Risk Assessment, Risk Management and Remediation for the Geological Disposal of Radioactive Waste and Storage of Carbon Dioxide

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Abstract Risk assessment, risk management and remediation in the fields of geological disposal of radioactive waste (RW) and storage of carbon dioxide (CO_2) are discussed and compared. In both fields detailed site characterization is a fundamental requirement and it is necessary to consider the evolution of the system over long timescales so that natural analogues for key processes can be valuable. Some of the most important differences are:

- In RW disposal, performance assessment methods have been developed over a period of more than 2 decades, whilst for CO_2 methods for modelling the system as a whole are still at an early stage of development.
- Similarly, mature regulatory regimes are in place in most countries with deep disposal programmes for RW, but this is not the case for the geological storage of CO_2.
- The possibility of material returning to the surface in the first few decades after operations cease is much more likely for CO_2, so that monitoring will be important. If surface leakage of CO_2 is detected during this period it should be possible to sink borehole(s) to extract some of the injected CO_2.
- For RW disposal systems, engineered barriers will inevitably degrade with time, whilst for CO_2 some of the important natural barriers may actually become more effective with time. This affects the way that risk assessments are undertaken and uncertainties managed.

Keywords Risk assessment • Risk management • Performance assessment • Remediation • systems modelling

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1 Introduction

For any technology the associated risks have to be assessed and managed. In this chapter, risk assessment, risk management and remediation in the fields of geological disposal of radioactive waste (RW) and storage of carbon dioxide (CO_2) are discussed and compared.

Different waste management options are appropriate for different categories of RW. Here consideration is restricted to those wastes that require geological disposal, as these are of most direct interest when making comparisons with the geological storage of CO_2.

The risks considered here are post-operational, after an RW repository has been closed or after CO_2 injection has ceased. The focus is on the methods used; a detailed consideration of the potential impacts from radionuclides and CO_2 returning to the accessible environment is given in the chapter on environmental impacts.

The term 'risk assessment' is used with slightly different meanings in different fields. The term 'risk' itself is used in a number of different ways. As indicated by the IAEA (2003), when used quantitatively, risk is usually defined to be the product of the probability that a specified hazard will cause harm and the consequence of that harm. Risk assessment, as applied in major hazards industries, is generally applied to the analysis of accidental events that can occur to operational plants and facilities.

In RW disposal programmes, performance assessment (PA) is used to assess 'the performance of a system or subsystem and its implications for protection and safety at a planned or an authorized facility' (IAEA 2003). PA is usually applied to analysing the post-operational (post-closure) evolution of systems that depend on passive environmental controls for this function, and part of the output from a PA may be expressed in terms of risks (particularly to human health and the environment).

Although this chapter is concerned with 'risk assessment', the term will here be used to cover the same ground as considered in PAs. Further discussion of the use of PA in the field of RW disposal and its relevance to carbon capture and storage (CCS) is given by Maul et al. (2007). In that paper, priorities were suggested for the development of performance assessment methods for CO_2 storage based on areas where experience from RW disposal can be usefully applied. These included, inter alia, dealing with the various types of uncertainty, using systematic methodologies to ensure an auditable and transparent assessment process, developing whole system models and gaining confidence to model the long-term system evolution by considering information from natural systems.

Some of the key issues that are addressed in this chapter are:

1. What methods are available to assess risks from geological disposal?
2. What options are available for risk management and remediation?
3. How does the regulatory regime affect how risks are assessed and managed?
4. What are the key technical challenges to demonstrating safety and what are the priorities for further research and development?
5. What can workers in each field learn from experience gained in the other?

Background material for the two technologies is given in Sects. 2 and 3 and some comparisons between the two are made in Sect. 4. The conclusions drawn on these topics are then summarized in Sect. 5.

2 The Geological Storage of Carbon Dioxide

2.1 Hazards and Regulations

A detailed discussion of potential impacts is given in the chapter on environmental impacts, but it is worth noting here that little is known about the direct impacts of CO_2 at the levels that may be seen when it returns to the accessible environment from a storage facility (West et al. 2005). In addition, a number of indirect impacts may be important. These include formation water/brine displacement, with the potential for adverse impacts on the quality of drinking water supplies.

In enhanced oil recovery (EOR) schemes, CO_2 is injected into oil reservoirs to increase the amount of oil that can be extracted, so that the primary motivation is not the geological storage of the CO_2. Such schemes are undertaken under the regulatory regime applicable to the original extraction process, and there are no explicit requirements to assess potential environmental impacts over long timescales (Stenhouse et al. 2005a). General regulatory criteria for CCS have yet to be fully developed in most countries. Regulatory frameworks are at various stages of development (see, for example, EC 2008 and Forbes et al. 2009), but there is little experience with their implementation.

2.2 Status of the Technology

CO_2 has been routinely used for several decades for EOR in several countries, notably the Permian Basin in the US, where there were 80 such projects in 2006 (Moritis 2006), although most of the CO_2 used was extracted from natural accumulations. At the Weyburn oilfield in Saskatchewan (Wilson and Monea 2004), CO_2 produced from the North Dakota coal gasification plant is transported via pipeline and then injected. Other projects include the Sleipner gasfield in the Norwegian North Sea (Torp and Gale 2003), where naturally occurring CO_2 within the methane natural gas is separated and injected into a saline aquifer below the seabed. A similar project is also being carried out in the Algerian In Salah gasfield (Riddiford et al. 2005).

The use of CO_2 in EOR projects is well established, but few projects have so far been initiated where the primary motivation is the geological storage of CO_2. If CCS is to become a major contributor to climate change mitigation, CO_2 from power plants will need to be captured and stored. The European Technology

Platform on Zero Emission Fossil Fuel Power Plants (ZEP) programme is aiming at 10–12 demonstration plants by 2015 prior to commercially available ‘zero emission’ fossil-fired power plants in 2020 (ZEP 2006). If this technology does become extensively employed there will be a requirement for a large number of storage sites in many countries.

2.3 Natural and Industrial Analogues

There are both natural and industrial analogues for CO_2 storage (Pearce et al. 2004; IPCC 2005). Holloway et al. (2005) show that natural systems can provide important information on specific relevant processes. Natural accumulations can provide information on trapping and migration mechanisms and provide field-based testing grounds for monitoring methods. Volcanic or tectonically unstable areas can provide valuable information on leakage impacts (e.g. Beaubien et al. 2008). Natural analogues can therefore provide information that is directly relevant to risk assessments.

Industrial analogues include natural gas storage and acid gas injection, and these provide experience relevant to the risk management of the injection and closure phases of CO_2 storage schemes, although this is less relevant to the post-closure period that is the focus of this chapter.

2.4 Containment Philosophy

Figure 1 illustrates some of the general features of geologic storage systems. CO_2 is injected at depth (several hundred metres below the surface) into a reservoir formation with a caprock, which provides the most important barrier to vertical movement back towards the surface. It is possible that some projects may use a reservoir without a conventional caprock, for example CO_2 may be injected into a shallow-dipping aquifer, sufficiently far from outcrop that trapping mechanisms will prevent the CO_2 from returning to the surface. The area over which potential impacts from the injection may need to be considered could be large, with horizontal distance scales of up to about 100 km being relevant.

The principal storage reservoirs are likely to be either oil and gas reservoirs or saline aquifers. Oil- and gasfields are generally characterized by proven traps with caprocks that can retain buoyant fluids for geological timescales. As illustrated in Fig. 1, possible pathways back to the surface (indicated by the red arrows) are via a well or a fracture that passes through the caprock.

Well integrity is one of the major issues for CO_2 storage, especially in mature onshore hydrocarbon fields where the numbers of wells can be large. Particularly in the cases of old wells, records may have been lost or may be inaccurate.

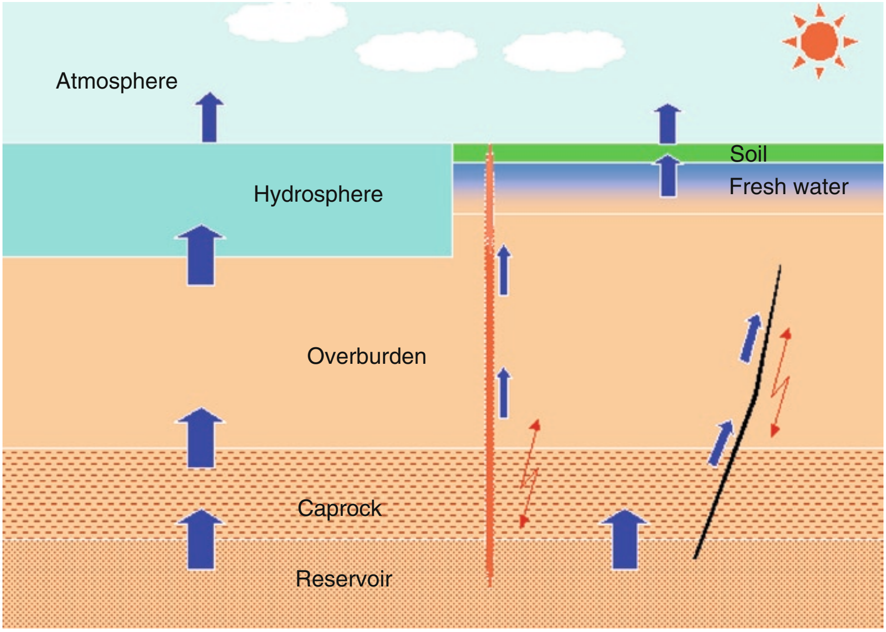

Fig. 1 Barriers and transport pathways for carbon dioxide (*see* Colour Plates)

Consequently, the existence, location or condition of wells may be unknown or uncertain.

There are a number of barriers, both physical and chemical, that can be part of the overall containment capacity of the system. In some geological settings there will be secondary seals, so that even if CO_2 is transported through the primary caprock, this may not result in transport all the way to the surface. Geochemical reactions may eventually immobilize some or all of the CO_2 and even if some CO_2 does reach the near-surface environment, there are a number of dispersive mechanisms that may result in surface fluxes being small.

2.5 *Risk Assessment*

Two different timescales of interest can be considered for risk assessments in this field. The first timescale is associated with the potential global impacts of CO_2 returning to the atmosphere. If the primary purpose of storing the CO_2 is to mitigate climate change effects, then timescales of a few centuries may be relevant (IPCC 2005), although it may be necessary to consider periods of several thousand years (Torvanger et al. 2006). The second timescale is associated with potential local impacts, which are more likely to constrain acceptable leakage rates; the relevant timescales will be determined by when such local impacts may be incurred.

Methods for assessing long-term risks are currently being developed. The Weyburn project (Wilson and Monea 2004) was amongst the first in which long-term site performance was considered (Stenhouse et al. 2005b).

Because of extensive experience in reservoir modelling in the oil and gas industries, several groups involved with assessment of the long-term fate of CO_2 have developed models based on reservoir simulation codes to investigate the transport of CO_2 (see, for example, Pruess 2004 and Rutqvist et al. 2002). There is extensive experience in this field of modelling coupled thermal, mechanical, hydraulic and chemical processes. These studies can represent the multiphase transport nature of the problem, but do not generally address in any detail the consequences in the accessible environment of potential releases from the system.

The systems approach to risk assessment is illustrated in Fig. 2, where reference is made to Features, Events and Processes (FEPs), which are different types of factors affecting the evolution of the system. It is possible to differentiate between FEPs that are external to the system (EFEPs) and those that are internal to the system. The EFEPs can combine to generate scenarios for system evolution. For example, relevant EFEPs might be associated with climate change and/or seismicity.

The system may be split up into a number of interacting subsystems and it is necessary to model all the relevant FEPs that affect the quantities of interest.

This approach has been used in other fields (particularly RW disposal) and FEP analyses have been undertaken for some CO_2 storage risk assessments (for example, Stenhouse et al. 2005b). Lewicki et al. (2007) conducted an audit of FEPs of natural systems that identified some of the key processes for CO_2 storage sites. These included secondary trapping and release in shallow reservoirs, specific events that release CO_2, faults and fractures acting as conduits for CO_2 migration and the importance of high-quality well completions.

Progress has been made in developing a generic FEP database for the geological storage of CO_2. Figure 3 shows an example entry in the FEP database described in Maul et al. (2005). The FEPs included in the database are not specific to any particular

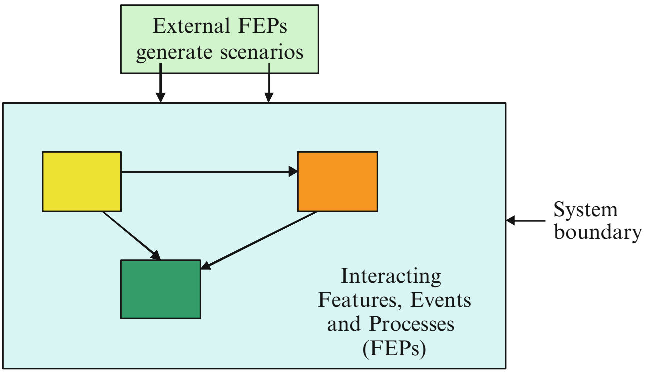

Fig. 2 Systems modelling

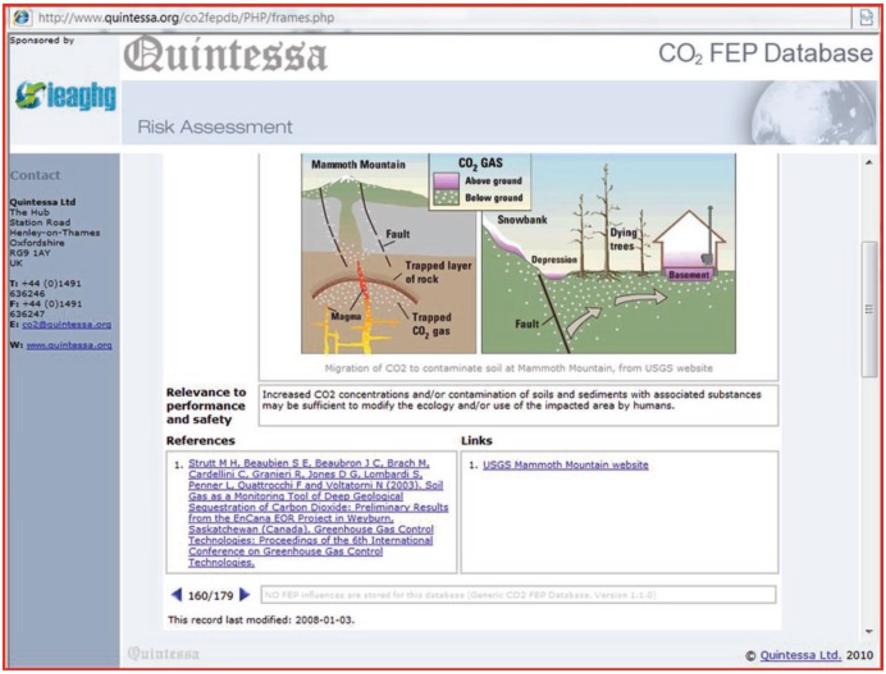

Fig. 3 An example entry in the generic FEP database (*see* Colour Plates)

model; different models will represent the FEPs in different ways, and there will not be a one-to-one correspondence between FEPs and model parameters.

This database is available through the OECD International Energy Agency (IEA) website (http://www.co2captureandstorage.info/riskscenarios/riskscenarios.htm), and has the potential to provide a basis for documenting the key sources of information. This database was originally produced in 2004, but continues to be maintained and was updated in 2008.

The development of models that satisfactorily represent the whole system remains at an early stage. With the extensive experience of detailed reservoir simulation modelling, the development of models for important specific processes, such as well leakage, and the computing power now available, most of the components required for the development of system-level models are available (see, for example, Pawar et al. 2006). The modelling and software development requirements are challenging, but not insuperable. The use of a system-level model for a natural analogue site has been demonstrated by Maul et al. (2009). Representing the potential impact of wells is one of the key challenges, and innovative methods are being developed for doing this (see, for example, Nordbotten et al. 2005).

Risk assessments may have to take account of both quantitative information from model calculations and qualitative information, for example from expert judgement. Methods for bringing these two types of information together are being developed (see, for example, Metcalfe et al. 2009).

2.6 Risk Management and Remediation

As indicated by the Intergovernmental Panel on Climate Change (IPCC 2005), risk management methods have yet to be fully demonstrated, but overall frameworks for risk management are being developed. In particular, the recent European Union Directive (EC 2008) provides such a framework, requiring, for example, that the operator should remain responsible for monitoring and undertaking any required remediation measures until responsibility for the storage site is transferred to the relevant competent authority.

The development of remote sensing techniques to detect CO_2 leakage is currently an active area of research (see, for example, Pearce et al. 2005). One way that small leakages may be detected is in changing patterns of vegetation growth. With slightly enhanced CO_2 levels crop fertilization effects may be seen, but at higher levels crop damage is seen (see, for example, Beaubien et al. 2008). There are also innovative techniques for monitoring subsurface CO_2 migration. Repeat seismic surveys have been used to monitor subsurface CO_2 at Sleipner (Arts et al. 2004) and satellite altimetry has been employed for this purpose at In Salah (Mathieson et al. 2009).

Research is also being undertaken into remediation options, including the recovery of CO_2 that has been injected if this proves to be necessary. Akervoll et al. (2009), for example, concluded that it would be possible to retrieve a significant proportion of the mobile CO_2 at Sleipner if serious problems with caprock integrity were detected.

3 Geological Disposal of Radioactive Waste

3.1 Hazards and Regulations

Despite residual uncertainties, a great deal is known about the impacts of radiation on humans and the environment (e.g. ICRP 2000), and associated regulatory criteria are well developed. Radiation doses can be calculated from human contact with radioactive materials, and a linear relationship between impacts on human beings and the radiation dose is then assumed—which is almost certainly a pessimistic assumption.

Safety criteria for RW repositories may be expressed in terms of radiation dose or risk, although the numerical values used in national regulations vary (NEA 2007). Regulatory requirements for the timescale over which quantitative PAs should be undertaken vary from country to country. There is a general acceptance that less reliance should be placed on calculations far into the future, but detailed quantitative calculations may be required for 10,000 years or longer (e.g. NEA 2007). Clearly, the long half-lives of some radioactive elements play a part in defining these assessment timescales, but long timescales are also necessary because: (1) well-located sites imply releases of contaminants only very far into the future;

and (2) ethical considerations mean that the same level of environmental protection should exist in the future as that which is applicable today.

3.2 Status of the Technology

RW disposal generally operates within national boundaries, with each state commissioning state-owned organizations to develop and implement the disposal plans and another agency to act as a regulator. The number of deep repositories in any country will be few. Deep geological disposal programmes are being developed in many countries. Examples include:

- In France, the Agence nationale pour la gestion des déchets radioactifs (ANDRA) is proposing a repository to be hosted in argillites in Meuse/Haute-Marne where an underground repository has been constructed. Granite has also been considered (ANDRA 2005).
- The US Department of Energy's (US DOE) Waste Isolation Pilot Plant (WIPP) commenced operations in 1999. The facility is located in rock salt (halite) in Texas. There is very little groundwater movement and the salt will flow to seal man-made structures in the rock to help isolate the waste (US DOE 2004).
- In Sweden, Svensk Kärnbränslehantering (SKB) is planning a deep repository in hard rock to be operational around 2020. A preliminary PA has recently been published (SKB 2006). Similar developments are being carried out in Finland.
- In Switzerland, the Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra) is considering a repository in a low permeability sedimentary host rock environment, the Opalinus Clay (Nagra 2002).

A summary of national programmes in the OECD is given in NEA (2005).

3.3 Natural Analogues

The whole concept of deep geological disposal is based on an understanding of the evolution of geological systems over long timescales, and so confidence in modelling the system is increased if information from natural systems can be used (see, for example, Miller et al. 2000). Almost all national disposal programmes are involved in natural analogue studies.

An example natural analogue site is Maqarin in Jordan (Alexander and Smellie 2002). This has enabled some aspects of models for interactions between repository host rocks and alkaline pore-fluids to be tested, which is important for repositories where cement is used. The results from this study are also relevant to understanding the long-term alteration that might occur in the rock that surrounds cement used as seals or to bond casings with the rock, in wells that penetrate a CO_2 storage site. Several other analogue studies for RW also have relevance to the geological storage of CO_2.

3.4 The Multi-Barrier Concept

A key concept in RW disposal is the multiple barrier principle, in which long-term safety is assured by a series of engineered and natural barriers (see, for example, Savage 1995).

These barriers prevent or reduce the transport of radionuclides in groundwater, which is generally the most important transport mechanism. The barriers may also influence the migration of gas (e.g. Rodwell et al. 2003). Some radionuclides, such as C-14, may be transported in the gaseous phase, which will be subject to many of the same transport processes as CO_2.

The use of multiple barriers to provide a range of safety functions is one of a number of siting and design principles that are observed in order to achieve so-called 'robust' systems. For example, at any given time in the evolution of a system, some safety functions may be 'latent', i.e. they operate only if other safety functions (unexpectedly) fail to operate. Others may be 'reserve', i.e. they may contribute positively to safety, but residual uncertainties in quantitative understanding of their contributions lead to their being omitted from conservative ('worst case') safety analyses. The relative importance of the barriers may change with time.

3.5 Risk Assessments

Significant advances have been made over the last 2 decades in PAs in this field. In particular, systematic PA methodologies help to ensure that the whole process is auditable and transparent. Figure 4 shows the stages in a typical methodology, which is based on an internationally developed methodology (IAEA 2004) for near-surface repositories, although the principles apply equally to geological disposal.

Systematic analysis of FEPs (see Sect. 2.5) that can influence radionuclide transport and the impacts of radionuclides on humans and the environment has proved to be effective for documenting and auditing PA models. The Nuclear Energy Agency FEP database (NEA 2000) has been widely used in this context.

For disposal concepts that rely on the performance of engineered barriers, the evolution of the system through coupled thermal, hydraulic, mechanical and chemical (THMC) processes can be complex (see, for example, SKB 2006). Modelling the evolution of such systems remains an area of intensive research activity.

Detailed supporting models will always be needed, for example, to investigate groundwater flows in three dimensions. However, the continuing increase in modern computing power means that the distinction between systems-level and detailed models is becoming increasingly blurred.

Probabilistic assessments are one powerful tool for investigating uncertainties and are widely used in the field of RW disposal, particularly where regulatory

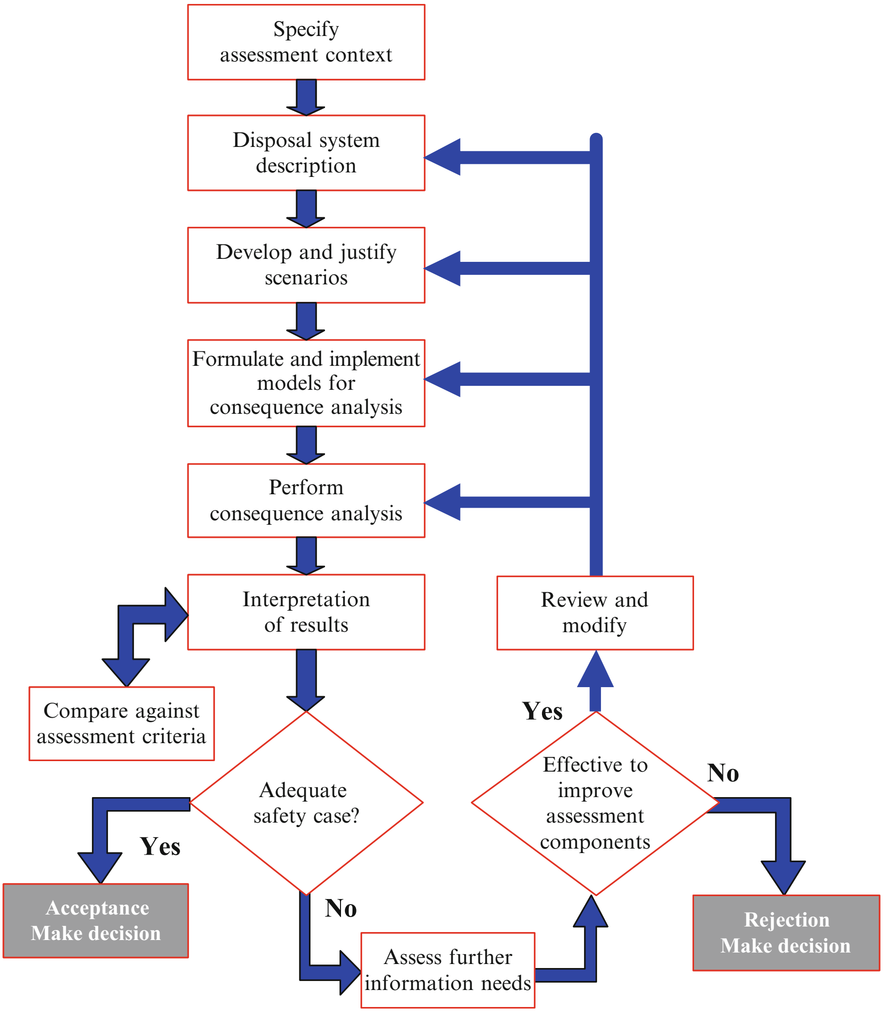

Fig. 4 A structured approach to performance assessment

criteria are expressed in terms of risk. However, experience in using these methods has highlighted a number of important problems that can arise:

- Probability density functions (PDFs) need to be defined for all input parameters, and for some of these the only way to do this is to use knowledge that experts in the field possess. Formal methods are available for using expert knowledge to elicit these (see, for example, O'Hagan et al. 2006), but this can be an extremely resource-intensive activity and it is frequently only possible to obtain such information for a few key parameters.
- The use of parameter PDFs can hide important distinctions between uncertainties due to our 'ignorance' of the system (which might change as more

information becomes available) and genuine variations due to, for example, system heterogeneities. If uncertainties and variability are not distinguished, the calculated spread in the endpoints of interest may be overestimated.
- Probabilistic assessments do not always properly represent correlations between parameters. If correlations exist, but are not properly represented, conclusions drawn from the calculated impacts may be misleading.
- Probabilistic calculations can result in counter-intuitive outputs. For example, it is possible that in admitting to a greater level of 'ignorance' in a key parameter we may actually decrease the calculated risks. This has been termed 'risk dilution' (Savage 1995).
- Probabilistic calculations can hide so much detail that the transparency of the proponent's case may be lost. The use of deterministic calculations to support conclusions drawn from probabilistic assessments can be helpful; these can be more readily reproduced by third parties and can exemplify the key features of the arguments being put forward.

3.6 Risk Management and Remediation

Some repositories are designed to facilitate the retrieval of waste over long periods, but the most important contribution to the management of risks is in the site selection process and the design of engineered barrier systems (EBSs). Measures such as restricting access to the site and the maintenance of records can be employed following repository closure, but, because of the long timescales involved, no reliance can be placed on remediation measures far into the future and the assurance of safety in regulatory criteria has to be demonstrated without human intervention.

4 Comparisons Between Technologies

4.1 Introduction

Based on the descriptions given in the previous two sections, the two technologies are compared in this section. Table 1 summarizes the key issues, and further details are then given in each case.

4.2 Basic Principles

For both RW disposal and the geological storage of CO_2 the fundamental concept is to isolate the material from the biosphere and natural resources for very long timescales. In both cases the feasibility of this approach is based on an understanding of the behaviour of natural systems, with many of the processes that affect the long-term

Table 1 Summary of technology comparisons

Issue	Geological Storage of Carbon Dioxide	Radioactive waste disposal
Basic principles	Natural processes provide isolation	Emphasis on the multi-barrier approach
Site selection and characterization	Mostly remote information, possibly supplemented by information from boreholes	Resource intensive; need to avoid natural resources
Assessment timescales	Not yet well defined, but likely to be up to several thousand years	Typically up to a million years
System evolution	Injected CO_2 may directly affect geosphere evolution	Construction of engineered barriers, but radionuclides are 'trace' contaminants
Leakage	Probability may reduce with time	Probability will generally increase with time
Risk assessments	System-level modelling methods beginning to be developed	Well established performance assessment methodologies
Regulatory regime	Generally not fully developed	Mature in most countries
Monitoring	Important for the first few decades	Required for public reassurance
Remediation	Should be feasible	Likely to be difficult

evolution of the system being the same. As discussed in Sect. 3.5, some natural analogues are relevant to both technologies.

The multi-barrier concept is emphasized in RW disposal, but can also be seen to be applicable to CO_2 storage, as a number of different barriers may operate. In the case of RW disposal, the near-field barriers are engineered, and their effectiveness will inevitably reduce with time. For CO_2 storage, borehole seals can also be considered to be engineered barriers. The respective roles of the natural and engineered barriers will depend on the type of the host rock.

4.3 Site Selection and Characterization

Detailed site characterization is a fundamental requirement for both concepts. In RW disposal the geosphere is an important barrier in the overall design concept and a detailed knowledge of the geology may be essential in order to make the safety case. Here the underground environment hosting the waste will be accessible via shafts, tunnels or drifts, but for CO_2 storage projects the amount of information will be much sparser, perhaps being limited to a few boreholes and indirect characterization such as seismic surveys. As discussed in Sect. 2, the most important features in the system for risk assessment may be abandoned wells, but it may simply not be possible to identify all such features in the area of interest as part of site characterization.

Selection of sites for the geological disposal of RWs includes avoiding locations with obvious natural resource potential. However, for CO_2 storage, it is almost inevitable that such regions will be utilized if CCS becomes a widely employed technology with possibly hundreds of storage sites in some countries.

This emphasizes that human intrusion scenarios are likely to be important in assessments for CO_2 storage.

As previously indicated, individual CO_2 storage projects may be significantly smaller in financial terms than national RW disposal programmes. This will directly affect the resources that will be appropriate for undertaking site characterization and risk assessments, subject to satisfying regulatory requirements.

4.4 Assessment Timescales, System Complexity and Uncertainty

In both cases it is necessary to consider the evolution of the system over long timescales, as materials may not return to the surface for many thousands of years (if at all). This issue has received detailed consideration by regulators in the field of RW disposal, but the regulatory regime is not yet fully developed in the field of CO_2 storage.

Because of the complexity of the natural system and the long assessment timescales, an integral part of any assessment is the management of uncertainties. Uncertainties can be categorized in a number of different ways, but one useful approach is to consider scenario, conceptual model and parameter uncertainties (e.g. Savage 1995). Scenario uncertainty reflects the fact that we can never know how the system is going to evolve in the future, and have to consider feasible examples of possible future evolutions. Conceptual model uncertainty reflects the fact that our models of natural processes will always be approximations, and that there may be several different models for the same process or groups of processes. For each model there will be uncertainty about the parameter values to use. This parameter uncertainty is, in a sense, the easiest to deal with, and there is often an over-emphasis on this type of uncertainty at the expense of inadequate consideration of the other sources. The assessment needs to demonstrate that all the different uncertainties have been addressed, and that the system performance remains satisfactory in the light of those uncertainties.

4.5 Modelling System Evolution and Material Transport

In the case of RW, radionuclides released from the near-field engineered barriers essentially act as 'trace' contaminants; they do not significantly affect the evolution of the system. On the other hand, an EBS employed in an RW repository may significantly modify the surrounding geological environment. The actual environmental changes that occur will depend upon the particular repository design and operation, which will in turn reflect the nature of the RWs. For example, where steel waste canisters are employed, corrosion may generate hydrogen gas, which might in turn influence groundwater pressures and hence flow (Rodwell et al. 2003). Another example is the emanation of an alkaline groundwater plume from a repository employing cementitious barriers. The mineralogy and porosity of the surrounding rock may be changed by reactions involving this plume.

In contrast, for CO_2 storage there would be no significant modifications to the geological environment caused by engineered systems other than boreholes, but the CO_2 itself could affect the environment. For example, CO_2 injected into deep geological strata could result in microseismic events or geochemical changes. The physical form of the CO_2 will vary with depth, as will its potential impact on system evolution. From this perspective, the technical challenge of modelling CO_2 transport may be considered to be more demanding (Pruess 2004).

Whilst there are more issues to address for the return of CO_2 to the surface ('leakage') on relatively short timescales, if this does not happen, the probability of leakage occurring may actually decrease with time as some of the natural barriers (e.g. dissolution into pore water, residual trapping and geochemical reactions with minerals) become more effective (see, for example, Benson 2005). There are, however, some processes that might lead to increased risk of leakage over time in some circumstances, notably degradation of borehole seals.

4.6 Risk Assessment Methods

As previously discussed, systematic PA methodologies are well established in the field of RW disposal, whilst the development of system-level models is at an early stage of development in the field of CO_2 storage.

4.7 Regulatory Regimes

In the field of radioactive disposal, regulatory regimes are well established in most countries that have a disposal programme. Some of these programmes have been in place for several decades. These regulatory regimes directly affect the type of risk assessment undertaken by the proponent, particularly through the specified safety requirements that have to be met.

Currently, CO_2 storage as part of EOR schemes is undertaken under the regulatory regime applicable to the original extraction process. If CCS becomes a widely employed technology with CO_2 from power plants being captured and stored, major developments in the regulatory regime will be required. It can be anticipated that the large number of demonstration plants currently planned will provide the impetus for this development.

4.8 Monitoring

Monitoring is an important aspect of the development and operation of both RW repositories and CO_2 storage sites. It is necessary to collect adequate baseline data representative of the undisturbed site, and operational and post-operational monitoring data can provide important inputs to the required assessments.

Because there will be extensive EBSs for RW, it is very unlikely that there will be releases from the repository soon after repository closure, and so surface-based monitoring is very unlikely to see radioactivity derived from the repository soon after repository closure. This does not apply to CO_2 storage where the natural barriers will be tested at an early stage. As discussed previously, if there is no short-term leakage from the host geology shortly after injection, retention processes may become more effective with time. Monitoring after operations cease is therefore likely to be an important feature of risk management for CO_2 storage. This monitoring will include the implementation of measures to detect surface leakage, but also surface-based monitoring of underground movements of CO_2, for example by carrying out repeated seismic surveys or even by using satellite altimetry. The length of time for which monitoring may be required has yet to be defined, but will depend upon the regulatory regime under which any particular project is undertaken. The period of monitoring could last for many decades following the end of operations.

4.9 Remediation

An important issue for risk management is remediation in the event that unacceptable levels of radionuclides or CO_2 are released at the surface. For a deep RW repository, remediation is highly unlikely to be required in the short term (few decades) after repository closure. Depending on the nature and extent of the contamination, some remediation techniques might be applicable, but the most effective response may be based on simply restricting human access to contaminated areas.

By contrast, if surface leakage of CO_2 is detected in the first few decades after injection has ceased, it would be possible to sink one or more boreholes to extract some of the injected CO_2 that had been injected at depth.

5 Conclusions

Given the discussion in Sects. 2–4, it is possible to summarize the conclusions that can be drawn for the key issues identified in Sect. 1. These are addressed in turn.

What methods are available to assess risks from geological disposal?

For RW disposal, systematic methods for PA have been developed over more than two decades. Radionuclide transport codes are well developed, although modelling the evolution of EBSs remains an active area of research. For CO_2 storage, extensive experience is available in reservoir modelling, but the development of methods to represent the evolution of the system as a whole over long timescales is at an early stage.

What options are available for risk management and remediation?

For both technologies the most important aspect of risk management is the selection of suitable sites. Surface-based monitoring in the first few decades after injection ceases is particularly useful for CO_2 storage, as remediation by, for example, removal of (some of) the CO_2 is a practical option on this timescale.

How does the regulatory regime affect how risks are assessed and managed?

In those countries where a risk-based criterion is used in regulations for RW disposal, this effectively requires the proponent to undertake probabilistic assessments. For CO_2 storage regulatory regimes are yet to be fully developed, and so there is scope for national and international authorities developing criteria that ensure that 'fit for purpose' risk assessments are undertaken.

What are the key technical challenges to demonstrating safety and what are the priorities for further research and development?

As discussed in Sect. 4, many of the technical challenges are similar in the two fields. In both cases it is necessary to model the evolution of a complex system over long timescales in the presence of inevitable uncertainties of different types. In the field of RW disposal regulatory criteria are frequently expressed in terms of risks as low as 10^{-6} per year. Demonstrating that this criterion is met over long assessment timescales may be challenging, depending on the host geology. If the host geology does not provide an effective barrier to radionuclide transport, then detailed information is needed in order to provide confidence in the performance of EBSs over thousands of years. Risk assessment in this field is a mature activity, but further research in the area of THMC modelling is needed for those disposal concepts that rely on the performance of the engineered barriers. For CO_2 storage, less detailed site characterization information may be available, and it may be necessary to demonstrate that consequences will be tolerable even if leakage occurs through unidentified abandoned wells. A key challenge is the development of methods that can represent all important processes in the system as a whole.

What can workers in each field learn from experience gained in the other?

Many tools that have been developed in the field of RW disposal either have been, or potentially could be, used in risk assessments of CO_2 storage. Examples include the use of generic FEP databases to audit assessment models and the use of general-purpose computer codes to enable systems-level modelling to be undertaken. Experience with the use of probabilistic methods (both good and bad) is a specific area where lessons learned in RW disposal are relevant to CO_2 storage assessments. Many of the techniques developed for reservoir modelling in the oil and gas industry are directly or indirectly relevant to the THMC modelling that needs to be undertaken in the field of RW disposal.

References

Akervoll A, Lindeberg E, Lackner A (2009) Feasibility of reproduction of stored CO_2 from the Utsira formation at the Sleipner gas field. In Gale J, Herzog H, Braitsch J (eds) Proceedings of the 9th International Conference on Greenhouse Gas Technologies. Energy Procedia, 1:2557–2564

Alexander WR, Smellie, JAT (2002) The maqarin natural analogue project (1989–1998). In Proceedings of the Eighth EC Natural Analogue Working Group Meeting European Commission Report EUR 19118 EN. European Commission, Luxembourg, pp 87–102

ANDRA (Agence nationale pour la gestion des déchets radioactifs—National Radioactive Waste Management Agency) (2005) Evaluation de sûreté du stockage géologique. http://www.andra.fr/interne.php3?id_rubrique=161

Arts R, Eiken O, Chadwick A, Zweigel P, van der Meer L, Zinszner B (2004) Monitoring of CO_2 injected at Sleipner using time-lapse seismic data. In Freund P, Kaya Y, Lior N (eds) Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies. Energy, 29:1383–1392

Beaubien SE, Ciotoli G, Coombs P, Dictor MC, Krüger M, Lombardi S, Pearce JM, West JM (2008) The impact of a naturally occurring CO_2 gas vent on the shallow ecosystem and soil chemistry of a Mediterranean pasture (Latera, Italy). In Busch A, Kühn M, Etheridge D (eds) EGU General Assembly 2007: Advances in CO2 Storage in Geological Systems—EGU (2007). International Journal of Greenhouse Gas Control, 2(3):373–387. doi: 10.1016/j.ijggc.2008.03.005

Benson SM (2005) Lessons learned from industrial and natural analogs for health, safety and environmental risk assessment for geologic storage of carbon dioxide. In: Benson SM (ed) Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results from the CO_2 Capture Project, vol 2, Geologic storage of CO_2 with monitoring and verification. Elsevier, London, pp 1133–1141

EC (European Commission) (2008) Directive on the Geological Storage of Carbon Dioxide. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0018:FIN:EN:PDF

Forbes SM, Verma P, Freedmann SJ, Curry TE, Wade SM, Venezia J (2009) WRI CCS guidelines and emerging geologic sequestration regulations: a comparative assessment. In Gale J, Herzog H, Braitsch J (eds) Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies. Energy Procedia, 1: 1759–1766

Holloway S, Pearce JM, Ohsumi T, Hards VL (2005) A review of natural CO_2 occurrences and their relevance to CO_2 storage. International Energy Agency Greenhouse Gas R&D Programme Report 05/08. IEA Greenhouse Gas R&D Programme, Cheltenham

IAEA (International Atomic Energy Agency) (2003) Radioactive Waste Management Glossary. IAEA, Vienna

IAEA (International Atomic Energy Agency) (2004) Safety Assessment Methodologies for Near Surface Disposal Facilities. IAEA-ISAM-1. IAEA, Vienna

ICRP (International Commission on Radiological Protection) (2000) Radiation protection recommendations as applied to the disposal of long-lived radioactive waste. ICRP publication 81. Annals of the ICRP, 28(4)

IPCC (Intergovernmental Panel on Climate Change) (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA (eds). Cambridge University Press, Cambridge, UK, and New York, NY

Lewicki JL, Birkholzer J, Tsang CF (2007) Natural and industrial analogues for leakage of CO_2 from storage reservoirs: identification of features, events, and processes and lessons learned. Environ Geol 52:457–467

Mathieson A, Wright I, Roberts D, Ringrose P (2009) Satellite imaging to monitor CO_2 movement at Krechba, Algeria. In Gale J, Herzog H, Braitsch J (eds) Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies. Energy Procedia, 1:2201–2209

Maul PR, Savage D, Benbow SJ, Walke RC, Bruin R (2005) Development of a FEP database for the Geological Storage of Carbon Dioxide. In: Rubin ES, Keith DW, Gilboy CF (eds) Greenhouse Gas Control Technologies: Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, vol 1. Elsevier, London, pp 701–710

Maul PR, Metcalfe R, Pearce J, Savage D, West JM (2007) Performance assessments for the Geological Storage of Carbon Dioxide: learning from the radioactive waste disposal experience. Int J Greenhouse Gas Control 1(4):444–455

Maul PR, Beaubien SE, Bond A, Limer L, Lombardi S, Pearce J, Thorne M, West J (2009) Modelling the fate of carbon dioxide in the near-surface environment at the Latera natural analogue site. In Gale J, Herzog H, Braitsch J (eds) Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies. Energy Procedia, 1:1879–1885

Metcalfe R, Maul PR, Benbow SJ, Watson CE, Hodgkinson DP, Paulley A, Limer L, Walke RC, Savage D (2009) A unified approach to performance Assessment (PA) of geological CO_2 storage. In Gale J, Herzog H, Braitsch J (eds) Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies. Energy Procedia, 1:2503–2510

Miller W, Alexander R, Chapman N, McKinley I, Smellie J (2000) Geological disposal of radioactive wastes and natural analogues. Lessons from nature and archaeology. Pergamon, Amsterdam

Moritis G (2006) CO_2 injection gains momentum. Oil Gas J 104(15):37–57

Nagra (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle—National Cooperative for the Disposal of Radioactive Waste) (2002) Project Opalinus Clay: safety report—Demonstration of the disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Technical Report 02-05. Nagra, Wettingen

NEA (Nuclear Energy Agency) (2000) Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive Waste: An International Database. OECD Nuclear Energy Agency, Paris

NEA (Nuclear Energy Agency) (2005) Radioactive Waste Management Programmes in OECD/NEA member countries. OECD Publishing, Paris

NEA (Nuclear Energy Agency) (2007) Regulating the long-term safety of geological disposal: towards a common understanding of the main objectives and bases of safety criteria. Report NEA No. 6182. OECD Nuclear Energy Agency, Paris

Nordbotten JM, Celia MA, Bachu S, Dahle HK (2005) Analytical solutions for CO_2 leakage between two aquifers through an abandoned well. Environ Sci Technol 39(2):602–611

O'Hagan A, Caitlin EB, Daneshkhah A, Eiser JR, Garthwaite P, Jenkinson D, Oakley J, Rakow T (2006) Uncertain Judgements: Eliciting Experts' Probabilities. Wiley, London

Pawar R, Carey J, Chipera S, Fessenden J, Kaszuba J, Keating G, Lichtner P, Olsen S, Stauffer P, Viswanathan H, Ziock H, Guthrie G (2006) Development of a framework for long-term performance assessment of geologic CO_2 sequestration sites. In: Røkke N, Bolland O, Gale J (eds) Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies. Elsevier, London, CD-ROM

Pearce JM, Czernichowski-Lauriol I, Lombardi S, Brune S, Nador A, Baker J, Pauwels H, Hatziyannis G, Beaubien S, Faber E (2004) A review of natural CO_2 accumulations in Europe as analogues for geological sequestration. In: Baines S, Worden RJ (eds) Geological Storage of Carbon Dioxide, vol 233, Geological society special publication. Geological Society of London, London, pp 29–41

Pearce J, Chadwick A, Bentham M, Holloway S, Kirby G (2005) Technology status review – monitoring technologies for the geological storage of CO_2. Technology Status Review Report DTI/Pub URN 05/1032. UK Department of Trade and Industry, London

Pruess K (2004) Numerical simulation of CO_2 leakage from a geologic disposal reservoir, including transitions from super- to subcritical conditions, and boiling of liquid CO_2. SPE J 9(2):237–248

Riddiford F, Wright I, Bishop C, Espie A, Tourqui A (2005) Monitoring geological storage: the In Salah gas CO_2 storage project. In: Wilson M, Morris T, Gale J, Thambimuthu K (eds) Greenhouse gas control technologies: proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, vol 2. Elsevier, London, pp 1353–1359

Rodwell WR, Norris S, Mäntynen M, Vieno T (2003) A thematic network on gas issues in safety assessment of deep repositories for radioactive waste *(GASNET)*. European Commission Report EUR 20620. European Commission, Luxembourg

Rutqvist J, Wu YS, Tsang CF, Bodvarsson G (2002) A modelling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock. Int J Rock Mech Min Sci 39(4):429–442

Savage D (ed) (1995) The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Waste. Wiley, Chichester

SKB (Svensk Kärnbränslehantering AB—Swedish Nuclear Fuel and Waste Management Company) (2006) Long-term safety for KBS-3 repositories at Forsmark and Laxemar—A first evaluation. Main report of the SR-Can project. SKB Technical Report TR-06-09. Svensk Kärnbränslehantering AB, Stockholm

Stenhouse MJ, Wilson M, Herzog H, Cassidy B, Kozak M, Zhou W, Gale J (2005a) Regulatory issues associated with deep (geological) CO_2 storage. In: Rubin ES, Keith DW, Gilboy CF (eds) Greenhouse Gas Control Technologies: Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, vol 1. Elsevier, London, pp 961–970

Stenhouse MJ, Zhou W, Savage D, Benbow S (2005b) Framework methodology for long-term assessment of the fate of CO_2 in the Weyburn field. In: Benson SM (ed) Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results from the CO_2 Capture Project, vol 2, Geologic Storage of CO_2 with Monitoring and Verification. Elsevier, London, pp 1251–1261

Torp TA, Gale J (2003) Demonstrating storage of CO_2 in geological reservoirs: the Sleipner and Sacs projects. In: Gale J, Kaya Y (eds) Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, vol 1. Pergamon, Amsterdam, pp 311–316

Torvanger A, Fuglestvedt J, Grimstadl AA, Georgescul S, Lindeberg E, Olevier ML, Rive N, Rypdal K, Skeie RB (2006) Climate impacts of leakage from geological CO_2 storage. In: Røkke N, Bolland O, Gale J (eds) Proceedings of the 8th International Conference on Greenhouse Gas Technologies. Elsevier, London, CD-ROM

US DOE (United States Department of Energy) (2004) 2004 WIPP compliance recertification Application (CRA)—Main Volume. DOE/WIPP 04-3231. Carlsbad, NM. http://www.wipp.energy.gov/library/CRA/CRA_Index.htm

West JM, Pearce JM, Bentham M, Maul PR (2005) Issue profile: environmental issues and the geological storage of CO_2. Eur Environ 15:250–259

Wilson M, Monea M (eds) (2004) IEA GHG Weyburn CO_2 monitoring and storage project: summary report 2000–2004. In Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, vol III. Petroleum Technology Research Centre, Regina

ZEP (Zero Emission Fossil Fuel Power Plants Technology Platform) (2006) A vision for zero emission fossil fuel power plants. European Commission Report EUR 22043. European Commission. Luxembourg