WHAT HAVE WE LEARNED FROM IEA GHG STORAGE ACTIVITIES

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INTERNATIONAL ENERGY AGENCY

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Executive Summary

This report summarises key learning points on CO_2 geological storage from Operating Phase 5 of the IEA Greenhouse Gas R&D Programme (IEA GHG), which commenced in 2005 and effectively coincided with the publication of the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC SRCCS). IEA GHG activities revolve mainly around contracted studies and organisation of the international research networks.

IEA GHG studies are chosen by programme members and sponsors from a wide list of proposals, ensuring those selected are focussed on topical technical issues. Study reports issued from 2005 onwards have contributed significant knowledge to major storage topics, including: regional capacity estimation; economics; environmental impact and risk assessment; well integrity and remediation of seepage; and development issues for deep saline formations.

IEA GHG has operated 3 international research networks on CO_2 geological storage since 2004/5, covering monitoring, risk assessment and wellbore integrity. A fourth network addressing subsurface modelling has been launched following a successful workshop held on this subject in February 2009. Network meetings are held on an annual basis and serve as a forum for the sharing of expert knowledge and ideas; meeting agendas are designed to maximise the time available for discussions. With the launch of a modelling network in 2009, the IEA GHG vision is for the monitoring, wellbore integrity and modelling networks discussions and outcomes to inform the risk assessment network, which should consider wider risk management issues and act as a forum for contact with regulators.

IEA GHG studies have assessed regional storage capacity for North America, Europe and the Indian Subcontinent has been undertaken. The 2008 report on the subcontinent can be regarded as 'novel' work in highlighting the significant potential for CCS in that region. Two IEA GHG studies in 2005 provided cost estimates for storage in Europe and North America, with mean reported costs per tonne in deep saline formations of €1 to €2.5 and US$13 respectively. The difference in these results reflects the European study using data from the highly permeable and relatively shallow Sleipner site. It is important to note that current technical and regulatory uncertainties provide obstacles to the meaningful prediction of CO_2 geological storage costs. IEA GHG is planning a new study on storage cost modelling in 2010 when further technical and regulatory developments have occurred.

Studies have highlighted the need for further research on environmental impact assessment in the context of CO_2 geological storage. Although there is an existing knowledge base on the effects of CO_2 on ecosystems, a number of gaps in knowledge have been highlighted. Regulatory and industry attitudes to risk assessment for CO_2 geological storage were examined in a 2007 questionnaire-based study. The study found no major discrepancies between attitudes of the two groups to risk assessment, which will provide an essential framework for the regulation of storage. Network discussions have recognised performance and impact assessments as twin components of risk assessment, which forms part of a wider risk management process that incorporates monitoring and mitigation. These discussions have also highlighted the fact that current understanding of performance assessment and environmental impacts renders quantitative risk assessment as problematic.

Integrity and remediation of CO_2 injection wells are not considered to be major technical obstacles to storage, but potential leakage from abandoned wells could be far more problematic for some storage scenarios. Research continues to focus on the effects of CO_2 on cements and other wellbore materials, however there is an increasing recognition that characterisation of pre-existing fractures and material interfaces in wells is required to understand leakage potential.

A 2008 IEA GHG study report provided a comprehensive review of development issues for deep saline formations, which are widely accepted as providing the largest theoretical CO_2 storage capacity worldwide. The report concluded that storage of CO_2 in deep saline formations can be regarded as a proven technological option. However, as highlighted in several presentations at the GHGT-9

conference in Washington DC in November 2008, further understanding of the related issues of brine displacement and pressurisation is required before widespread utilisation of these formations for storage is possible.

Major knowledge gaps and research areas in CO_2 geological storage highlighted by IEA GHG activities since 2004 include:

- Consistent global approach to methodology for capacity estimation and storage coefficients;
- Research into the related effects of pressurisation and brine displacement on storage in deep saline formations;
- Improved regional estimates for Africa, Latin America and Asia (excluding China and Japan);
- Addition of representative range of case studies to aquifer (deep saline formation) storage best practice manuals and incorporation of site characterisation procedures
- Creation of best practice manuals for other storage scenarios – depleted gas fields, CO2-EOR and ECBM;
- Improvement of cost-effective monitoring strategies, including new techniques;
- Improve long term coupled modelling of geological storage, with improved understanding of geochemical processes;
- Quantification of potential leakage rates for storage sites;
- Health impacts of CO_2 release with/without impurities – especially long term effects and thresholds;
- Management of liability and requirements for and duration of post-injection monitoring.

IEA GHG will continue to focus on these knowledge gaps, through selected studies and the continued activities of the international research networks.

1. Introduction

This report is intended to provide a summary of key learning points from recent IEA Greenhouse Gas R&D Programme (IEA GHG) activities related to the geological storage of CO_2.

The report summarises key learning points from IEA GHG operating Phase 5, which commenced in 2005 and effectively coincided with the publication of the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC SRCCS). That publication provides a useful reference point for the subsequent knowledge on storage acquired through IEA GHG activities.

IEA GHG activities fall into two main categories: technical studies, selected by programme members and sponsors from proposals drawn up by IEA GHG staff and from other sources; and three international research networks on CO_2 storage, covering the topics of monitoring, risk assessment (RA) and wellbore integrity. A fourth network on the modelling of CO_2 geological storage has been launched in February 2009, following the success of a workshop on that theme, organised jointly by IEA GHG, BRGM, Schlumberger and CO_2GeoNet.

IEA GHG studies are typically undertaken by contractors, selected through a competitive tendering process. IEA GHG studies typically involve desk-based reviews undertaken over a six month period, followed by an independent expert review process. The fact that these studies are selected from a wider list of proposals by IEA GHG members, ensures that the studies focus on topical themes and address or identify knowledge gaps.

Network activities revolve around annual meetings, with venues rotated around the world to avoid regional bias. The meetings are held over 2 to 3 days and agendas, set in advance by organising committees that include IEA GHG staff and independent technical experts drawn from both industry and academia, are designed to maximise the opportunities for discussion and debate. Network meetings are particularly effective at highlighting gaps in knowledge and research; these findings can be used to stimulate further work, including IEA GHG studies or other activities. Examples include a questionnaire-based, IEA GHG study on regulator understanding of CCS risk assessment in 2007 following a risk assessment network meeting, and the creation and maintenance of the IEA GHG Monitoring Selection Tool following discussions in the monitoring network.

Other IEA GHG activities on CO_2 geological storage include participation in practical R&D or demonstration projects, normally to assist with dissemination of results. Another important role for IEA GHG is as co-organisers and ‘guardians’ of the GHGT conference series. Some general learning points from the GHGT9 conference held in Washington DC during November 2008, have been included in this report.

2. Storage Studies

2.1 Introduction

This section summarises key learning points from IEA GHG studies on CO_2 storage completed between February 2005 and February 2009. A list of these reports is presented at the end of the section. Findings are considered mainly in the context of storage in deep saline formations (DSF, also referred to as deep saline aquifers), depleted gas fields and CO2-EOR schemes, which collectively are considered to represent the most advanced prospects for widespread storage CO_2 storage.

The key learning points set out below, are structured in terms of broad storage project phases and associated technical topics: regional assessments and storage capacity estimation; site selection and characterisation; monitoring; modelling; wellbore integrity; environmental impact assessment; risk assessment; and storage economics.

2.2 Regional Assessments and Storage Capacity Estimation

Assessment of regional storage potential can be considered in terms of both methodologies for the estimation of regional storage capacity and the actual assessments of various geographic areas. Recent IEA GHG studies have contributed to the knowledge base in both of these aspects of regional assessment.

Detailed work on methods for storage capacity estimation has been undertaken by both the CSLF and US DOE in recent years, and the 2008 IEA GHG study on DSF storage presents a discussion of these methodologies.

Estimates of regional storage capacity should always be supported by clear statements defining the methodologies and nature of assumptions employed. This allows quoted capacities to be placed in the context of techno-economic resource classification schemes – for example, the CSLF 'pyramid' shown below in Figure 1. Such an approach facilitates comparison of results from different regional studies.

DSF storage typically accounts for 90% or more of regional or global geological storage capacity according to many studies – so the underlying assumptions used for DSF storage capacity calculations have a fundamental effect on estimates of total capacity. The US DOE and CSLF approaches are computationally equivalent, although two major assumptions can cause discrepancies in capacities derived by the methodologies:

- Whether to limit capacity estimates in DSF to structural traps (favoured by CSLF) or consider entire formations (favoured by US DoE), and
- How capacity is considered in terms of storage as free-phase or dissolved-phase CO_2.

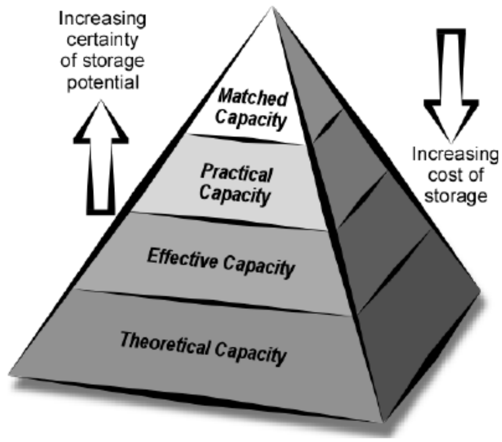

Figure 1. CSLF Resource Pyramid

IEA GHG reports have recently contributed to the worldwide picture of potential geological storage capacity with studies undertaken for North America, Europe and the Indian sub-continent. The resulting estimates, which should be regarded as 'theoretical' on the CSLF pyramid, are summarised in the table below.

2.3 Summary of IEA GHG Study Regional Storage Capacity Estimates

Storage Type	**Theoretical Regional Storage Capacity (Gt CO_2)**		
	North America	**Europe**	**Indian Subcontinent***
Deep Saline Fmns	3700	1500	Not calculated**
Depleted Gas	40	33	5.4 – 6.2
Depleted Oil/EOR	12	7.0	1.0
ECBM	65		0.35

All capacities quoted to 2 significant figures
* India, Pakistan, Bangladesh, Sri Lanka combined figures
** Not calculated due to insufficient data

The results from the 2008 study of the subcontinent are of particular note – these represent novel work in an important region with little previous assessment. In contrast, the results quoted from the 2005 studies for North America and Europe are superceded by detailed work, e.g. the US DOE Carbon Sequestration Atlas, or the EU GeoCapacity Project.

The 2008 study on DSF includes an updated world map with theoretical storage capacities:

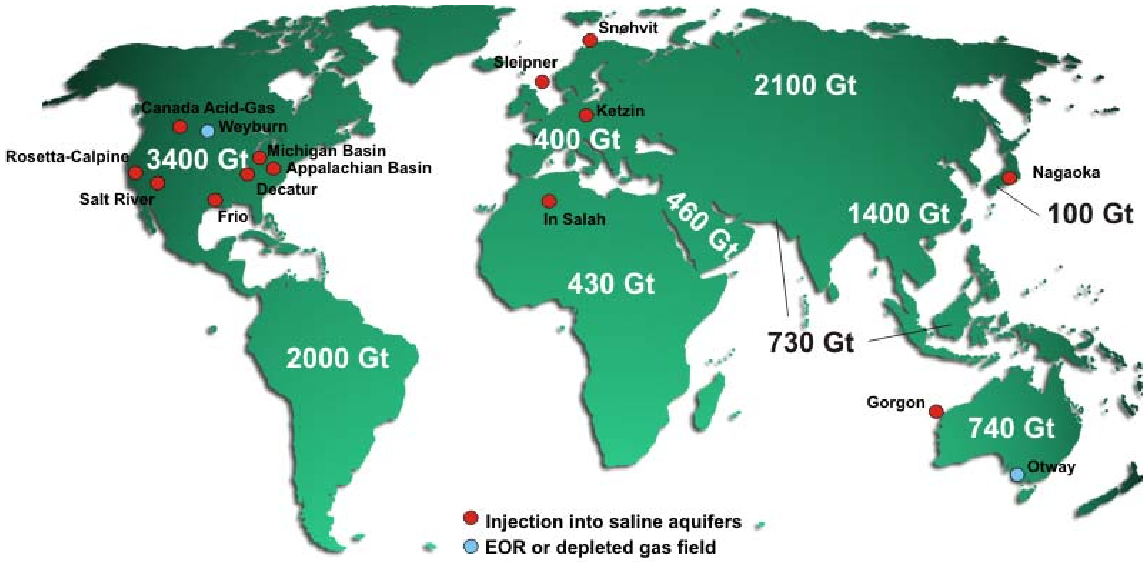

Figure 2. Map showing projects injecting or having injected CO_2 into deep saline formations. Also shown are projects in an advanced planning stage (see text for details) as well as the Weyburn and Otway pilot projects. The first-order theoretical storage capacity estimates are based on the map by (Dooley et al., 2006) and updated with values for North America (DOE, 2007a), Japan (Li et al., 2005), Brazil (Ketzer et al., 2007), and China (Li, 2007).

Key remaining knowledge gaps are identified as:

- Consistent global approach to methodology for capacity estimation and storage coefficients;
- How the related issues of over-pressurisation and brine displacement, in the context of deep saline formation storage, may affect regional storage capacity estimation;
- Improved regional estimates for Africa, Latin America and Asia (excluding China and Japan).

2.4 Site Selection and Characterisation

Site selection is of paramount importance in minimising risks associated with CO_2 geological storage and thus gaining stakeholder acceptance and regulatory approval of CCS schemes.

Both the 2005 study on experiences of the natural gas storage industry, and the 2007 study on remediation of seepage, highlighted the importance of the site selection process. Both studies considered leakage through wells as the principal risk scenario and whilst operational wells can be comprehensively engineered, abandoned wells present greater challenges for effective monitoring and remediation. Both reports therefore highlight that the storage site selection process should place great emphasis on the possible presence and condition of abandoned wells.

The 2008 study on DSF storage considers both site selection and site characterisation, the latter defined as geological evaluation on progressively more detailed scales, and fundamentally interlinked with the site selection process. Site selection can be aided by a screening process; the SACS/CO2STORE Best Practice Manual, for example, lists key geological indicators for storage site suitability. Data for the screening stage will often be sourced from existing regional geological surveys, or petroleum exploration and development records.

Geological characterisation requires a description of reservoir structure including mapping of top depth, thickness and compartmentalisation. Properties of reservoir, cap rock and overburden must also be understood. Key datasets required are summarised as:

- 2D seismic data sufficient to characterise broad reservoir structure,
- High quality 3D seismic volume for injection site and adjacent areas, with emphasis on resolution for the reservoir and overburden,
- Sufficient wells to provide representative core samples and logs.

Remaining knowledge gaps can be listed as follows:

- Addition of representative range of case studies to aquifer storage best practice manuals;
- Combining best practice and site characterisation manuals;
- Creation of best practice manuals for other storage scenarios – depleted gas fields, CO2-EOR and ECBM.

2.5 Monitoring

Monitoring of projects can be arbitrarily divided between deep-focussed techniques addressing transport and fate of CO_2 in the reservoir, and shallow/surface techniques to act as a warning system for migration to sensitive environmental receptors or the atmosphere.

Recent IEA GHG studies have not focussed on monitoring technologies, although considerable progress has been made by the international monitoring research network.

The 2008 DSF study includes a summary of monitoring undertaken at injection sites. At Sleipner, 4D seismic has been successfully deployed but this technique is relatively expensive; 4D gravity has also been shown as a useful tool for qualitative assessment. At the Frio and Nagaoka injection sites, 4D vertical seismic profiling and cross-well electromagnetics allowed quantitative tracking of the CO_2 plume.

Monitoring technologies for shallow groundwater, soil and atmosphere have been researched and developed, but still require successful demonstration.

Knowledge gaps have been identified as:

- Improvement of cost-effective monitoring strategies, including new techniques,
- Techniques that allow in-situ quantification of injected CO_2,
- Additional monitoring and verification data from injection projects.

2.6 Modelling

Modelling here is defined as the quantitative prediction of the transport and fate of CO_2 in the subsurface, caprock performance and leakage scenarios. Modelling of the wellbore environment is considered as a separate specialised topic. Predictive modelling is considered crucial as a tool for demonstrating the suitability and safety of storage projects, especially given the long timescales for which storage of CO_2 is required. Predictive modelling needs to encompass multiphase flow, geochemistry and geomechanics.

Recent IEA GHG studies have focussed on the wider risk assessment framework, of which modelling forms a component. Nevertheless, the 2008 study on aquifer storage provides considerable detail on the current status of modelling techniques.

Current numerical modelling codes can incorporate hydrodynamic, geomechanical and geochemical processes. The effects of heterogeneity, relative permeability, hysteresis, convective mixing and brine co-injection have all been the subject of recent research. Similarly, leakage scenarios have been investigated, including assessment of self-enhancing and self-limiting geochemical and geomechanical processes.

According to the 2008 study report, important knowledge gaps remain, including:

- Understanding of long term geochemical processes; modelling codes have yet to incorporate several factors including ‘reactive surface area’, the role of adsorption and ion exchange,
- Development and comparison of coupled simulation models for long term predictions (the report notes requirements for advances in upscaling of processes, and a lack of field data for calibration),
- Quantification of leakage rates through faults and fractures, utilising analogue or field data.

2.7 Wellbore Integrity

The IEA GHG 2007 study on seepage remediation lists a ‘focus on well integrity’ as one part of a five-pronged strategy to prevent and remediate seepage, recognising leakage through wells as a key risk scenario.

Loss of mechanical integrity can lead to internal and external migration through injection wells; based on comparable industries, indicative early warning factors could include monitoring of pressure, flow rate, mechanical integrity, and the use of monitoring techniques including downhole video, noise logs, temperature logs, radioactive tracers and cement bond logs. Remedial measures for injection wells could include wellhead repair, packer replacement, tubing repair, squeeze cementing, patching casing or well plugging.

Leakage from abandoned wells is more problematic. The 2007 seepage reports summarises action points as: review available records; formulate detailed plan for well intervention and remediation; perform drilling access to wellhead; assess nature of seepage; possible remediation techniques include injection of heavy brine, installation of casing patch or squeeze cementing, re-plugging according to best practice guidelines.

The 2008 aquifer study describes leakage through abandoned wells as significant, particularly at onshore locations with high concentrations of wells. Wellbore leakage raises the potential problem of CO_2 interactions with standard Portland cement and this topic has been the subject of much research effort, as reported by the IEA GHG international research network on wellbore integrity.

Research effort is also being focussed on the coupling of migration through cement and reactions within the matrix. A key factor here is the characterisation (width and permeability) of pre-existing fractures through cement, since diffusive transport of CO_2 through cement is considered to be too slow to affect integrity. A further challenge is then for reactive transport modelling simulations to match laboratory experiments and field data.

2.8 Environmental Impact Assessment

Two 2007 studies addressed environmental impacts – DNV researching overall environmental impact assessment (EIA) and BGS considering onshore impacts. A further study by Dr Rachel Dunk, on subsea ecosystem impacts, was finalised in 2008.

For the DNV study, thirteen EIA or SEA (strategic environmental assessment) frameworks from national governments or international organisations were assessed in terms of the applicability for CCS. These frameworks adopt similarly structured methodologies including phases for screening and scoping, impact assessment, management plans and monitoring programs. None of the frameworks make specific reference to CCS, which is a new technology, and most would require amendment to meet the minimum requirements of the Kyoto mechanisms (e.g. Clean Development Mechanism, CDM).

The DNV report recommended unitary international guidance incorporating EIA and Health and Safety for CCS, and such guidance should include a risk based approach for modelling of releases, inclusion of a full carbon balance, guidance on long term liability and separate procedures for abandonment.

The BGS study provided a review of available information on the effect of CO_2 on terrestrial ecosystems. The report stated that short term risks from fugitive emissions during operations would be relatively easy to identify and remediate. In contrast, greater uncertainty surrounds long term risks associated with migration and seepage from the storage reservoir. Localised effects of leakage could include: detrimental effects on human and animal health; inhibition of plant growth; alteration of bio-diversity; changes in biochemistry; and deterioration of groundwater quality.

The study found that there is a considerable wider body of knowledge of CO_2 effects on ecosystems. However, many human exposure studies have centred on healthy individuals, and studies in relation to natural analogues are affected by the presence of H_2S or SO_2 in volcanic gases. The report also highlighted a low level of current relevant research.

The 2008 report on subsea ecosystems, assessed relative potential impacts of storage leaks in relation to natural fluxes and exchanges of CO_2 which occur across the world's oceans. The report concluded that storage leaks are unlikely to cause widespread impacts, but localised impacts will depend on properties including location, duration, quantity and rate of leakage.

The studies highlighted the following knowledge gaps for EIA:

- Probabilistic quantification of impacts,
- Balancing climate change mitigation against negative local impacts,
- Health impacts of CO_2 release with/without impurities – especially long term effects and thresholds,
- Management of liability,
- Acceptable CO_2 levels for various ecosystems,
- Identification of key indicator species for subsea ecosystems.

2.9 Risk Assessment

Risk assessment (RA) provides a structured framework for the assessment of potential adverse impacts and is used in a wide variety of applications. Risk can be defined as a function of both the impact/severity of a potential hazard, and the probability of that hazard occurring. Risks can be assessed qualitatively, based solely on expert opinion and engineering judgement, or quantitatively (QRA). Deterministic or probabilistic approaches to QRA may be employed; for complex systems which need to account for variability and uncertainty, probabilistic calculations are required as deterministic QRA is may give misleading results.

The magnitude of potential impacts and consequently levels of risk, are anticipated to decline with time after injection is completed, due to the progressive trapping of stored CO_2 by secondary mechanisms including dissolution and mineralisation. These processes are likely to reduce pressure and diminish leakage potential, by decreasing the proportion of CO_2 stored as free-phase. A key challenge facing researchers is to better understand and quantify the various trapping mechanisms that determine the long-term fate of injected CO_2, allowing more accurate determination of storage capacities and better assessment of associated risks. These factors are of particular importance for DSF storage projects, where greater potential capacity must be weighed against greater levels of uncertainty.

Monitor Scientific undertook a study on behalf of IEA GHG in 2007 on the role of risk RA in the regulatory framework. This study, the need for which was identified by the IEA GHG international research network on RA, initiated dialogue with regulatory bodies concerning the application of RA to CCS. A briefing document and accompanying questionnaire was sent to actual/potential implementers and regulators of CCS projects.

The briefing document included several key messages, including the relatively long timescales that CCS projects require RA to cover, the difficulty in predicting leakage rates, and the importance of analogues (industrial/natural) and monitoring to demonstrate confidence in CCS.

Analysis of the questionnaire responses, encouragingly, showed no major discrepancies between regulator and implementer opinions. Implementers stressed the need for clear regulatory guidance, standardised RA methodologies and assessment criteria, and improved predictive modelling with support from experimental and analogue data. Regulators emphasised the importance of R&D in shaping regulatory opinion and also noted the need for leakage detection and for verification of storage capacity estimation.

The 2008 IEA GHG aquifer study provides a useful review of risk assessment approaches. The report notes the absence of a consistent risk assessment methodology for CCS projects and quotes the report of the third (2007) workshop of the international research network, which states that current knowledge would restrict meaningful RA for CCS to qualitative or semi-quantitative methodologies such as FEP (features, events, process) analysis. In particular, quantification of potential leakage rates through faults, caprocks and well bores would be required to inform QRA.

2.10 Storage Economics

Two IEA GHG studies reported in 2005 looked at the economics of CO_2 storage in North America and Europe respectively, with cost curves reporting the estimated cost per tonne of CO_2 stored. The resulting mean costs are summarised in the table below.

2.11 *Mean Estimated Storage Costs from 2005 IEA GHG Studies*

Storage Scenario	Mean Reported Storage Cost	
	Europe (€/tonne)	North America ($/tonne)
Saline aquifer	1 – 2.5	12.5
Depleted gas field	2	12.5
Depleted oil field	2	16.6
CO2-EOR	30	Not calculated
ECBM	Not calculated	9.5

The table above shows estimated storage costs from the North American study, which considered only onshore scenarios, significantly higher than those from the European study. The reason for this is that whilst the European study used injectivity data from the Sleipner site, where CO_2 is injected into the highly permeable and relatively shallow Utsira Formation, the North American study assumed lower injectivity based on trial projects from that region.

An example cost curve graph is shown below. Note the increase in storage cost with increasing total use of available storage. This pattern is replicated in all of the cost curves, and is principally due to increasing costs of wells and injection operations as progressively deeper and more problematic geological formations are utilised for storage.

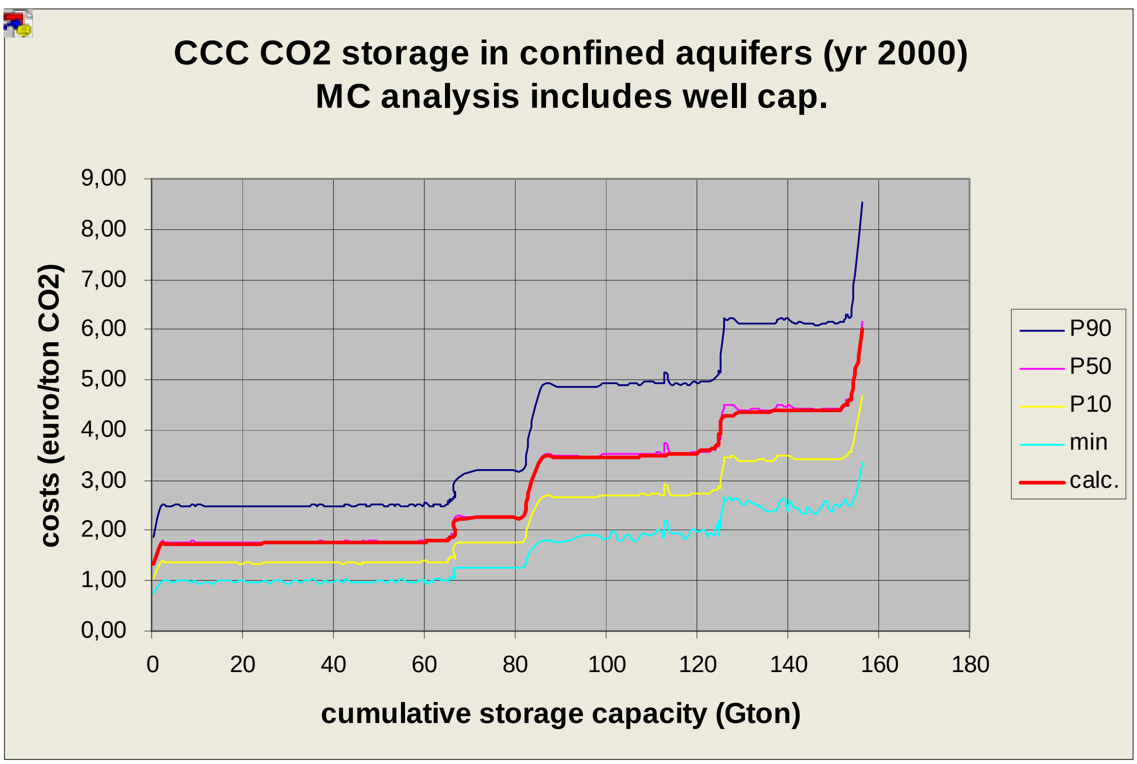

Figure 3: An example Cost Curve from the European Cost Curves IEA GHG Study.

The study also highlighted a major difference between the two regions in terms of proximity of CO_2 industrial point sources and potential storage 'sinks'. The North American study highlighted that most point sources are located within 160 km of potential storage opportunities, indicating that extensive long distance pipelines may not be required. In contrast, the majority of European storage potential lies in the North Sea, a considerable distance from point source emissions and therefore transmission/pipeline costs will have a major bearing on the economics of CCS, raising the typical cost per tonne of CO_2: as calculated by the study, from 1 to 3 Euros for storage alone, to 4 to 5 Euros for transport plus storage.

Further estimates on storage economics were presented in the 2007 IEA GHG study on remediation. This report showed that for the case study of a 1,000MW coal-fired plant operating over a 30 year period, total costs for seepage prevention, monitoring and remediation between $120m and $130m could be anticipated. This could equate to a total cost for these activities of $0.50 per tonne of CO_2 stored, as opposed to total CCS costs of $35 to $50 per tonne.

It should be noted that at present, technical and regulatory uncertainties collectively present a significant obstacle to the meaningful prediction of CO_2 storage costs, and in particular to the development of a generic storage cost calculator – a proposed IEA GHG study which has been temporarily shelved, pending the completion of current studies on storage capacity coefficients, site characterisation, injectivity, storage in depleted hydrocarbon fields and CO2-EOR. Many of these technical aspects will be addressed by current or proposed IEA GHG studies and by the work of the IEA GHG international research networks.

2.12 Remediation

The 2007 study on remediation assessed available options for seepage prevention and remediation. In addition to the remediation cost considerations described in section 2.11 above, the report examined technical options. A five part strategy was recommended:

- Site selection process
- Focus on well integrity
- Phased simulation modelling
- Comprehensive monitoring
- Establishment of contingency measures

Seepage prevention measures would include a rigorous site selection process, monitoring and well integrity logging. Remediation measures could include pumped abstraction and aeration of contaminated groundwater, soil vapour extraction processes for leakage into the vadose zone, and extraction of shallow CO_2 accumulations using directional drilling.

2.13 Conclusion

IEA GHG study reports represent a considerable body of knowledge on CCS, and recent (post 2004) studies have provided reports that serve as reference documents for key aspects of CO_2 storage science including DSF storage, regional storage in North America, Europe and India, storage economics, environmental impact and risk assessment, and remediation options for seepage.

The study reports have identified various knowledge gaps, listed below. Current and future IEA GHG studies will continue to seek to address these areas, in conjunction with the work of the international research networks. However, as noted in the recent study report on aquifer storage, geological storage of CO_2 can be successfully and safely applied today, as shown in various pilot and commercial demonstration projects around the world. Moreover, progress on areas of priority R&D requires, to a large extent, data from an increased number of large scale storage operations.

2.14 Major Knowledge Gaps Identified by IEA GHG Studies

IEA GHG studies have identified significant knowledge gaps and priority areas of future R&D for CO_2 storage projects, these are considered to include:

- Consistent global approach to methodology for capacity estimation and storage coefficients,
- Improved regional estimates for Africa, Latin America and Asia (excluding China and Japan),
- Addition of representative range of case studies to aquifer storage best practice manuals,
- Combining best practice and site characterisation manuals,
- Creation of best practice manuals for other storage scenarios – depleted gas fields, CO2-EOR and ECBM,
- Improvement of cost-effective monitoring strategies, including new techniques,
- Additional monitoring and verification data from injection projects,
- Improve long term modelling of geological storage, with improved understanding of geochemical processes,
- Quantification of potential leakage rates for storage sites,
- Probabilistic quantification of impacts,
- Balancing climate change mitigation against negative local impacts,
- Health impacts of CO_2 release with/without impurities – especially long term effects and thresholds,
- Management of liability,
- Acceptable CO_2 levels for various ecosystems.

2.15 List of IEAGHG Study Reports on CO_2 Storage 2005 - 2008

Building the Cost Curves for CO_2 Storage: European Sector. 2005/2, TNO.

Building the Cost Curves for CO_2 Storage: North America. 2005/3, Battelle.

A Review of Natural CO_2 Occurrences and Releases and their Relevance to CO_2 Storage. 2005/8, BGS.

Safe Storage of CO_2: Experience from the Natural Gas Storage Industry. 2006/2, Woodhill Frontier Ltd.

Environmental Assessment for CO_2 Capture and Storage. 2007/1, DNV.

Role of Risk Assessment in Regulatory Framework for Geological Storage of CO_2: Feedback from Regulators and Implementers. 2007/2, Monitor Scientific.

Study of Potential Impacts of Leaks from Onshore CO_2 Storage Projects on Terrestrial Ecosystems. 2007/3, BGS.

Remediation of Seepage from CO_2 Storage Formations. 2007/11, ARI.

A Regional Assessment of the Potential for CO_2 Storage in the Indian Subcontinent. 2008/2, BGS.

Aquifer Storage – Development Issues. 2008/12, December 2008.

2.16 References

The references from this section include the IEA GHG study report listed in section 2.14 above, and the following external references:

- Carbon Sequestration Leadership Forum (CSLF) Phase I Final Report from the Task Force for Review and Identification of Standards for CO_2 Storage Capacity Measurement, CSLF-T-2005-09, August 2005.
- Carbon Sequestration Leadership Forum (CSLF) Phase II Final Report from the Task Force for Review and Identification of Standards for CO_2 Storage Capacity Measurement, CSLF-T-2007-04, June 15, 2007.
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- Li et al., 2007, CO_2 geologic storage in China: potential and early opportunities, Joint Workshop on IGCC & Co-Production and CO2 Capture & Storage, Beijing, Belfer Center for Science and International Affairs.
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3 International Research Networks

3.1 Introduction

The IEA Greenhouse Gas R&D Programme (IEA GHG) has operated 3 international research networks since 2004/05, covering the topics of wellbore integrity, monitoring and risk assessment. Each network meets on an annual basis and shares presentations of new data, fresh results and key knowledge developments. The meetings include discussion sessions and are all followed by a comprehensive meeting report summarising the presentations and discussion sessions.

3.2 Wellbore Integrity

The network meetings have demonstrated that there is a sound knowledge base on wellbore integrity, with large repositories of information available from the oil and gas industries. This knowledge base includes an understanding of the potential issues with long-term integrity of wells.

Wells drilled into saline aquifer formations are likely to be purpose-built, and therefore compliant with the relevant regulations and best practices applicable, and are potentially less liable to leakage due to this fact. Additionally, there are generally fewer wells penetrating saline formations, therefore reducing the number of leakage pathways and minimising the chances of leakage.

The study of wellbore integrity in oil and gas fields is subject to a different range of issues; that of extensive historic exploitation, leading to a great number of well penetrations into the target storage formations. This results in a large number of potential leakage pathways through old, poorly abandoned or completed wells. However due to the larger quantity of data available on these fields compared with saline aquifers, there will likely be more information available on which to inform the risk assessment processes. This means that although the risks of injecting into these formations may be slightly increased, they can be more readily quantified, ensuring that reservoir suitability and site selection can be judged more effectively, and subsequently minimising risks on an individual reservoir basis.

A clear distinction must be made between old abandoned wells, newer wells which are completed / abandoned to higher standards, and new, purpose-drilled wells drilled in accordance with regulatory guidelines and best practices. Historically, drilling legislation was designed primarily to control drilling and extraction processes, and as CO_2 storage was not considered, long-term containment of buoyant CO_2 was not a concern. Wells drilled for CO_2 injection and storage will likely have to be subject to more stringent controls regarding methods of completion, and well abandonment procedures may need to be enhanced to generate greater confidence in storage operations.

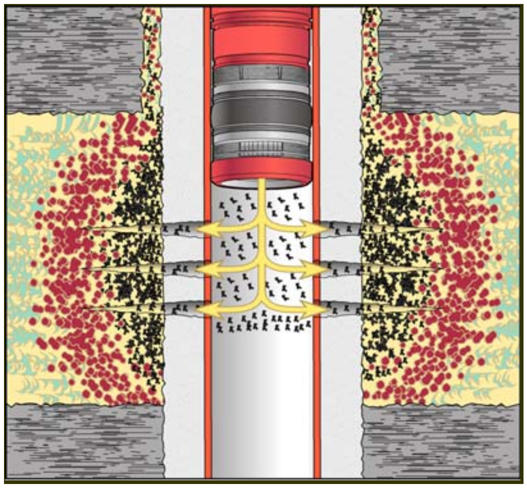

Figure 4: Demonstrating the most secure method of cased hole abandonment. This is injection of a cement into the retainer and application of pressure to squeeze the cement to form a seal at the sand face, perforations and wellbore. This ensures that the seals between the various elements of the wellbore are sealed against CO_2 ingress as effectively and securely as possible, without the wellbore being cemented to the surface.

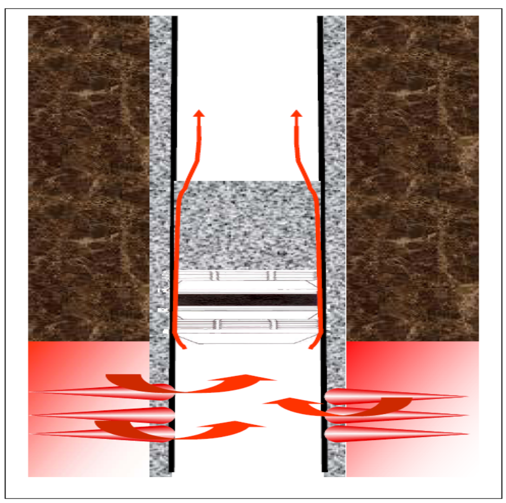

Figure 5: Illustrating a typical zonal abandonment procedure. Here, a bridge plug is installed and capped with cement. However, the seal is comparatively small and reservoir fluids can attack the metal and elastomers, which will lead to corrosion. This will eventually cause a leak of injected CO_2 to overlying parts of the formation, or the surface.

In many situations, cements and wellbore systems studied in laboratories perform to a lesser degree than those in the field. Resolution of these differences is likely to prove vital in developing high-confidence models of wellbore performance. The network has identified several contributory factors. They include: the availability and flow of water; the initial condition and curing of the cement in both the experiments and field; and the quality of well completion. A successful model should account for these differences and provide predictions that match both laboratory and field data.

The development of CO_2 resistant cements is another consideration. Although they are more expensive than standard Portland cements, CO_2 resistant cements provide improvements in wellbore integrity and subsequent reductions in wellbore failure, both of which are strong arguments for their future utilisation. Further development of resistant cements could reduce their costs and facilitate their wider use.

3.3 *Risk Assessment*

Risk assessment is generally defined as the probability of an event occurring multiplied by the impact severity. In the context of CCS, risk assessment is often defined as: 'the means of identifying, estimating or calculating and evaluating potential risks of storage to human health and safety, the environment and assets'.

Risk assessment, which is 'problem orientated', was identified by the network as part of a larger risk management framework, which focuses more on monitoring and remediation and is 'solution orientated'. A consensus was quickly reached, for CCS risk assessment and communication of results, emphasis should be placed on 'solutions' ahead of 'problems'.

The participants agreed that site characterisation would need to be a 'step wise' process, with initial pre-screening to eliminate poor prospects, allowing efforts to be concentrated on those sites with the greatest potential. Risk assessment was identified as one tool that can be used in the early screening of storage sites, and discussions highlighted that risk assessment and site characterisation both work in an iterative manner, and are involved over different project stages from preliminary screening to permitting and implementation. It was also noted that data requirements for the risk assessments increase at each progressive stage.

Natural storage analogues were discussed and identified as a means to build confidence in CCS:

- Helping geologists to understanding leakage and trapping mechanisms,
- Verification of numerical models and risk assessment procedures,
- Interpretation and risk management,
- Helping to communicate the safety of CO_2 storage sites.

Figure 6: The Latera Caldrea, an area of approximately 50 km^2, about 150 km north-west of Rome, Italy. Gas seeps occur throughout the heavily cultivated valley, where people live and farming is practised.

Risk assessment studies have provided guidance on likely seepage rates from storage sites, but not potential impacts of leakage. Environmental Impact Assessments (EIA) can provide the framework for assessment of long term impacts. However, the meeting noted there was little research underway to assess the potential effects of CO_2 leaks that could allow an EIA to be compiled and agreement was reached to address this knowledge gap.

There was consensus that risk assessment is only part of the risk management framework that needs to be given to regulators; remediation is another important issue. Delegates felt strongly that regulators need to be reassured that storage is a proven technology.

Risk assessment studies, based on 'state of the art' modelling simulations, can predict the long term fate of injected CO_2 and aim to assess potential for, and impact of, leakage in both the short and long-term. Risk studies can also assist the development of monitoring programmes for injection sites. To gain stakeholder acceptance of CCS, regulators and the wider public will need to have confidence in the predictions made by the risk assessment studies. To gain such confidence it will be necessary to understand the different approaches being used and underlying assumptions; results should be produced in an open and transparent manner, so that implications for ecosystems and human health can be fully appreciated.

The current level of understanding does not enable operators and interested parties to undertake quantitative risk assessments, and this is seen as a long term goal for research projects underway around the world.

3.4 Monitoring Network

The first network meeting determined that the largest single asset available to operators of CCS projects was the large monitoring 'tool box'. Discussions swiftly moved to technology development and the combination and integration of complementary techniques into monitoring programmes. The coupling of 3D and 2D seismic surveys, described below, is an example of this. Overall, the network has helped build confidence that the costs entailed in monitoring programmes for geological storage projects need not be prohibitive.

Seismic surveying technology has proven to be a very effective tool for the monitoring and verification of underground gas storage, as is required for CCS. The negative aspect of 3D seismic surveying is the expense associated with repeat surveys. However, it has been demonstrated that after an initial 3D seismic survey, repeat surveys can be performed as a series of 2D seismic surveys. These provide valuable information on the evolution of the subsurface plume, while minimising costs as 2D surveying techniques are considerably cheaper than comparable 3D surveys. Many other technologies can be used to great effect, and these are all included in the IEA GHG Monitoring Selection Tool, as described below.

Having identified this 'tool box' of monitoring techniques, a database was established to perform analysis of the tools available, and to identify the situations for which they are best suited. IEA GHG contracted the British Geological Society (BGS) to design and maintain a web based selection tool to create monitoring programmes for any given scenario. The finished product, known as the Monitoring Selection Tool is available on the IEA GHG website: www.co2captureandstorage.info.

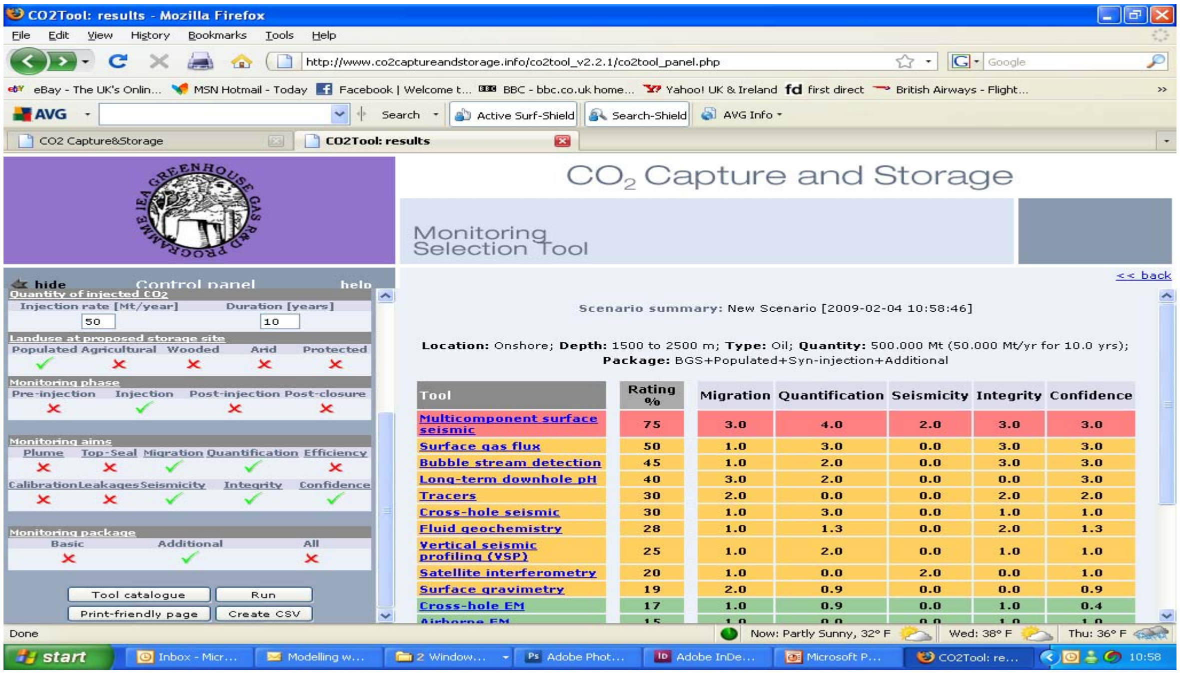

Figure 7: A screen shot of the IEA GHG Monitoring Selection Tool.

As well as industry and academia, the meetings have also attracted government representation and this has helped to foster a co-operative approach to the development of regulatory requirements for monitoring. Technical experts and regulators have worked together to lay out realistic, yet thorough, procedural guidelines for comprehensive monitoring and verification of injected gases, both deep underground and in the shallow subsurface environments.

The monitoring element of CCS activities has the potential to have a profound impact on the widespread implementation of CCS worldwide. Monitoring can provide the basis of demonstrable security of storage, and it can also play a major role in the education of local populations and the general public.

3.5 Knowledge Expansion and Confidence Building

Successful implementation of CCS schemes requires a thorough understanding of geological storage formations and the adjacent strata, and monitoring is a key requirement for confidence building amongst stakeholders, allowing demonstration of site suitability for storage and providing reassurance of safe operation through leakage detection.

Such confidence building will prove vital in taking CCS technologies from cutting-edge, pilot-scale projects and ventures, to the wide-scale implementation and commercialisation necessary to achieve significant cuts in CO_2 emissions to the atmosphere. Education of local populations and the wider public is vital for the acceptance of CCS schemes. Accountable monitoring is essential to demonstrate secure, long-term storage with minimal associated effects on local and regional ecosystems and populations.

Monitoring programmes are required to cover all phases of a project. Pre-injection monitoring techniques must establish the suitability of the storage site and determine baseline conditions prior to injection. Operational monitoring is used to determine plume evolution, calibrate predictive models and to act as an early warning mechanism for leakage from the storage formation. Post-injection monitoring is required to demonstrate successful and secure CO_2 storage, which supports the commercial objective of allowing the surrender of permits and licences.

3.6 Networks Future Focus

During discussions at a joint network meeting in New York in 2008, the value of the existing networks was confirmed by participants and consensus was reached that another 3 year period of annual meetings would be appropriate, before the next joint meeting. With the launch of the modelling network in 2009, the IEA GHG vision is for the monitoring, wellbore integrity and modelling networks discussions and outcomes to inform the risk assessment network, which should consider wider risk management issues and act as a forum for contact with regulators.

The 2008 joint network meeting also agreed technical areas of future focus for the 3 existing networks:

Wellbore Network:
- Discrepancies between laboratory and field research require investigation; if necessary, new laboratory experiments should be designed to replicate field conditions better;
- Test projects in new and existing CO_2 field sites should be initiated, to utilise recent advances in knowledge and to allow the integration of further technological advances;
- Complementary field studies should be designed with supporting laboratory tests and modelling simulations to allow the matching of theoretical and field data, and to improve confidence in modelling techniques;
- Discussions on modelling simulations should be facilitated, for example on the merits of numerical or analytical techniques; and
- Collection and analysis of industrial oil and gas field experience of wellbore integrity should be fostered.

Monitoring Network:
- Discussion of results from practical research projects as they become available: which aspects of monitoring programmes work well together?
- Integration of new techniques into the framework of the IEA GHG Monitoring Selection Tool;
- Assess the potential use of monitoring for the accurate quantification of injected $CO_{2;}$
- Focus on seismic surveys: applicability, maximisation of information derived and integration with other monitoring techniques;
- Adequacy of existing monitoring programmes and relevance to different stakeholders; and
- Duration of post-monitoring injection.

Risk Assessment Network:
- Risk assessment guidelines? – are they required and if so, what is the best way of formulating them?
- What level of confidence can be placed in modelling results generated for CCS projects?
- How long do we need to monitor for after the cessation of CO_2 injection?
- What use is the accident/worst case scenario risk assessment approach to the overall risk assessment process?

4 Conclusions

- IEA GHG activities on CO_2 geological storage revolve mainly around contracted studies and organisation of the international research networks,
- Since the publication of the IPCC SRCCS in 2005, the fifth operating phase of the IEA GHG programme has contributed to the further development of storage research,

4.1 IEA GHG Studies

- The programme members participate in a study selection and approval process, ensuring that IEA GHG studies remain focussed on topical issues related to storage,
- Study reports issued since 2004 have contributed significant knowledge to major storage topics, including: regional capacity estimation; economics; environmental impact and risk assessment; well integrity and remediation of seepage; and development issues for deep saline formations,
- Regional storage capacity assessment for North America, Europe and the Indian Subcontinent has been undertaken. The 2008 report on the subcontinent can be regarded as 'novel' work, highlighting the significant potential for CCS in that region but also some of the major barriers,
- Two IEA GHG studies in 2005 provided cost estimates for storage in Europe and North America, with mean reported costs per tonne in deep saline formations of 1 to 2.5 Euros and 13 US Dollars respectively. The difference in these results reflects the European study using data from the highly permeable and relatively shallow Sleipner site. It is important to note that current technical and regulatory uncertainties provide obstacles to the meaningful prediction of CO_2 geological storage costs,
- Studies have highlighted the need for further research on environmental impact assessment in the context of CO_2 geological storage. Although there is an existing knowledge base on the effects of CO_2 on ecosystems, a number of gaps in knowledge have been highlighted,
- Regulatory and industry attitudes to risk assessment for CO_2 geological storage were examined in a 2007 questionnaire-based study. The study found no major discrepancies between attitudes of the two groups to risk assessment, which will provide an essential framework for the regulation of storage,
- Integrity and remediation of CO_2 injection wells is not considered to be a major technical obstacle to storage, but potential leakage from abandoned wells could be far more problematic for some scenarios. Research continues to focus on the effects of CO_2 on cements and other wellbore materials, however there is an increasing recognition that characterisation of pre-existing fractures and material interfaces in wells is required to understand leakage potential,
- A 2008 study report by CO2CRC in Australia provided a comprehensive review of development issues for deep saline formations, which are widely accepted as providing the largest theoretical CO_2 storage capacity worldwide.

4.2 IEA GHG International Research Networks

- IEA GHG has operated 3 international research networks on CO_2 geological storage since 2004/5, covering monitoring, risk assessment and wellbore integrity. A fourth network addressing subsurface modelling, has been launched following a successful workshop held on this subject in February 2009,

- Network meetings are held on an annual basis and serve as a forum for the sharing of expert knowledge and ideas; meeting agendas are designed to maximise the time available for discussions,
- The wellbore integrity network has demonstrated that a significant knowledge base exists from experience in the petroleum industry,
- The existence of abandoned wells presents a major leakage pathway for many storage scenarios, particularly in onshore petroleum provinces,
- Network discussions have identified that the existence of micro-fractures and well material interfaces will govern leakage mechanisms,
- Risk assessment network meetings have allowed discussion of the inter-relationship between site characterisation, performance assessment, environmental impact assessment, risk assessment and risk management,
- Performance and impact assessments are recognised as twin components of risk assessment, which forms part of a wider risk management process that includes monitoring and mitigation,
- Natural analogues studies, and attitudes of regulators to risk assessment, are examples of two specific topics that have been debated at network meetings,
- The network has also identified that current understanding of performance assessment and environmental impacts renders quantitative risk assessment as problematic,
- The monitoring network continues to assist in the development of cost-effective monitoring strategies,
- The online Monitoring Selection Tool, maintained and updated by the BGS, is an example of an added value IEA GHG activity resulting from network discussions,
- The IEA GHG future vision for the overall network structure is for the monitoring, wellbore integrity and new modelling networks to feed discussion outcomes and into the risk assessment network, which would consider the wider risk management process and act as a forum for dialogue with regulators.

4.3 Knowledge Gaps

Major knowledge gaps and research areas in CO_2 geological storage highlighted by IEA GHG activities since 2004 include:

- Consistent global approach to methodology for capacity estimation and storage coefficients,
- Research into the related effects of pressurisation and brine displacement on storage in deep saline formations,
- Improved regional estimates for Africa, Latin America and Asia (excluding China and Japan),
- Addition of representative range of case studies to aquifer (deep saline formation) storage best practice manuals and incorporation of site characterisation,
- Creation of best practice manuals for other storage scenarios – depleted gas fields, CO2-EOR and ECBM,
- Improvement of cost-effective monitoring strategies, including new techniques,
- Improve long term coupled modelling of geological storage, with improved understanding of geochemical processes,
- Quantification of potential leakage rates for storage sites,

- Health impacts of CO_2 release with/without impurities – especially long term effects and thresholds,
- Management of liability and duration of post-injection monitoring.

5 Recommendations and IEA GHG Activities

Future research into geological storage of CO_2, including IEA GHG studies and research network activities, should be guided by the knowledge gaps identified by IEA GHG activities and summarised in this report. Current IEA GHG activities are addressing many of these gaps in a number of areas:

- A study on the use of setting and use of coefficients to refine regional storage capacity estimates has been commenced in September 2008. This study will draw on modelling and field experience from around the world and build on the output and findings of the CO2CRC report,
- The key issues of pressurisation and brine displacement for deep saline formations will be discussed in the modelling and risk assessment networks and may be the subject of a future IEA GHG study,
- Wellbore integrity issues are being addressed through a study being undertaken by TNO on behalf of IEA GHG, in addition to the ongoing work of the research network,
- Leakage scenarios will continue to be considered by the risk assessment network,
- Knowledge gaps in storage science, concerning the need for improved understanding of geochemical processes and application of coupled predictive models, will be key topics for discussion in the recently formed IEA GHG modelling network,
- IEA GHG is co-funding a study on site characterisation by DNV that aims to develop qualitative ‘best practice’ procedures, whilst a second proposed study by ARC will consider quantitative criteria,
- A study to be commissioned in 2009 will address the issues surrounding the design of injection schemes for CO_2 geological storage,
- The IEA regulators network is providing an important contribution to the rapid development of regulation in various parts of the world,
- During the GHGT9 conference in Washington, over-pressurisation of aquifers and brine displacement were highlighted as two linked, key issues that could affect the total capacity available for storage in saline aquifers. These are amongst the issues being considered by the new modelling network,
- The monitoring network will continue with the goal of assisting the development of cost-effective monitoring programmes.