initially for pilot and demonstration projects; then resulting from these experiences, possibly a modified regulatory framework will be designed for commercial-scale projects. Hopefully, this later regulation will be national in scope.

Does a specific regulatory framework exist for CCS projects in your country?

- It seems that existing laws could define a regulatory framework that could be applied to CCS projects involving the storage of pure CO₂ any major difficulties. However, the regulations would need to be adapted/modified to cover CO₂ containing impurities. In any case, the status of CO₂ containing impurities needs to be determined.
- Existing laws are available to cover CO₂ injection and CO₂ emissions.
- No national regulatory framework currently exists. Most proponents believe that some existing petroleum regulations can be modified to apply especially to most of the operational aspects, but additional guidelines relating specifically to risk assessment, monitoring and abandonment are still required and will need to be “purpose built”.
- While there are currently no explicit regulations that address the long-term storage of CO₂ in the subsurface, many jurisdictions have regulations that control the exploration and production of oil and gas resources, including injection of fluids, including CO₂, into the subsurface. The prominence of pilot-scale projects that incorporate CO₂ storage appears to be influencing how regulatory bodies consider regulatory requirements that address storage.
- An existing framework exists if CO₂ is stored in conjunction with enhanced oil recovery (EOR), or enhanced gas recovery (EGR). However, if CO₂ is injected for storage only, it is unclear what regulations, if any, are relevant. In addition, existing underground injection regulations, which might be relevant for the storage-only option, vary regionally. Currently, authorisations have been given for pilot injections into saline formations.

Does/should the regulatory framework address timeframes?

- No specific framework other than consideration of analogue hydrocarbon and hazardous waste models. I personally would expect that such a framework would include a pre-operation “certification” that includes RA and subsequent efforts to validate the reservoir simulation using monitoring data (5-20 years) and pre-closure “certification”.
- Currently, under existing law, CO₂ injection is regulated for 25 years, with a monitoring and reporting program. For the storage aspect, RA will be required to cover behaviour for thousands of years.



- This organisation's opinion is that at least two timeframes should be defined: one for greenhouse gas inventory control (several decades), and one for HS&E impacts (several thousand years).
- Suggestion (individual) that 50% of the stored CO₂ must be kept in the local region within 200 years. That will accomplish the GHG reductions we need before we have a more sustainable economy with a greater variety of low GHG-emitting energy sources and technologies in play. At that point, anthropogenic emissions will be so low that some leakage (as long as it doesn't have undesirable consequences at the surface (i.e. no rapid large bursts) would be acceptable and we will have accomplished a significant reduction in our impact on climate.
- The regulatory framework should be flexible enough to recognise the site-specific nature of various CO₂ storage sites and therefore not be prescriptive as to the frequency or necessarily the complexity of RA undertaken. In a similar manner to the undertaking of monitoring activities, each site will have different surface infrastructure/operations and subsurface characteristics which will influence the risk profile especially in the area of storage site containment. As a minimum, XXX expects that RA and background monitoring will be required pre-injection, with RA and monitoring during injection and immediately post injection. Thereafter, both RA and monitoring will take place using fit-for-purpose technology and at a frequency and location that depends strongly on the behaviour of the storage site, both in an absolute sense and also in comparison to how the site was initially predicted to behave from forward dynamic modelling.
- Several timeframes should be identified for which RA results must be provided, as the factors that affect the fate and migration of CO₂ change with time. These timeframes and nature of associated risks would be dependent on the type of storage reservoir under consideration. For instance, a depleted oil or gas field may require different risk analysis results due to the number of wells present while a saline aquifer would have a limited number of wells but could be laterally unconfined.
- 500-600 years.
- An effective timeframe addressing operatorship and liability is one timeframe needed, as is a timeframe for environmental efficacy so that all parties can assess whether the projects will accomplish something of public, economic and environmental good.
- A timeframe of 1,000 to 10,000 years represents a period of time for which results of reservoir simulations have credibility. Beyond that, for many processes, one begins to doubt if the processes are understood well enough. That (1,000-10,000 year) timeframe is also "very long" in societal terms. Given the fact that practical technology approaches are already available for



remediation and mitigation of leakage, in 1,000 years technology advances could easily be such that there would be little continuing concern over impacts of leakage.

Does/should the regulatory framework address CO₂ leakage rates / fluxes?

- Personally, I could support addressing leakage rate from point sources such as faults / wells but not flux rate from the entire field. With leakage rate assessment, well-understood monitoring technology exists and, in some cases, intervention may be possible. Flux-rate determination would be expensive but would change (decrease) with time as reservoir pressure decreases.
- Risks must be dealt with according to the specific site. Individual sites should be planned to retain more than 90% over thousand years.
- This organisation's opinion is that:
 - For greenhouse gas inventory control, the regulatory framework should address the *release rate/flux over the entire site* (storage zone and surroundings).
 - For HS&E impacts, the regulatory framework should address the *leakage rate/flux at finite points* in various compartments of the entire site, *and site-specific local consequences*. Evidence from natural sites with CO₂ releases at the surface shows that the main mechanism is point leakage along linear structures (faults, fractures). Fluxes should be used with great caution: e.g. a leakage rate over a large area might be harmless, but the same leakage rate leaking from a point might be lethal for the direct environment.
- CO₂ flux, regional containment boundaries, and timeframe should all be tied together.
- This organisation fully expects that the [country's] regulatory framework will comprehensively address the question of CO₂ storage site leakage. The main purpose would be to provide assurance of long-term safe and secure storage. Given that “acceptable leakage” rates for CO₂ storage sites have yet to be quantified, this organisation believes that the resultant framework will address both leakage from the intended storage site (possibly into shallower reservoirs) as well as leakage/flux at the surface.
- It is important to recognize that a small amount of CO₂ will leak (and perhaps even seep to the surface) and strict requirements like zero leakage/seepage are unnecessarily restrictive. Studies to date indicate that an allowable rate of seepage of up to 0.1%/yr would still result in an effective outcome when dealing with GHG emissions reductions [IPCC, 2005b]. This rate is not an indication of what the research community anticipates the actual rate to be; rather, it is considered an upper bound (or tolerance level) for the earth to deal with slow and steady CO₂ seepage to the atmosphere, considering the need to maintain atmospheric GHG concentrations below a certain level. A regulatory



framework should therefore incorporate a CO₂ leakage rate/flux that is in keeping with the protection of human and ecosystem health and safety.

- Leakage rate should be a performance-based rate, not an arbitrary rate, e.g. an MIT report shows that ocean sequestration can be effective at a 20%/year leak rate.
- A minimum acceptable leakage rate should be specified, but this must also be tied to other HS&E metrics to arrive at an agreed upon safety and GHG effectiveness level.
- I am in favour of designing for zero leakage. By this, I mean designing for zero leakage based on our best understanding of the geologic structure as well as for likely or possible other geologic structural interpretations and ranges of properties. Clearly this leaves open the need to define what is meant by “likely” or “possible”. In reality I believe this will be a matter of negotiation.
- Yes, for the purpose of carbon credits, otherwise, this should be assessed on a case-by-case basis. Zero leakage should be the aim/basis of CCS projects, although small, diffuse leakages in pipeline joints etc. may be unavoidable (*cf.* natural gas industry).

Do you favour a specific assessment methodology for CCS projects?

- It is essential for the future of CCS for those involved to agree on a basic set of principles that could be issued as a framework.
- Methods are still under development.
- An RA methodology should be developed, agreed by all and included in Best Practice standards. Such methodology does not exist yet, and may combine the various methodologies that are being explored now in several projects. A current RA methodology should at least have some phases in which modelling is carried out. The interaction and feedback between a large number of processes (physical, chemical, geomechanical) do not allow for an up-front judgement by expert-panels. The potential outcomes should be tested using models (which will help us to increase our understanding as well).
- Although our organisation has a preferred methodology, we accept that, by various countries/organisations following various methodologies and sharing the results, ultimately a better and more appropriate RA methodology should result. Ultimately we see it as probably appropriate also that several methodologies should be applied to early projects to compare and contrast both the approach and the results.
- An RA methodology for all cases has not yet been decided. A specific RA methodology may not be appropriate for all cases and localities/governments. However, some agreement on acceptable approaches will be necessary.



- I see particular value in 2 types of RA methodologies. Initially, screening level analyses could be very valuable in selecting sites for geologic storage, particularly a methodology that is able to incorporate a comprehensive number of factors while taking into account the likely sparseness of hard data. Thereafter, scenario analyses will be useful in evaluating the risks for those sites that pass the screening stage. FEP databases are of great practical value in developing scenarios.
- This is an area where development/further research is required. The FEP methodology was used in a “dry-run” exercise, but there may be other approaches that are better or as good. This remains to be evaluated.

Do you use/favour a specific modelling approach?

- We currently use a methodology that combines a reasonable mix of expert opinion with an assessment process that is compatible with that used in other industries (e.g. civil engineering projects) and with the spirit of existing national standards.
- No, several approaches - experience is still not varied enough to select one or a few.
- Probabilistic modelling should be preferred over deterministic modelling where this is possible (and where CPU-time allows). Accordingly, one should strive for the development of more complex probabilistic models that are capable of including more processes simultaneously (e.g. back-coupling of geochemical reactions on geomechanical behaviour). However, probabilistic modelling results are extremely difficult to communicate to the public.
- No, as long as the methodology and approach are open to public and technical scrutiny, then I don't believe it matters.
- Yes, currently using numerical models.

Should more than one modelling approach be used?

- Numerical, analytical, probabilistic approaches all have their potential role. Thus, the modelling approach depends on the issue and the data available.
- At the current state of science various models used for modelling CO₂ behaviour and interactions in the reservoir are still in the academic stage and not tested very thoroughly (e.g. coupled flow geochemical models) or are still under development (e.g. coupled geochemical – flow –geomechanical models). Models that appear to be capable of modelling the leakage of CO₂ from the reservoir up to the surface are extremely simplified. Thus, this immature stage of model development does not allow us to rely on one modelling approach, since each of them might still have major shortcomings.
- There is a certain amount of rigour (and believability) in achieving the same results from different approaches. It also convinces the public that the modelling is predicting a reasonable set of scenarios for the future.



- Yes, models need to cover identified risks and their processes in each case.
- I personally support application of different types of RA methodology so long as they incorporate a basic, agreed upon set of principles or framework.
- Analytic approaches should be used whenever possible, since they tend to be more transparent, and, often less time consuming, than developing numerical models. Numerical models, however, will most certainly be needed. Reservoir simulation, in particular, will be an essential part of scenario analysis.

Do/will you address uncertainties in RA for CCS projects?

- Within our organization, uncertainties (geologic system features, costs, etc.) are addressed with a specific uncertainty management process. This process identifies “issues” and classifies them with respect to uncertainty level, impact and “learnability”. Uncertainties that have a high impact, yet are learnable through further work, are prioritized.
- Yes, but far too wide a question to give a brief answer.
- Uncertainties in the geometry and petrophysical characteristics of the reservoir and its caprock: these are the uncertainties of the geological model and will be addressed by geostatistical analysis. Thermohydrodynamical, geochemical and geomechanical modelling uncertainties are much more difficult to estimate. Monte Carlo simulation could be a way to handle them but it is highly CPU-time consuming.
- Conceptual model uncertainty is one of the key issues. A thorough site characterisation is required before the injection starts. Should be further improved after the injection start by the lessons learned from the monitoring. Thus, site characterisation should be a key element of RA.
- Without having conducted a proper RA (performance assessment but not RA), it is difficult to say exactly what the uncertainties will prove to be. However, one could approach uncertainties with good, logical explanations to demonstrate that they are reasonable and that the end result of the RA makes good sense.
- Yes, uncertainties are handled by various distributions both with regard to likelihood as well as impact.
- The greatest uncertainty will be borehole leakage in regions of past oil and gas production. Accordingly, we will (i) locate adjacent boreholes from existing public and operator records; and (ii) run cement logs in existing boreholes.
- Yes, look at the distributions of expected values for most of the key parameters that go into the numerical models.
- For field pilot tests of CCS, there are uncertainties in the geology of the sites and the physical properties of the reservoir and seals. These are addressed through (i) scenario analyses in which different plausible geologic models are



assembled, and (ii) sensitivity analyses in which ranges of physical property values are assigned to the different models.

- In our opinion, all uncertainties such as those described in the briefing document should always be declared and discussed. One particular uncertainty that must be addressed is the fact that it is impossible to verify any RA results on the longer term (due to the time perspective of CCS).

Are any forms of monitoring linked to RA results / predictions for existing/planned CCS projects?

- Yes, surface seismic and observation wells will be used to calibrate / match the reservoir simulation.
- Yes – using techniques that match the identified processes and risks. Monitoring will be conducted before, during and after CO₂ injection period. When operator and authorities agree that predictions are reliable, monitoring should be reduced and eventually cease.
- Up until now, monitoring has been at a research stage. Two kinds of problems are addressed: monitoring the progression of the CO₂ plume, and monitoring leakages at the surface. Different geophysical, geochemical, hydrogeological and physical monitoring methods could be applied. All of them, except 4-D seismic, are at an evaluation and testing stage. Site-specific monitoring strategies have to be developed, using a combination of the most relevant monitoring techniques for the specific site characteristics and RA predictions. The duration of the monitoring will also be site-specific. The monitoring strategy may evolve as a function of the timescales of interest, i.e. could be revised at the end of the injection period according to the results obtained and revised RA.
- In order to build a good RA model and good inputs for performing the comprehensive RA prediction, one would need a variety of geoscience data from monitoring surveys over several years. I would suggest that a robust RA model built in this manner could be adapted to different CCS projects with a minimum set of data, including: seismic (if available), soil-gas, geochemical and fluids, cement integrity indices (yet to be defined), age of wells and types of cements and steels used in wellbores and abandoning processes, groundwater. I would expect that one survey of each would work for a robust model. Long-term monitoring to assure the integrity of a storage site would have to be minimal and inexpensive and could include something like a permanent seismic array or passive seismic and groundwater and soil-gas monitoring. The frequency of measurement would likely be annual in the early years but go to decades and possibly several decades apart as storage becomes more long-term.
- Ultimately, monitoring programs should be designed NOT around RA but around risk management decisions. The monitoring results (or output) should be



tied to answering questions related to how best to manage risks in a timely, efficient and economic manner.

- Although no formal RA is planned for pilot tests, an extensive monitoring programme will be carried out. One of the objectives of the monitoring programme will be to demonstrate the containment of CO₂ by the reservoir.
- The monitoring has not been specified yet [for our storage project] but will most likely be linked to RA. We expect that the competent authority, responsible for issuing the permit, will specify the monitoring time required. There is also a possibility of recommending a monitoring plan to the authorities, and this is likely to be done.

Will you carry out an integrated assessment?

- Yes, the approach is proprietary at present but such issues are under consideration.
- RA will be mandatory and also cover surface/sub-surface HSE consequences.
- We believe that a fully-integrated site-specific RA linking CO₂ migration and possible HS&E impacts is needed to increase confidence with all kinds of stakeholders.
- It is fully expected that the results of ongoing monitoring both for the key subsurface risk events as well as for surface, near surface and above surface fluxes, will be routinely integrated into forward modelling to predict CO₂ movement both within and outside the intended storage site.
- Information required by regulators will be submitted, currently driven on a case-by-case basis.
- The way in which the RA will be carried out has not been determined yet, but is currently under investigation. Most likely, the issue of the connection between leakage and HSE effects must be addressed.

Do/will you make use of natural or industrial analogues?

- Yes, CO₂-EOR, natural gas storage and natural analogues. Also well reliability information.
- Analogues have been and should be used as basis for judgement, especially for long-term consequences.
- Yes, volcanic and sedimentary natural analogues; gas storage industrial analogues. Two types of natural analogues are extremely useful. Sites with natural CO₂ leaking at the surface are used as test sites for evaluation of monitoring techniques and HS&E impacts, and for developing fully-integrated RA. Sites with geological reservoirs of natural CO₂ are used also to test monitoring techniques and to study the geological characteristics of the reservoir and caprock as well as the long-term impact of CO₂ storage. Natural analogues are a key element for risk communication with stakeholders. Natural



gas storage is now a common practise, quite well accepted by the public. With reference to certain aspects of gas storage, RA standards will increase confidence of stakeholders on RA for CO₂ storage, at least for short timescales.

- Yes. In a specific natural analogue project, wellbores and fractures from a relatively old (50 years) gas field will be studied to determine the impact of the CO₂ (cement integrity, steel casing degradation and fracture sealing).
- Extensive use of local natural analogues (high CO₂ gas fields) has been made in supporting predictions of CO₂ behaviour in the subsurface. In addition, our RA approach compares other engineered systems (i.e. dams) with CCS as analogues which are recognised, and for which the risks are deemed acceptable, by various communities.
- Yes, CO₂ natural reservoirs; e.g., McElmo Dome, Sheep Mountain, Bravo Dome.
- Oil and gas fields, natural analogues, natural gas storage, acid gas storage, and deep waste water injection can all be used to illustrate that, under the proper conditions, CO₂ storage should be safe and effective. For human activities, the level of engineering work and site characteristics can be used as references for comparison with the site in question.
- Natural gas storage; studies on natural analogues of naturally occurring CO₂.
- Nothing specified yet, but experiences from natural gas storage, EOR activities, available results from other CCS projects, experimental work *etc.*, will be used to verify results and support a planned CCS project in other ways. For the capture part of a CCS project, existing methodologies can and will be used.

Are you, or is your organization, involved in risk communication?

- Full openness is a key foundation of this organisation, and leakage is what the public is concerned about.
- Leakage is the main concern in this context - for example, the Lake Nyos disaster is always mentioned by the public. Another frequent concern involves the possible occurrence of an earthquake that would destabilise the CO₂ storage. These issues are addressed using observations/arguments such as the following:
 - Careful site selection will be made for CO₂ storage projects, according to safety criteria, with monitoring being carried out both during and after the injection period. Remediation strategies will be prepared in advance in case of any unwanted event (the ultimate one might be to deliberately release and disperse the CO₂ in the atmosphere. If this is done for only one of the many future CO₂ storage sites, it will not significantly affect the target of global GHG reduction and would solve any local problem). Standards for site selection, monitoring and remediation are actively being developed by the researchers worldwide, with international cooperation.



- The existence of numerous natural CO₂ reservoirs worldwide shows that geological formations, under certain conditions, can trap large amounts of pure CO₂ efficiently for millions of years.
- Natural CO₂ releases without any associated risk do exist also in many areas. Sometimes they may cause a problem, BUT they are easily managed.
- Not acting now is taking the greatest risk. Global warming effects and ocean acidification with marine ecosystems modifications are already measured and will get even stronger. CCS is an additional option that is needed in addition to other options in order to halve annual worldwide CO₂ emissions by 2050, thus hopefully avoiding major catastrophic climatic impacts.
- We are in the process of building a Public Education/Outreach programme to help inform public policymakers and other interested parties (industry, NGOs) about CCS. This will feed into the development of an acceptable public policy and regulatory framework for widespread deployment of CCS.
- A risk communication strategy is being developed for the proposed CCS pilot project. It will be informed by a RA and will be broadly based on current risk communication practice used in the oil and gas industry. Our organisation currently addresses risk communication through issues management plans included in our overall CCS communication strategy.
- The final phase of an ongoing project will broaden its focus beyond the technical challenges, to encourage CO₂ geological storage and will provide information and recommendations to address policy issues such as regulatory requirements, public communications and outreach and business requirements. The Public Communications theme plan is being developed and is expected to provide useful information to both policy makers and the general public.
- Public Workshops using integrated assessment tools are organised as part of a public outreach programme for an upcoming CO₂ storage project.
- Not directly, but indirectly, through communication with the research community, and through written material that the interested public has access to.

Should the implementer and/or regulator be involved in risk communication involving CCS projects?

- Both. The regulator should provide an objective assessment of the due diligence effort.
- Both regulator and implementer. There should be total openness, and a transparent evaluation process.
- Both. The regulator should communicate on the general benefits of CCS on climate change and on the safety rules, risk assessment and management that the regulatory framework will require from the implementer. The implementer should communicate on how risks are assessed prior and during the project and how they will be managed during the project life and beyond.



- Both, but for the regulator, only in a technical support role to a professional and credible communicating group (probably an NGO).
- Both. Behind the scenes, the regulator will provide advice as to how the risk is best managed. Those risk activities that have been put in place in accordance with the regulator's advice can then be publicly endorsed by a spokesperson for the regulatory agency and give additional comfort to communities that the proper safety procedures are being implemented. We believe that it is primarily the implementer's role to put the risk communication plan into action. Activities would include briefing key stakeholders; briefing spokespeople; agreeing key messages with other spokespeople, e.g. those from the regulating agencies; and ensuring that the community, stakeholders and media are fully and regularly informed in a timely manner.
- I think that it is important for both parties to be involved in communicating to the public. In one particular study on Public Attitudes towards the geological disposal of CO₂, one important element was that the public wanted the regulator to have a strong influence and management presence in the projects. The regulator could explain the regulatory process, provide explanations regarding regulatory requirements and illustrate how these requirements are protective of human health and the environment. The regulator could also discuss how the risks are assessed at project sites and address contingency plans, provide feedback on regulatory compliance of companies, and be willing to challenge industry in the interest of the public, etc. The regulatory authority needs to preserve its role as credible and unbiased for the public to trust in the process and in turn gain acceptance on CCS projects, where appropriate. The implementer could communicate project-specific information, explain why certain sites are chosen, illustrate how they manage the site on a day-to-day basis, and provide site visits to increase the public's knowledge and comfort with CCS projects.
- Yes, the regulator should be involved:
 - From the start
 - In the risk screening and FEP development
 - In the integration of the monitoring data into the analysis
 - In the selection of Decision criteria
 - In the design of Corrective action
 - In the implementation
- The entire process will need to be open. The regulator must be seen to want storage to be acceptable and effective. Otherwise, this approach to GHG control will not be available. The regulator must be an advocate for the process, but not for specific sites until they have been approved.

Do you favour some form of risk assessment protocol or technical standard?

- Standards are useful wherever they have been established and recognised.
- I favour a framework based on agreed-upon principles.
- Standards specific to CO₂ storage should be developed internationally, based on the first Best Practice documents as well as on the on-going research.
- We need to develop technical standards and protocols, and our national standards body is working on this. We will need national standards to reduce domestic GHG emissions. However, given the nature of the Kyoto Protocol and any subsequent treaties, we will need international protocols in order to demonstrate our reductions and trade emissions credits.
- With various countries/organisations following various methodologies and sharing the results, a better and more appropriate RA methodology should ultimately result. Once there is one agreed RA approach for CCS, then it would be appropriate to have a standard or protocol; until then it is suggested that the various pilot and demonstration projects and the various RA approaches applied to them will largely determine when and how this might happen.
- As markets develop for CO₂ credits, international standards can play an important role to level playing fields and ensure that adequate comparisons can be made as consistent processes are used to calculate emissions.
- Would like to see standards develop, as that will facilitate both regulators and applicants reaching reasonable conclusions about sites under consideration for storage, and will facilitate a reasonable pace for the permitting process. If each site has a “one-off” process, progress is likely to be slow. International standards would be preferred, but national standards may be the best we can do in the early years and would be better than none.
- Not in terms of how to perform a RA (the competent authority will establish necessary requirements). But some sort of standard risk assessment criteria would be helpful for both the regulator and the implementer.

Are there any specific gaps in terms of risk assessment for CCS projects?

- I believe that quantitative information from analogues should be sought where possible. Benchmarking of various methodologies (based on an agreed framework) is key to stakeholder confidence.
- Generally, from the oil & gas and geothermal industries, existing methods and tools are available. However, we lack experience from a variety of different sites with CO₂ injection. In particular, sealing properties for different caprocks need to be studied more.
- Several gaps are identified below:



- Basic experimental data on PVT behaviour of CO₂ containing impurities (e.g. H₂S).
- Certain types of CO₂ specific experimental data with respect to the thermodynamics and kinetics of certain minerals.
- The use of coupled models is still quite rare, but it forms the key to assessing the impact of CO₂ and its risk of leakage. Coupled models need to be used on a wider variety of problems or test cases and should be used for sensitivity analysis (or, even better, for Monte Carlo analysis, although this will remain unlikely in the near future due to calculation time constraints).
- The impact of geochemical reactions on geomechanics is poorly addressed up to now and should be resolved. Geomechanical events could occur over short or long timescales due to geochemical reactions in the reservoir, in the caprock, and in the wellbore completions, including specific locations such as in fractures.
- We need to clearly understand what we actually need to demonstrate to the public in our RA in order to achieve public acceptance (and to develop appropriate regulations), i.e. what data, what conclusions, how do we package it (technical jargon vs. common language). Good RA is the key to good regulations (an appropriate regulatory body would issue a licence). Major gaps that need to be defined include what leakage/seepage is acceptable, timeframe for storage (that must be clearly demonstrated through RA), and regional containment zone. We also need to put all CCS projects on a uniform basis and measure them all (via RA) in terms of predicted performance in the same way, i.e. through protocols, standards, regulations. We are currently permitting activities on the basis of hydrocarbon recovery for energy use (i.e. economic value, not “disposal”). We are not permitting CCS activities, CCS just happens to be coincidental - this is a somewhat *ad hoc* approach to licensing CCS projects. That does NOT mean, however, that we have the protocols, standards, regulations or public approval necessary to store CO₂ geological for a long period of time.
- Our organisation believes that there is still a long way to go before an “agreed approach” is found. As such there really is a RA methodology “gap”; as indicated above in Question 16 (Technical Standard/Protocol), which will be addressed by application of various RA methodologies to as many pilot, demonstration and commercial scale projects in the early years of CCS.
- Three items:
 - Borehole leakage and borehole sealing longevity;
 - Duration of long term monitoring since that action will greatly control cost;
 - Long-term stewardship.
- The question has to be answered “No” as projects are going forward now. The biggest issue is gaining experience and acceptance for one or more RA techniques. For numerical methods, there are questions about the use of



petroleum industry simulation software for CCS problems, given the areal and temporal scales involved.

- What criteria to base the assessment on, and environmental ecosystem effects. In addition, although currently we do not know everything about CCS, when a RA is performed, the RA should be updated/revised as and when new information and research results become available. In this way, the assessment is an ongoing process, also during the operational phase. New information should then be taken into account and the methodologies used, for example in relation to monitoring/decommissioning, should be adapted.

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ANNEX I: Risk Assessment and Geological Storage of CO₂: Briefing Document

January 2006

**Michael Stenhouse
Malcolm Wilson
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Executive Summary

This Briefing Document summarises the current status and role of risk assessment (RA) in support of CO₂ capture and storage (CCS) projects, both now and in the near future, the focus being on the *geological CO₂ storage* aspect of CCS. The current status of RA has been evaluated under a number of headings, which are also used in the questionnaire as a means of grouping series of questions.

The key points are:

- **Role of RA in a regulatory regime:** RA, as the method of demonstrating safety, is likely to be a key part of the regulatory regime for CCS projects. While it should be a major component in any submission for a permit/licence, RA is unlikely to be the only means of demonstrating or assuring safety.
- **RA Timeframes:** Two RA timeframes are relevant to CCS depending on the needs of the regulator, whether for greenhouse gas reduction and inventory control, or for HS&E impact. The upper limit for RA is likely to be several thousand years. While a specific value for each timeframe would help to define the maximum time for RA predictions, such values do not need to be specified explicitly, as long as the RA addresses all relevant risks.
- **CO₂ Leakage rate/flux:** Leakage flux/rate of CO₂ and cumulative CO₂ leakage are likely outputs from RA predictions and, as such, could be part of the regulatory requirement for CCS projects. However, any regulatory requirement for leakage rate/flux limits must be based on a good scientific understanding, ultimately linked to specific hazards and their possible consequences.
- **RA Methodologies:** More than one methodology exists that can be applied to CCS projects, although there is no consensus yet on the merits and shortcomings of different techniques. A number of groups are moving towards the scenario and FEP approach. The above methodologies are not necessarily mutually exclusive, and all rely on expert opinions to varying degrees.
- **RA Modelling Approaches:** Several types of modelling approach exist and these serve different purposes and are not mutually exclusive. Whatever approach is carried out, the boundary conditions and underlying assumptions should be specified. Carefully devised benchmarking exercises will enhance modelling credibility and confidence.

- **Uncertainties:** There are many uncertainties in natural systems and a number of techniques can be used to address these uncertainties. The adequacy of a RA will depend to what extent the different types of uncertainty are addressed in assessment calculations.
- **Monitoring:** Monitoring will play a key role at all stages of CCS projects. A variety of monitoring techniques are available in support of RA, either for baseline measurements or to verify and validate modelling predictions. Which technique(s) to use will depend largely on detection limits, the need for minimal intrusion at storage reservoir depth, and cost.
- **Comprehensiveness / Integration:** To date, a fully-integrated RA, which links CO₂ leakage from the storage reservoir to an evaluation of end-points such as HS&E impacts, has not been carried out for CCS-related projects. Such a fully-integrated approach will help to increase confidence with stakeholders, including regulators and the general public.
- **Role of Analogues:** Natural Analogues (NA) serve a number of purposes linked to RA, the most quantitative purpose being to validate predictive modelling results. In the absence of quantitative information, NA examples can be used to increase understanding, by identifying geological environments that are suitable for long-term CO₂ storage, and, on the other hand, by providing good reasons why bad sites leak. A key role of industrial analogues is to illustrate to stakeholders how CO₂ leaks can be managed and mitigated.
- **Risk Communication:** Stakeholder acceptance, in particular public acceptance, is considered key to developing CCS projects in a timely manner, and RA is a critical component of public acceptance. All indications suggest that science-based information is not sufficient to satisfy public concerns, and other avenues of communication, e.g., natural and industrial analogues, are needed to support the science-based approach, particularly when RA techniques are not easy to communicate.
- **RA Technical Standard / Protocol:** RA is not new and already exists under a number of regulatory frameworks. Where RA for CCS projects would differ from most industrial and engineering projects is in the timeframes associated with geological CO₂ storage and, therefore, the need to demonstrate confidence in long-term predictions.

Finally, a number of RA needs are discussed at the end of this document.



I1 Introduction

I1.1 Purpose of Briefing Document

Monitor Scientific (MSCI) is carrying out a study for IEA Greenhouse Gas Research and Development Programme (IEA GHG), to provide a briefing document on the current status and role of risk assessment (RA) in a regulatory regime for overseeing CO₂ capture and storage (CCS) projects, both now and in the near future.

CCS involves capturing anthropogenic CO₂ from sources such as coal-fired power plants or manufacturing industries (*e.g.*, iron and steel or cement manufacture), and injecting the CO₂ into deep geological formations such as depleted oil and gas fields, saline aquifers, and coal beds. As will be discussed below, the focus of the review is on the *geological storage*⁷ aspect of CCS projects (see *Figure I-1*), since the operational phase of CO₂ capture and associated risks are similar to those of routine engineering or industrial projects and the RA needs are also similar [Pacala 2003]. This briefing document on RA for geological CO₂ storage will be used as the basis for obtaining feedback primarily from regulators, and also from implementers who are involved in the planning and management of storage projects.

Another objective of the study is to identify key gaps associated with RA and its role in regulatory oversight, and, hence, specify RA needs against a timeline of planned and anticipated CCS projects. This component of the study will rely on the feedback from regulators and implementers.

I1.2 Risk and Risk Assessment

Risk is generally the likelihood of suffering harm from some activity, which can be expressed in terms of the following questions;

- What can go wrong (hazard)?
- What is the likelihood of that happening (probability or frequency)?
- What is the magnitude of the consequences?

More formally, risk equates to the product of probability that an event will occur and the consequences of the event if it does occur. In a broader context, RA is simply an assessment of the safety of a certain activity, in this case the geological storage of CO₂. Holloway [1997] was one of the first researchers to discuss safety aspects of geological storage. More recently, Damen *et al.* [2003] provide a good discussion of possible health, safety and environmental (HS&E) risks in this field.

⁷ Although the abbreviation “CCS” is used throughout this document, the focus is always on geological CO₂ storage.



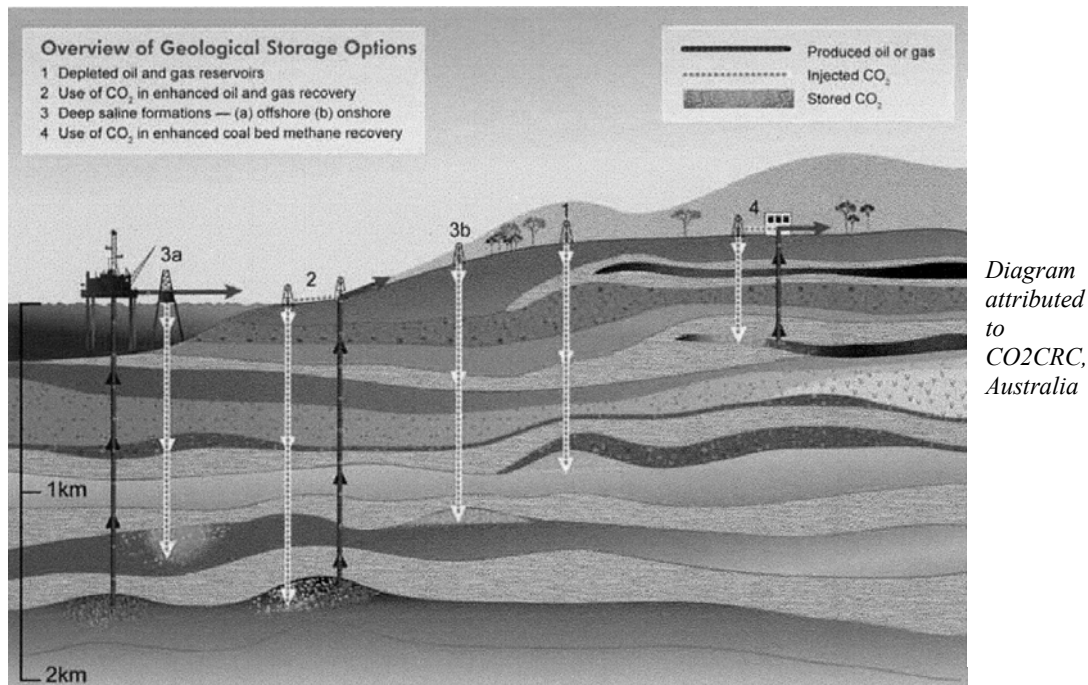


Figure I-1: Geological storage of CO₂ [from IPCC, 2005a].

I1.3 Layout of Briefing Document

The current status of RA in CCS has been evaluated under a number of headings, which are also used in the questionnaire as a means of grouping series of questions.

Supporting information comes from papers a number of sources covering the last few years (mainly 2002-2005): peer-reviewed and other relevant papers from the GHGT6 and GHGT7 Conferences, publications from the internationally-sponsored CO₂ Capture Project (CCP), papers presented at the Annual Conferences on Carbon Capture & Sequestration in Alexandria, Virginia, and presentations at relevant workshops sponsored by IEA GHG, U.K. Department of Trade and Industry (DTI), and the U.S. Environmental Protection Agency (EPA).

In this document, *migration* refers to the general movement of CO₂ (in any direction) away from its storage reservoir, whereas *leakage* is specific to upward movement of CO₂ to the surface/near-surface environment, where the major environmental impacts are expected to occur. *Release* is used in this document to mean loss or return of CO₂ to the atmosphere.



12 Discussion of Relevant RA Topics

12.1 RA Needs for Regulatory Oversight of CCS Project

Two major considerations will influence regulatory guidance and oversight of CCS projects:

- *Permanence* (or storage performance): the need to keep the CO₂ underground and no longer contribute to atmospheric CO₂ concentrations;
- *Environmental impacts*: the need to avoid harmful HS&E impacts.

The requirements of RA will depend on which of the above is being addressed, although the two concerns are not mutually exclusive. In the former case, RA needs only to demonstrate that the CO₂ remains underground, although the way in which this can be accomplished is a challenge. For potential HS&E impacts, the level of detail required in assessing a range of possible impacts would appear to be greater.

Detailed discussion of this topic is perhaps premature since, to our knowledge, only two projects (see *Figures I-2, I-3*) have been conducted to date *solely* for CCS, *viz.* the Sleipner Project in the North Sea, operated by Statoil, which involved the stripping of CO₂ from natural gas and its injection under the North Sea, and the more recently initiated In Salah Gas CO₂ Storage Project in Algeria, operated jointly by BP, Sonatrach and Statoil, similar to Sleipner but onshore. Thus, most CCS-relevant projects that have been carried out so far involve enhanced-oil-recovery (EOR), *e.g.*, IEA Weyburn CO₂ Monitoring and Storage Project, Rangely Field, acid gas injection in Canada [Bachu and Gunter, 2004], or CO₂ storage as a pilot or feasibility project, carried out at a research scale, *e.g.*, the Frio Brine Pilot Project [Hovorka *et al.*, 2003]. To a large extent, therefore, responses to the questionnaire will provide important input to this topic.

COMMENT: *RA, as the method of demonstrating safety, is likely to be a key part of the regulatory regime for CCS projects. While it should be a major component in any submission for a permit/licence, RA is unlikely to be the only means of demonstrating or assuring safety.*



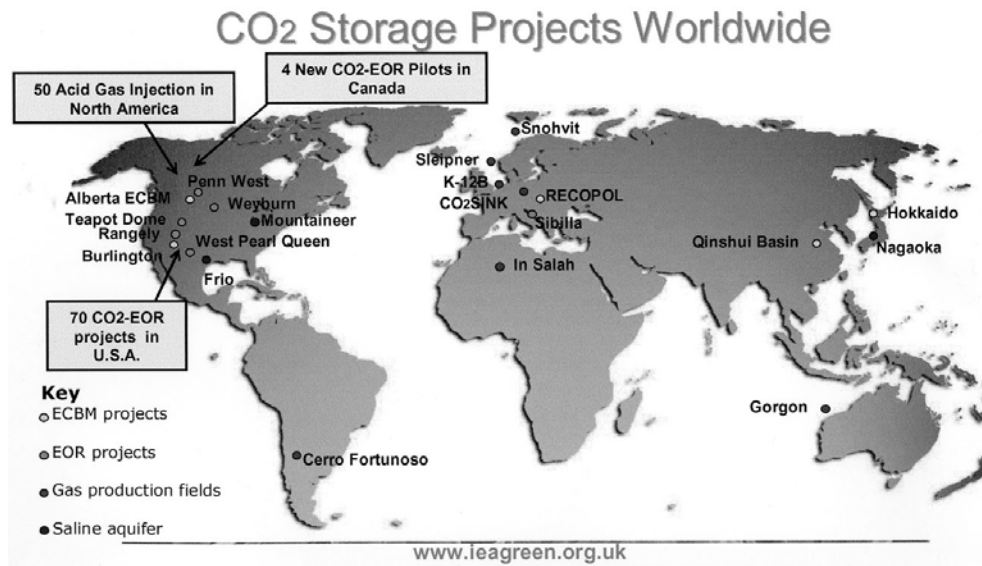


Figure I-2: CO₂ injection and storage projects worldwide [courtesy IEA GHG]⁸.

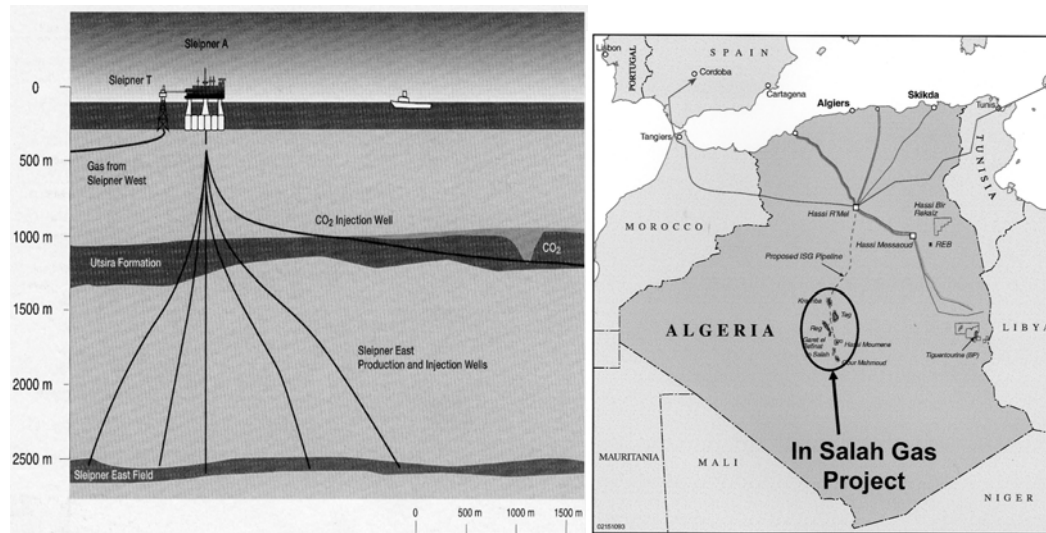


Figure I-3: Two CCS projects – Sleipner (above left) [Arts *et al.*, 2004], and the In Salah Gas Project (above right) [Wright *et al.*, 2005].

12.2 Timescales of Interest

Each of the considerations for regulatory oversight identified in the previous section has a timeframe associated with it, although there is no consensus yet on the extent of these timeframes [Stenhouse *et al.*, 2005a].

On the issue of permanence, the latest IPCC report defined several time periods corresponding to different period of atmospheric CO₂ levels (see Figure I-4). The IPCC report noted that it would take a “very long term” of time for the stabilization of

⁸ Some of the numbers (of projects) quoted in this diagram have now increased; for example, 82 CO₂-EOR projects in USA (Oil and Gas Journal, Vol. 104, Issue 15, April 17, 2006). Figure A2 also does not show the 25 pilot/field tests to be conducted during Phase 2 of the DOE Regional Carbon Sequestration Partnership Program (see Table 3 of main text).



atmospheric CO₂ levels to be impacted by the storage of CO₂, *i.e.*, time periods lasting centuries or millennia [IPCC, 2005b].

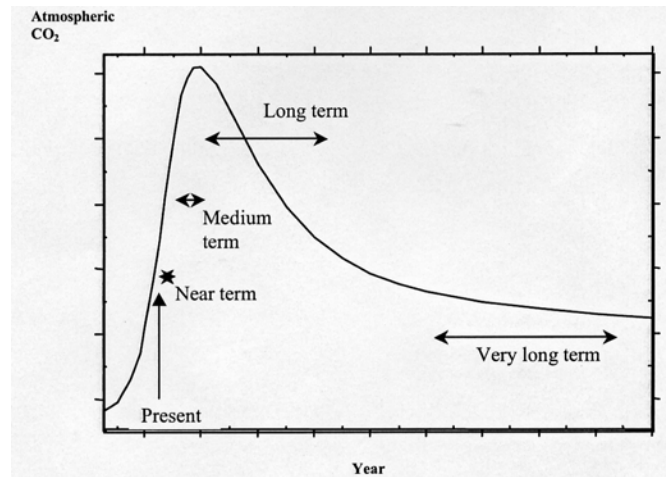


Figure I-4. Expected atmospheric CO₂ levels as a function of time [IPCC, 2005b].

NOTE: “Near term”, “medium term”, “long term”, and “very long term” correspond to years, decades, centuries, millennia, respectively. The diagram is for illustrative purposes only.

The time estimates associated with the risk of HS&E impacts (see Figure I-5) range from hundreds of years up to 10,000 years. As long as reservoirs contain large volumes of CO₂, the potential exists for CO₂ to leak to the surface and cause some detrimental effect within the biosphere. Key processes that will act to keep CO₂ underground include mineralization reactions (mineral trapping) and dissolution of CO₂ in deep formations (solubility trapping=>ionic trapping) where groundwater flow is negligible, although the timeframes for such processes can be long - thousands of years at a minimum [Gunter *et al.*, 2004; Ennis-King and Paterson, 2003].

On the other hand, modelling work carried out on CO₂ storage in saline formations has indicated that immobilisation of more than 90% of the supercritical CO₂ phase via dissolution and/or residual gas saturation (CO₂ being trapped in small pores, can occur over shorter time periods [Doughty and Benson, 2006; Holtz *et al.*, 2004]. On the same theme, Leonenko *et al.* [2006] have proposed a novel engineering solution to speed up the dissolution of CO₂ in aquifers.

In terms of specific projects related to CCS, Ennis-King *et al.* [2005] performed simulations on four potential storage sites over thousands of years, and for the IEA Weyburn project, 5,000 years was used as an (arbitrary) upper limit for modelling predictions [Zhou *et al.*, 2005a; Walton *et al.*, 2005]. Within the Sleipner Project, Lindeberg and Bergmo [2003] modelled the dissolution of free CO₂ over periods up to 7,000.

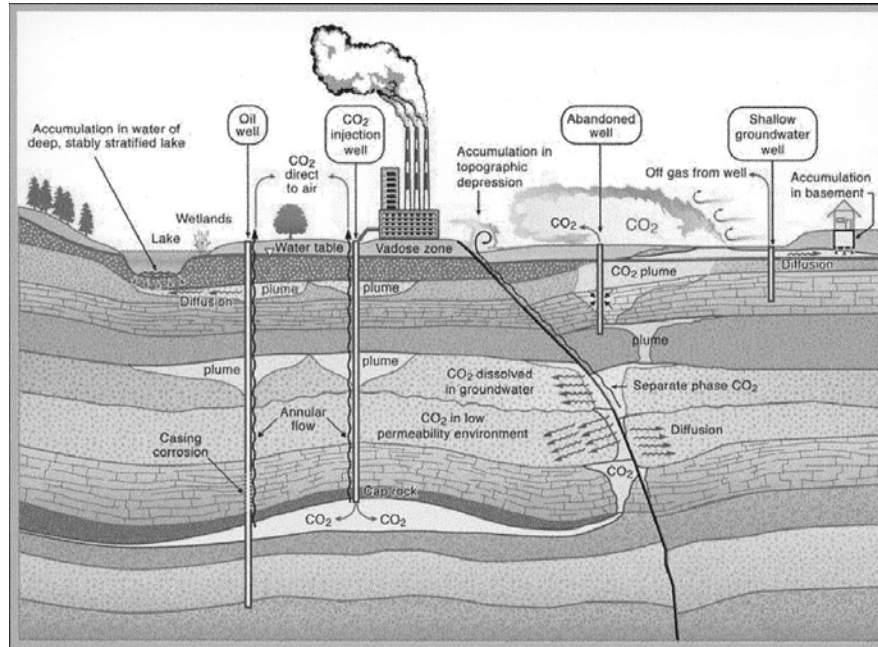


Figure I-5: Overview of risks from CO₂ leakage [from Benson, 2003].

As one possible regulatory analogue for this timeframe, the U.S. EPA's Underground Injection Control (UIC) Program (established under the Safe Drinking Water Act) requires the retention of hazardous waste underground up to 10,000 years as mandated by the US Congress [EPA, 2005]. Such an established standard is currently under consideration for its suitability to CCS.

COMMENT: Two timeframes are relevant to CCS depending on the needs of the regulator, whether for greenhouse gas reduction inventory control, or for HS&E impacts, with an overall timeframe for RA of several thousand years. While a value for each timeframe would help to define the upper limit for RA predictions, such values need not be specified explicitly, as long as the RA addresses all relevant risks.

12.3 CO₂ Leakage Flux/Rate

In terms of potential impacts from CCS projects and the timeframes involved, the risk output from a RA study will depend largely on the rate of loss (flux) of CO₂, if any, to the atmosphere (relevant to greenhouse gas reduction), as well as CO₂ leakage to a number of environmentally-sensitive end points (e.g., potable aquifer, dwellings, agricultural settings – relevant to HS&E impacts), and cumulative loss of CO₂ over time. Thus, in a regulatory context, CO₂ leakage or release flux may be the key criterion. For example, Mahasenan *et al.* [2003] discuss a risk and consequence assessment methodology that uses CO₂ fluxes as the key measures of risk and consequence to a variety of end-points: humans, animals, biota, agriculture, and water resources.

In terms of specific CCS-related projects, no leakage to the surface has been detected at Sleipner and Weyburn, as predicted. In a more mature EOR project, at Rangely,



Colorado, small amounts of CO₂ leakage to the surface have been detected, although a significant source of the CO₂ may be due to biogenic conversion of deep-sourced methane [Klusman, 2003] and not to injected CO₂. In any case, arboreal measurements indicate no impact on plant ecosystems.

As a cautionary note, many leakage rates cited initially in the literature were based on a limited understanding of geological settings, and should not be used as the basis for regulatory evaluation of risk [Stenhouse *et al.*, 2005a; Bradshaw *et al.*, 2005].

COMMENT: Leakage flux/rate of CO₂ and cumulative CO₂ leakage are likely outputs from RA predictions and, as such, could be part of the regulatory requirement for CCS projects. However, any regulatory requirement for such leakage rates/fluxes must be based on a good scientific understanding, ultimately linked to specific hazards.

12.4 RA Methodologies

A number of different RA methodologies have been, and are being applied, to CCS-related projects. The main methodologies are¹:

- Scenario analysis (see Figure I-6): Different scenarios, each representing one possible evolution of the CO₂ storage system, are analysed in terms of CO₂ migration/leakage. Scenarios are generally supported by a consideration of features, events and processes (FEPs⁹) that are relevant to possible CO₂ migration and are used to describe the storage system and scenarios [Maul *et al.*, 2005; Wildenborg *et al.*, 2005].

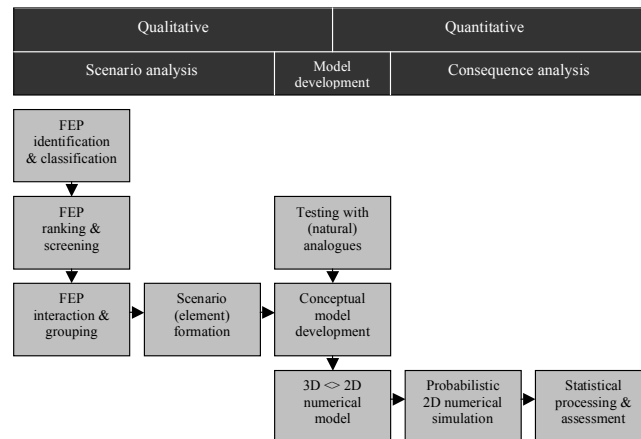
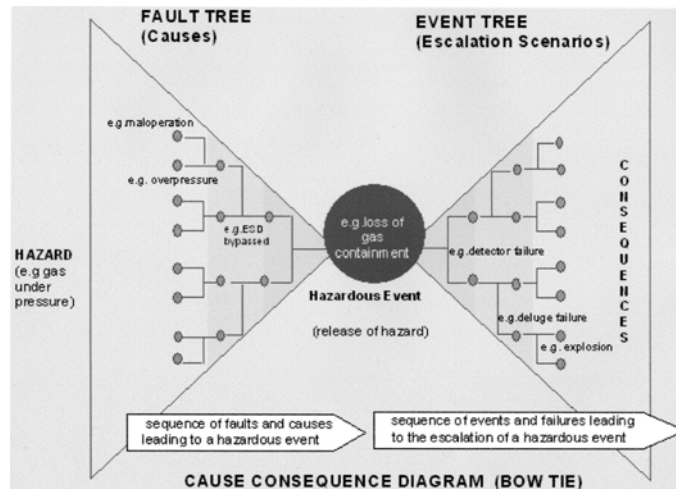


Figure I-6: Example of scenario analysis approach [from Wildenborg *et al.*, 2005].

- Fault / event tree analysis (see Figure I-7): A network of pathways for CO₂ release and migration, from the storage reservoir to the point of interest, is evaluated as a combination of possible steps, normally in a probabilistic manner. Probabilities are attached to each component path of each tree.

⁹ For those not familiar with FEPs, a visit to the FEP database website at <<http://www.quintessa-online.com/co2/>> will provide a good overview.





*Diagram
courtesy of
International
Association of
Oil & Gas
Producers*

Figure I-7: Example of fault tree / event tree approach; application to gas storage.

- Expert judgment, whereby the conclusions of those having relevant experience and expertise in a specific area, are solicited to ‘derive’ the probability of a release and estimate its characteristics (CO₂ leakage flux/rate, cumulative release). A variation of this approach was used within the GEODISC project [Bowden and Rigg, 2005] whereby the consequences were evaluated for a range of different factors (including stakeholder acceptance, legal claims, HS&E impacts) as well as the likelihood of these consequences occurring. This approach yielded a semi-quantitative Risk Quotient (see Figure I-8) and was used in Australia to assess and compare different sites for geological CO₂ storage.
- Screening-level analysis: One example of this method, a spreadsheet-based analysis, has been used to assess and compare HS&E risks from a number of potential CO₂ sequestration sites [Oldenburg 2005]. This qualitative approach is based on expert opinion to evaluate the performance of each barrier between the storage reservoir and the biosphere (primary and secondary containment as well as the ability to attenuate CO₂ leakage), and allows for uncertainties.

COMMENT: *More than one methodology exists that can be applied to CCS projects, although there is no consensus yet on the merits and shortcomings of different techniques. A number of groups are moving towards the scenario and FEP approach. The above methodologies are not necessarily mutually exclusive, and all rely on expert opinions to varying degrees.*

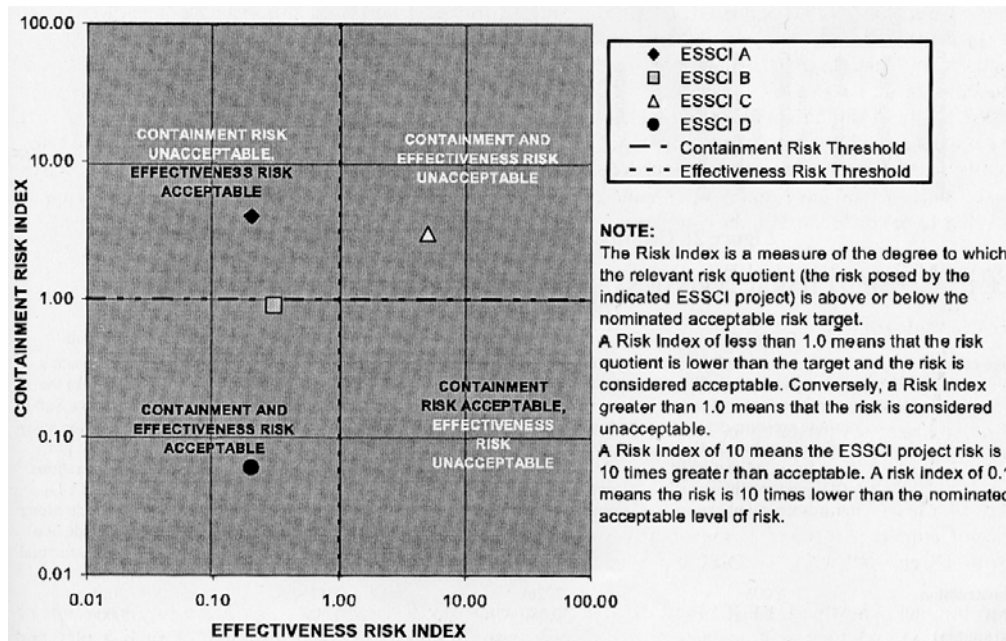


Figure I-8: Output from RISQUE methodology [from Bowden and Rigg, 2005].

12.5 RA Modelling

In parallel with RA methodologies, a variety of approaches are available for quantitative estimation [Celia *et al.*, 2003], which can be classified under three general categories, *viz.*

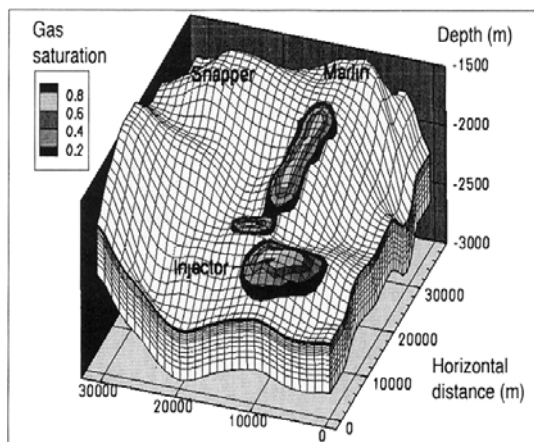
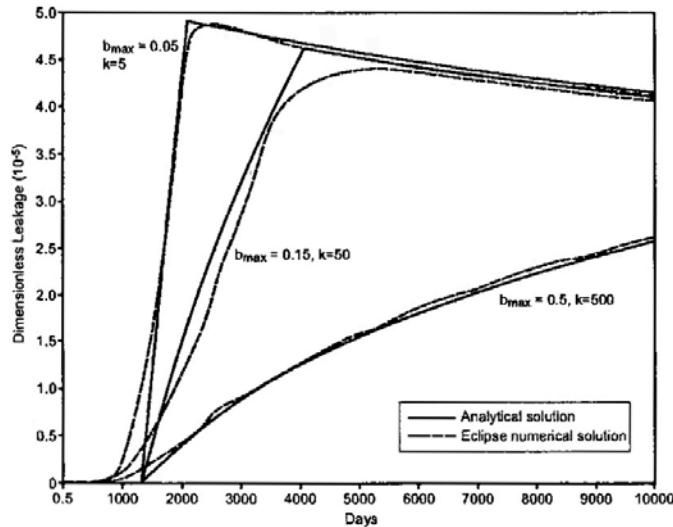


Figure I-9: Output from numerical modelling of gas saturation in possible storage reservoir, 200 years after injection has stopped [from Ennis-King *et al.*, 2005].

- Numerical models, which use spatial and temporal discretization methods to model detailed processes describing the system evolution over space and time (see *Figure I-9*). Several commercial simulators developed for the oil&gas industry have been adapted for CO₂ sequestration purposes [e.g., Schlumberger / GeoQuest 2003; Nghiem *et al.*, 2004], as well as public domain codes, e.g., TOUGH2 [Pruess 2005].

- Analytical / Semi-analytical models* are mathematical models in which the solution to the equations used to describe changes in the system can be expressed as an analytical or semi-analytical function, typically as a function of time in the case of RA for CCS projects. Analytical models are often advantageous in solving a sub-system of the total system (e.g., well-bore leakage, Figure I-10).

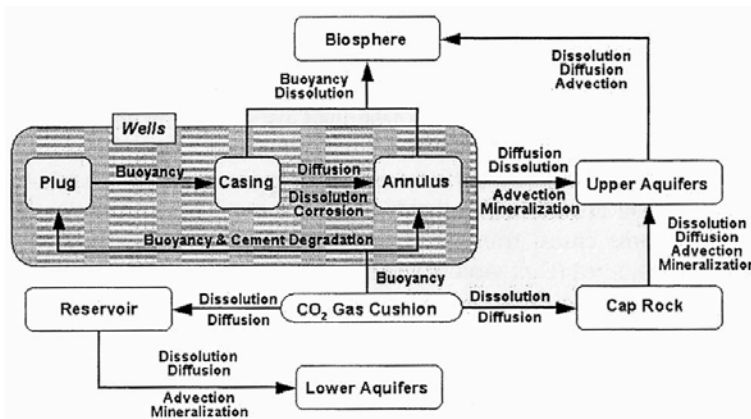


Results (y-axis) are presented as dimensionless leakage -- leakage rate divided by injection rate, normalized by the ratio of formation permeability to leaky-well permeability.

Best-fit values of the fitting parameter, b_{max} (which defines the degree of upconing), are shown for each curve. The best fit was obtained via comparison of the analytical solutions with the output from numerical simulations using Eclipse.

Figure I-10: Leakage rates of CO₂ through an abandoned well, based on three different (arbitrary) permeability (k) values assigned to the leaky well [from Celia *et al.*, 2005].

- Compartment or mixing-cell models cover a large family of models [e.g., see Figure I-11, Walton *et al.*, 2005], where the model comprises a series of individual compartments representing different physical domains of the total storage system. Such models vary in their degree of complexity, this being linked to the number of cells or compartments.



Strictly, the diagram on the left is a process flow sheet showing the mass transport pathways. However, the individual compartments can be considered as components of the 'system', i.e., storage reservoir, surrounding geosphere, wellbores, and biosphere. Here, the focus is on wellbore leakage.

Figure I-11: Example of compartment model approach [from Walton *et al.*, 2005].

In principle, all of the above models can be run deterministically or probabilistically. In the former case, one or two values (e.g., 'best estimate' and 'pessimistic' values) are

used for each input parameter. For the probabilistic case, parameter uncertainty is represented in terms of ranges or distributions of at least the key parameters (see *Section I2.5.1*). In practice, numerical models are complex and are normally used deterministically to reduce computing time. A hybrid approach was used in the Weyburn project, in which the geosphere was assessed deterministically and well-bore leakage was treated in a semi-probabilistic fashion [Zhou *et al.*, 2005b].

COMMENT: *Several types of modelling approach exist and these serve different purposes and are not mutually exclusive. Whatever approach is carried out, the boundary conditions and underlying assumptions should be specified. All of the above can be run deterministically or probabilistically, but there is no consensus on which treatment is preferable. Carefully devised benchmarking exercises will enhance modelling credibility and confidence.*

I2.5.1 Treatment of Uncertainty

Several types of uncertainty are associated with assessment modelling, the main sources being:

- *Parameter uncertainty*, associated with input parameters, is normally recognized and addressed in modelling approaches. *Sensitivity analysis* helps to determine the key parameters – those that have a significant impact on the output (e.g., CO₂ leakage flux or concentration). In probabilistic modelling, parameter uncertainty is represented by probabilistic density functions (PDFs) (e.g., see *Figure I-12*) Thereafter, typically thousands of simulations are performed by sampling parameter PDF's randomly (Monte Carlo approach) resulting in a corresponding distribution for the calculated result (impact/consequence).

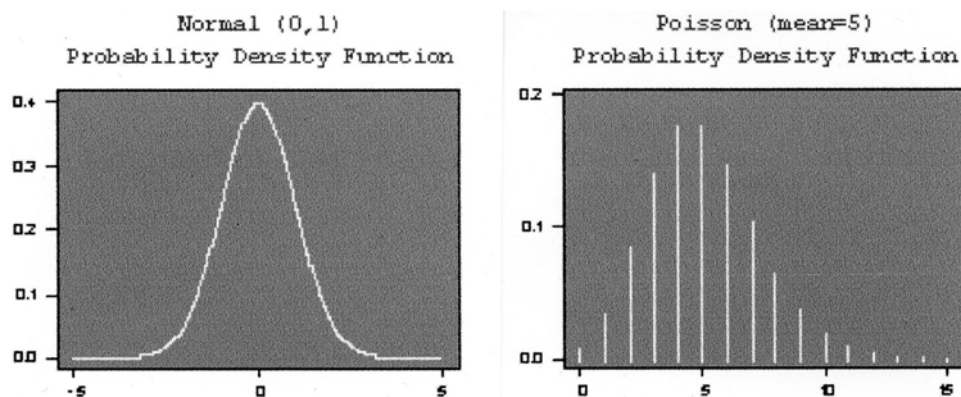


Figure I-12: Two examples of probability distribution functions: normal (above left) and Poisson (above right).

- *Conceptual model uncertainty*, concerning how the real world is represented and abstracted (see *Figure I-13*). Such uncertainty can be assessed by comparing alternative conceptual models / conceptual model results.

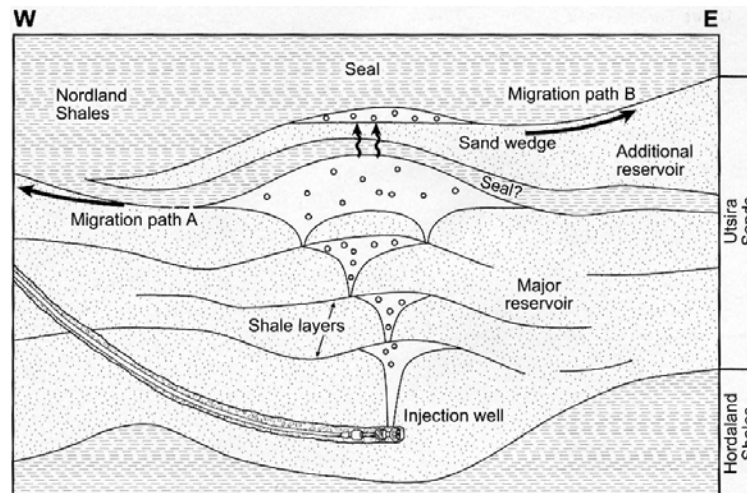


Figure I-13: Updated conceptual model for Sleipner [from Zweigel *et al.*, 2004].

*NOTE: Original predictions of short-term (months to years) CO₂ movement at Sleipner had been based on a simpler conceptual model and did not match observations. Using the above updated conceptual model, containing inter-bed shale layers, reservoir simulations matched time-lapse seismic monitoring observations [Arts *et al.*, 2004] more closely [Zweigel *et al.*, 2004].*

- **Modelling uncertainty**, concerning the underlying mathematical modelling and its inherent assumptions, *e.g.*, boundary conditions. Upscaling is also a challenge when modelling CO₂ migration in the geosphere, especially with CO₂ in the gas phase. Modelling uncertainty can be assessed qualitatively by comparison of results from different mathematical models, via *benchmarking exercises* [*e.g.*, Pruess *et al.*, 2003], which are recommended to enhance modelling credibility and confidence.
- **Scenario/event uncertainty**: concerning whether all scenarios/events representing hazards have been identified.

Specific uncertainties relevant to CCS-related projects concern particularly:

- **Wellbore locations and wellbore characteristics**: A number of authors have identified wellbores as a key area of uncertainty [*e.g.*, Espie 2005; Zhou *et al.*, 2005b]. The number of wells may be well defined in regions with good datasets, but less so in other areas. Substantial uncertainty is also associated with the timeframes for well-bore degradation processes, including geo-mechanical damage, hydro-chemical damage, and chemical degradation of cement or steel [Moreno and Chalaturnyk, 2005].

COMMENT: *There are many uncertainties in natural systems and a number of techniques can be used to address these uncertainties – probability/statistical analysis, best-known numerical values from empirical or experimental work, and expert*

judgment. The adequacy of a RA will depend to what extent the above types of uncertainty are addressed in assessment calculations.

12.6 Role of Monitoring in RA

Monitoring has been, and continues to be, a major aspect of geological CO₂ storage projects, although not all modelling is linked to RA needs. Monitoring and detection of CO₂ leakage to the surface / near surface are key to ensuring safety and effectiveness of geological CO₂ storage.

In the context of RA, monitoring can be used to:

- Provide baseline data, which, as well as providing data that can help to distinguish project-related CO₂ releases from background, can be used as initial conditions to RA model input.
- Verify and validate modelling predictions concerning (short-term) CO₂ migration, thereby helping to calibrate long-term predictions of RA models (see, for example, note under *Figure I-13*). Given the long timescales associated with modelling and its predictions, the challenge for short-term monitoring results, *e.g.*, over several years, is to be able to provide acceptable verification.

Many monitoring techniques are site dependent, such as offshore, onshore, shallow, or deep formations. Pearce *et al.* [2005] provide a good summary of monitoring techniques (see *Figure I-14*) and Benson *et al.* [2004] discuss specific applications (see *Table I-1*). The information included in these tables indicates that all of the techniques can provide some indirect input to RA modelling and analysis. In this regard, detection limits will often determine which techniques are appropriate.

COMMENT: Monitoring will play a key role at all stages of CCS projects – during pre-injection, injection, and post-injection. A variety of monitoring techniques are available in support of RA, and which technique(s) to use will depend largely on detection limits, the need for minimal intrusion at storage reservoir, and cost. A primary role for such monitoring will be to verify and validate modelling predictions.

			Onshore only	Onshore and Offshore	Offshore only	Primary use	Secondary use	
Seismic	Acoustic imaging	3D/4D surface seismic						
		Time-lapse 2D surface seismic						
		Multicomponent seismic						
		Boomer / Sparker						
		High resolution acoustic imaging						
	Well-based	Microseismic monitoring						
		4D crosshole seismic						
Sonar Bathymetry		Sidescan sonar						
		Multi-beam echo sounding						
Gravimetry		Time-lapse surface gravimetry						
		Time-lapse well gravimetry						
Electrical- / Electro-magnetic (EM)		Surface EM						
		Seabottom EM						
		Crosshole EM						
		Permanent borehole EM						
		Crosshole ERT						
		ESP						
Fluids	<i>Downhole / Springs</i>	Downhole fluid chemistry						
		pH measurements						
		Tracers						
	<i>Marine</i>	Seawater chemistry						
		Bubble stream chemistry						
		Gases	<i>Atmosphere</i>	Short closed path (NDIR & IR lasers)				
				Short open path (IR diode lasers)				
				Long open path (IR diode lasers)				
			Eddy covariance					
			<i>Soil gas</i>	Gas flux				
Gas concentrations								
Ecosystems		Ecosystem studies						
Remote sensing		Airborne hyperspectral imaging						
		Satellite interferometry						
Others		Airborne EM						
		Geophysical logs						
		Pressure / Temperature						
		Tiltmeters						

Figure I-14: Potential CO₂ monitoring techniques and their application [from Pearce *et al.*, 2005].

12.7 Comprehensiveness of RA

Comprehensiveness in this context means to what extent a fully-integrated RA was carried out for specific CCS-related projects, or whether only a sub-component of the overall RA process was addressed.

To our knowledge, no assessment for a CCS-related project (including EOR, acid-gas injection, natural gas and pilot CO₂ storage projects) has been fully integrated (as depicted in *Figure I-15*) or has covered a broad range of end points or HS&E impacts¹⁰. Only selected impacts have been covered [Saripalli *et al.*, 2003; Rice, 2003 - human health and CO₂ concentrations in air; Stenhouse *et al.*, 2005b – human health, indoor air and contaminants in drinking water; Jaffe and Wang, 2003 - contaminants in drinking water]. Of these, Saripalli *et al.* [2003] discuss a number of sources of hazard in terms of acute and diffuse as they relate to CO₂ leakage to, or releases at, the surface.

¹⁰ A recent exception to this generalisation is the environmental risk assessment conducted as part of the draft EIS submission for the Gorgon Project [Chevron-Australia, 2005].



Table I-1: Monitoring approaches for geologic storage of CO₂ [from Benson *et al.*, 2004].

	Wellhead and Formation Pressure	Injection and Production Rate	Temperature	Well Logs	Fluid and Gas Composition	Seismic Geophysics	Electrical and Electromagnetic Geophysics	Gravity	Land Surface Deformation	Tilt Measurements	Airborne or Satellite Imaging	Soil Gas and Vadose Zone Monitoring	Surface Flux Monitoring	Atmospheric CO ₂ Monitoring	Micro-Seismicity
Establish baseline conditions for assessing impacts of CO ₂ storage	Y		Y	Y	Y	Y	P	P	P		P	P	P		P
Ensure effective injection controls	Y	Y	Y	Y											P
Detect location of CO ₂ plume	P	Y		P	P	Y	P	P	P	P					P
Assess integrity of shut-in, plugged or abandoned wells	P			Y	P	P					P	P	P	P	
Identify and confirm storage efficiency and processes	Y	Y		Y	P	Y	P								
Model calibration and performance confirmation – compare modelling predictions to monitoring data	Y	Y	P	Y	P	Y	P								
Detect and quantify surface seepage											P	Y	Y	Y	
Assess HS&E impacts of leakage					Y	Y	P	P	P	P	P	Y	P	P	P
Monitor micro-seismicity associated with CO ₂ injection								P	P	P					Y
Design and evaluate remediation efforts	P			P	P	Y	P				P	P	P	P	
Provide assurance and accounting for carbon trading	Y	Y				P									
Evaluate interactions or impacts with other resourcese, e.g. coal, water, oil&gas, minerals	P	P			Y	Y	P								
Settle legal disputes, e.g. due to leaks, seismic events, ground movement	P			P	P	Y	P	P	P	P	P	P	P	P	P
Assure public where visibility and transparency are of prime importance	Y	Y		P	Y	Y	P	P	P	P	P	P	P	P	P

These authors provide a summary table of consequence values for different hazards (see Table I-2), separated into severe, moderate, and low.

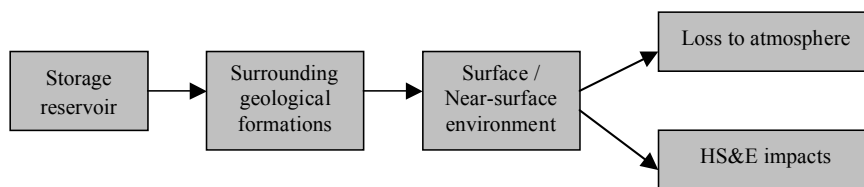


Figure I-15: Elements of RA integration.

Table I-2: Consequence value table for various hazards [Saripalli *et al.*, 2003].

MEDIA*	CONSEQUENCES		
	Severe [1]	Moderate [0.5]	Low [0.1]
Air (280 ppm)	Lethal, habitat loss (>10%)	Injuries (>5%)	Discomfort (> 1%)
Buildings (280 ppm)	Injury, evacuation (>5%)	Irritation, discomfort (>2%)	Noticeable, no harm (>1%)
Groundwater (10 ⁻⁴ M or 0.2%)	Acidity, well corrosion, irrigation loss (> 6%)	Mild acidity and corrosion (> 2%)	Elevated, low acidity without significant impacts (>0.2%)
Surface water (10 ⁻⁵ M; 0.022%)	Acidity, CO ₂ explosion, fish kills (>2%)	Higher acidity, mild toxicity; Effect on irrigation (>1%)	Elevated, low acidity with no significant impacts (>0.022%)
Soils (1-2%)	Low pH, tree kills, animal deaths (>8%)	Moderate acidity, tree/crop/soil cover loss (>3%)	Mild suppression in pH with no significant impacts (>2%)
Biota (10 ⁻⁵ M)	O ₂ depletion, lethal (>4%)	Injure life functions (>2%)	Mild toxicity (>0.5%)

NOTE: *: Normal concentration shown for each type of media within ().

(X) is concentration of CO₂; [X] is magnitude of consequence as used in their computer model to assess risk.

Assessments for CCS-related projects have typically focussed on:

- *Storage performance*, *i.e.*, identifying how much CO₂ will migrate away from the storage reservoir [*e.g.*, Weyburn - Zhou *et al.*, 2005a; Walton *et al.*, 2005; Sleipner - Arts *et al.*, 2004].
- *Specific aspects of CO₂ migration and leakage*, Evaluation of one component, or a subset of the storage system, *e.g.*, covering geo-mechanical processes, caprock integrity, well-bore leakage processes, geochemical modelling, CO₂ build-up in the near-surface, or specific environmental impacts.

COMMENT: *To date, a fully-integrated RA, which links CO₂ leakage from the storage reservoir to an evaluation of end-points such as HS&E impacts has not been carried out for CCS-related projects. On the other hand, CCS technology is still under development and there is not yet a full understanding of all of the processes that can lead to harmful impacts, and how to model all of these processes. Such an integrated approach will help to increase confidence with stakeholders, including regulators and the general public.*

12.8 Role of Natural and Industrial Analogues in RA

Natural analogues (NA) have several roles to play in RA, *viz.*

- Provide evidence of the existence/stability of natural CO₂ reservoirs, *i.e.*, proof of concept [IEA, 2005; Bradshaw *et al.*, 2005; Baines and Worden, 2004], Good examples of natural CO₂ storage reservoirs exist [Stevens *et al.*, 2005; Streit and Watson, 2005], which can help to identify geologies that are suitable for long-term CO₂ storage (*Figure I-16*). Oil and gas fields, for example, are



often highlighted as examples of reservoirs that have been able to contain hydrocarbon accumulations for geological time periods, *i.e.*, millions of years.

- In cases where there are natural occurrences and leakages/releases of CO₂, identify the characteristics of leakage pathways, as well as describing the associated impacts, if any [EC, 2005].
- Provide measurable CO₂ leakage rates/fluxes in systems that can be modelled quantitatively, thereby validating predictive modelling results. Unfortunately, the number of NA examples in this category is limited, although Streit and Watson [2005] have attempted to provide illustrative leakage rates from different geological storage reservoirs throughout the world.

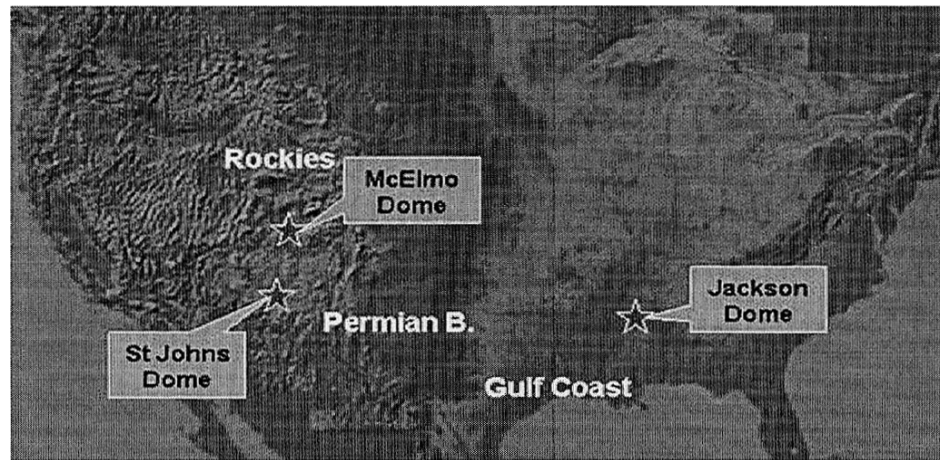


Figure I-16: Evidence of long-term CO₂ storage -- three natural CO₂ fields in the USA [from Stevens *et al.*, 2005].

The first two categories above are particularly important for risk communication to stakeholders. NA examples have been used successfully to

- Validate geochemical modelling studies, thereby increasing confidence in long-term predictions covering hundreds to thousands of years [Gaus *et al.*, 2005]
- Identify mechanisms that result in CO₂ retention in the subsurface, *e.g.*, fluid-mineral reactions [Baines and Worden, 2004].
- Develop and demonstrate methodologies for monitoring CO₂ leakages above natural accumulations.

Benson *et al.* [2002] have provided a review of natural and industrial analogues and the lessons they can provide concerning HS&E RA for CCS-related projects, *e.g.*, investigations of natural and man-made accidents where large amount of CO₂ or natural gas are released.

COMMENT: NA serve a number of purposes linked to RA, the most quantitative purpose being the validation of predictive modelling results. In the absence of quantitative information, NA examples can be used to support risk communication with



stakeholders, by identifying geological environments that are suitable for long-term CO₂ storage, and, on the other hand, by explaining why bad sites leak.

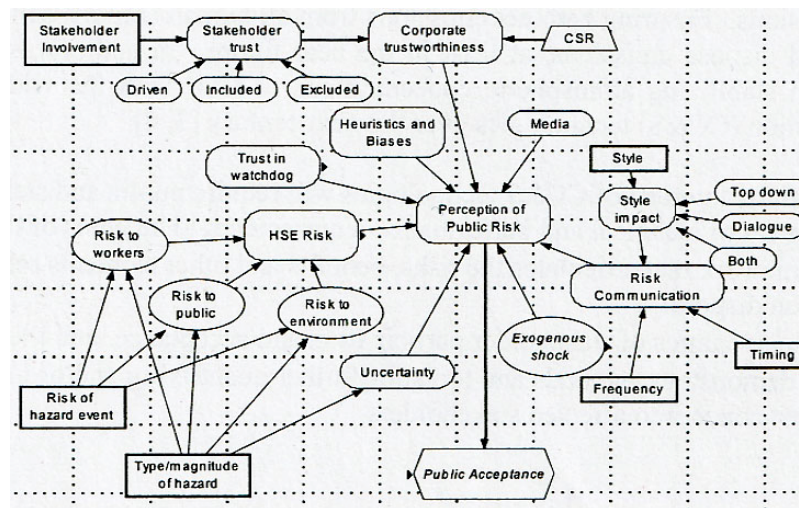
12.9 Risk Communication to Stakeholders

Key stakeholders in CCS projects include the implementers, the governing regulatory authorities, the scientific community in general, and the general public. For CCS projects to proceed successfully at the substantial scale demanded by the GGR requirement, the general public is perhaps the most important of all stakeholders. A number of authors have noted the importance of stakeholder involvement to RA, project development and the development of standards [e.g., Mahasenan *et al.* 2003 – see *Figure I-17*; Espie, 2005; Senior *et al.*, 2005].

Stakeholder involvement ranges from public outreach associated with specific projects (see *Figure I-18*), to more formal input at public hearings such as that used in the Environmental Impact Assessment (EIA) process. There was a strong stakeholder outreach component to the Mountaineer Project [Gupta *et al.*, 2003] and the Frio Brine Pilot Project [Hovorka *et al.*, 2003], including a discussion of hazards and risks that focussed on human health.

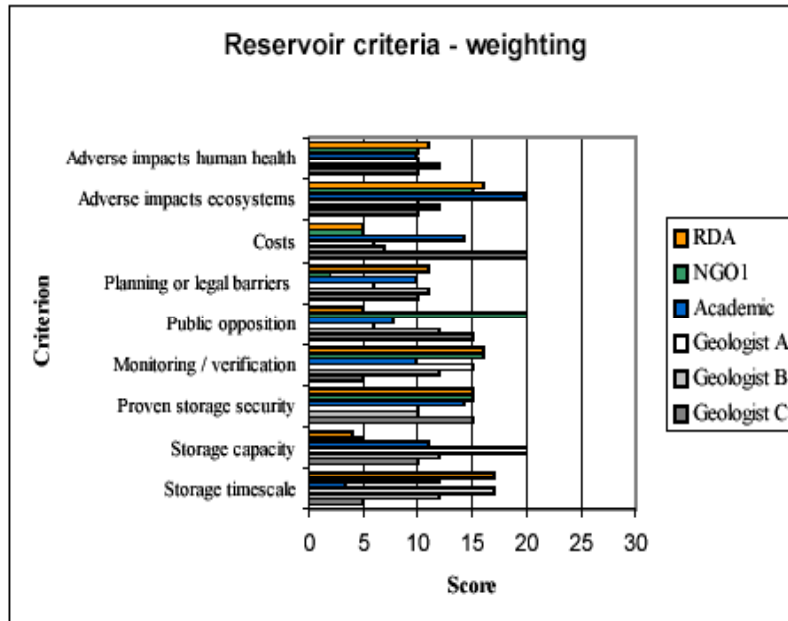
Several studies have been conducted over the past few years to assess public awareness of CCS, including public perception of risk. Key results from such studies have been:

- The need to compare geological storage with other options, not just view in isolation [Palmgren *et al.* 2005].
- Science-based information is not necessarily adequate to overcome concerns [Tokushige *et al.*, 2005].



In addition to the perceived hazards and risks associated with CCS, the authors note that other factors play a role in public perception and, hence, public acceptance; e.g., biases, trust in the various organizations involved, and media coverage.

Figure I-17: Factors affecting public perception of risk from CCS projects [from Mahasenan *et al.*, 2003.



Application of multi-criteria assessment: Different types of reservoir were rated according to a pre-established set of criteria. The diagram on the left shows the relative importance of the different criteria among participants. The overall assessment ranked oil&gas reservoirs most suitable, followed by traps within aquifers, aquifers outside traps, and onshore sites.

(RDA=Regional Development Agency)

Figure I-18: Stakeholder feedback on CCS issues [from Gough *et al.*, 2002].

COMMENT: Stakeholder acceptance, in particular public acceptance, is considered key to developing CCS projects in a timely manner, and RA is a critical component of public acceptance. All indications suggest that science-based information is not sufficient to satisfy public concerns, and other avenues of communication, e.g., natural and industrial analogues, are needed to support the science-based approach, particularly when RA techniques are not easy to communicate.

I2.10 Need for Technical Standard / Protocol

Reference to other industrial and engineering fields suggests the importance of a technical standard for RA e.g., Australian / New Zealand Standard for Risk Management [AS/NZS, 2004], Norwegian Standard for Risk Analysis [NSF, 1991]. Given the anticipated widespread application of CCS technology and the development of CCS projects in the near future, on a national and international basis, some form of technical standard or protocol would enhance progress, such as the Best Practice Manual developed within the SACS (Saline Aquifer CO₂ Storage) Project [Holloway *et al.*, 2003].

At a top-level, several risk analysis / risk management schemes [e.g., Bouchard and Delaytermoz, 2003; Espie, 2003] conform to the following:

- Characterization of the storage system and its surrounding geology;
- Identification of hazards and probability of occurrence;
- Assessment of the magnitude of their consequences;
- Monitoring plan, and
- Definition of mitigation measures.



This is not unlike the EIA process, in particular with the inclusion of monitoring and mitigation measures. The EIA process has been used in certain projects related to CO₂ storage [e.g., Koide *et al.*, 2003] and appears amenable to application to CCS projects in many countries [Stenhouse *et al.*, 2005b].

COMMENT: The RA process is not new and already exists under various regulatory frameworks. Where RA for CCS projects would differ from normal industrial and engineering projects is in the timeframes associated with geological CO₂ storage and the need to demonstrate confidence in long-term predictions.

12.11 Current Status of RA Plus Gaps / Needs

Published results on large-scale CCS-related projects, in particular CO₂ injection into the Forties and Weyburn Fields, have focused on storage performance. In this respect, predictive modelling indicates that the geology of each site is capable of containing the CO₂ for thousands of years [Le Gallo *et al.*, 2005; Zhou *et al.*, 2005; Walton *et al.*, 2005]. On the other hand, small amounts of leakage through wellbores are predicted, although the results indicate that such leakage is small – significantly less than 0.01% of the total CO₂ injected [Zhou *et al.*, 2005; Walton *et al.*, 2005].

Much work is underway in this area, however. RA was a major research focus in Phase 1 of the CCP, working on methodology development. In addition, IEA GHG has sponsored a RA network, involving participants worldwide. Besides promoting the exchange of information on RA issues, IEA GHG has organized a number of RA Workshops over the past 3 years¹¹, aimed at addressing the key concerns of those actively involved in CCS projects, and has worked to disseminate information and conclusions from these Workshops.

¹¹ British Geological Survey (BGS, Keyworth, 2002); U.K. Department of Trade and Industry (DTI, London, 2004); Netherlands Institute of Applied Geoscience (TNO, Utrecht, 2005; Lawrence Berkeley Laboratories, October 2006). Also Workshops on wellbore integrity (Houston, April 2005; Princeton University, March 2006).



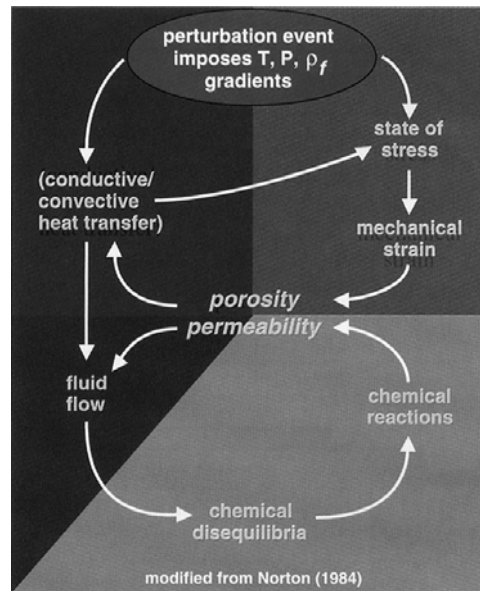


Figure I-19: Integrated thermal, hydrological, geochemical and geomechanical processes (from Johnson *et al.*, 2004).

Nevertheless, several gaps, RA needs and questions remain, the most relevant being:

- The need for integrated/coupled geochemical-geomechanical-transport modelling. While significant steps have been made in this area [*e.g.*, see Figure A19, Johnson *et al.*, 2005], there is a need for a more routine application of coupled modelling to establish the impacts of, for example, geochemical reactions which can bring about porosity and permeability changes (decreases as well as increases).
- As discussed in Section I2.7, the need for purpose-designed tools for integrated assessment covering predictions of CO₂ migration from the storage reservoir into surrounding formations, CO₂ leakage, if any, to the surface / near-surface environment, and calculation of the resultant risks (see Figure I-15).
- Improved databases to support assessment modelling, in particular for probabilistic calculations. A systematic approach to data collection and analysis is recommended, with integration of information from different geo-disciplines.
- Discussion of what can be considered to be an acceptable risk.

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