Programme Area: Carbon Capture and Storage

Project: MMV FRP

Title: Executive Summary

Abstract:

Effective, but practical and economic, monitoring of CO2 storage sites is a critical part of ensuring that CO2 is safely stored, legislative requirements are met and public confidence in CCS is gained and maintained. A large amount of work is going on in the area worldwide, with experience being gained through a series of CO2 injection projects both onshore and offshore. The ETI identified development of Measurement, Monitoring and Verification (MMV) tools to meet UK requirements as a key focus area for its CCS Programme, and undertook this Flexible Research Programme (FRP) Project to identify UK needs and priorities for technology development.

Context:

This desk-based survey of UK requirements for Measurement, Monitoring and Verification (MMV) of offshore CO2 storage sites was designed to provide a clear view of the developing legislation, state of the art of MMV technologies and field experience in UK offshore applications. The study reviewed UK legislative requirements, features of likely UK storage sites and potential MMV technologies. From this, MMV technology development requirements were identified to give an understanding of the main technology gaps and to establish where ETI resources should be focused to deliver future technology development. The Project provided valuable and focused information about the technology and developing regulatory environment and identified priorities for the development of MMV technologies to meet UK requirements.

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ETI Executive Summary

Programme: Carbon Capture and Storage

Project Name: MMV Tools – UK Requirements Study

Introduction

Effective, but practical and economic, monitoring of CO_2 storage sites is a critical part of ensuring that CO_2 is safely stored, legislative requirements are met and public confidence in CCS is gained and maintained. A large amount of work is going on in the area worldwide, with experience being gained through a series of CO_2 injection projects both onshore and offshore. The ETI sought two key outcomes from this FRP Project:

- To provide a clear view of priority MMV technologies and methodologies which the ETI should consider funding;
- To provide improved understanding of what a practical monitoring plan will comprise in 'typical' UK CO2 storage projects.

The project was undertaken by British Geological Survey (BGS), supported by two subcontractors (TNO and Quintessa).

The key deliverable of the project was a comprehensive report on MMV requirements, technologies and strategies, in two Volumes. Volume 1 comprises the main part of the report: Volume 2 provides an extended review of current MMV technologies and supporting appendices. The report includes the following:

- An up-to-date synthesis of UK and EU regulatory requirements for offshore storage;
- An assessment of likely leakage fluxes based on real site measurements and scenario modelling, with respect to the sensitivity, accuracy and applicability of monitoring tools, currently available and under development;
- A review of current MMV technologies and their capabilities;
- Practical guidelines for recommended monitoring strategies for a range of potential UK offshore storage sites, to cover both qualitative ('where is it') and quantitative (eg 'how much is leaking') measurements;

- Identification of opportunities for integration of different MMV tools to reduce cost and add value to individual measurements.
- Identification and prioritisation of the key technical and methodological developments in monitoring capability which will be required to implement UK offshore storage. This is the key project outcome and will require close interfacing between technological development and regulatory requirements.

MMV Background

Figure 1 illustrates some typical features which may be found in a UK offshore storage site and the challenges MMV needs to meet.

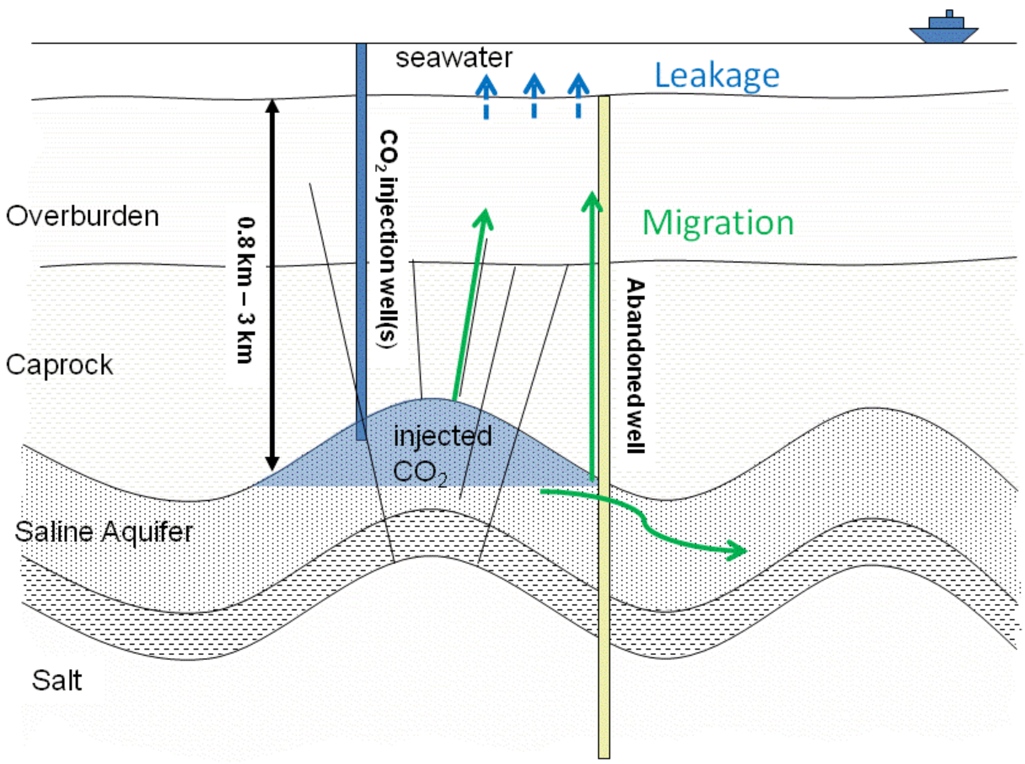

Figure 1 Typical Features in a UK Offshore Storage Site

CO2 is injected into porous rock formation deep under the sea bed, such as a depleted oil or gas reservoir or a saline aquifer. The store will have impermeable cap rock above and below it. Given the depth, the CO_2 will be in liquid or supercritical form. As it is lighter than the saline water which is likely to be in the store, it will tend to accumulate at the top of the formation. Figure 1 shows large undulations, but in many cases, the roof of potential stores may be essentially flat or have small 'lumps and bumps'. In many formations it slopes gradually upwards, possibly eventually emerging on the sea bed or even on land. Hence the first role of MMV will be to track CO_2 movement as it migrates laterally from the injection point. In the example above, CO_2 movement will be confined by the structural features in the cap rock (like an up-turned 'bucket'). In many other stores (including depleted gas wells), CO_2 will be constrained laterally by impermeable boundaries (eg caused by faulting of the rock). However in others there are no direct constraints to lateral migration. Containment then might rely on it getting caught in the 'lumps and bumps' in the roof or other mechanisms. These include trapping CO_2 in the fine pores of the structure ('residual trapping'), dissolution in the water and mineralisation. Whilst ultimately providing permanent trapping of the CO_2, these processes are slow, taking place over timescales of years, decades or even millenia. When an operator wishes to demonstrate the integrity of a site (eg as part of the licensing process for a site), they will perform reservoir modelling to justify how containment will be achieved. During operation, MMV will be required to track the CO_2 in the store and validate these models.

With any CO_2 store there are risks that CO_2 might move upwards out of the store. Figure 1 illustrates two possible scenarios. Firstly CO_2 may move around the outside of an abandoned well which penetrates the store, where the cement that seals it has degraded (the North Sea is littered with such wells). A possible (but less likely) scenario is that the CO_2 finds its way in to the well and the cap fails. The second risk area is where the cap rock has some geological faults (shown as black lines in Figure 1), through which CO_2 might penetrate. Once through the cap rock, the CO_2 can move up through the overburden to the sea bed. However, this process can take many years, the CO_2 is likely to diffuse outwards and there may be further 'traps' before it reaches the sea bed. Hence it is self-evident that if an operator needs to monitor potential leaks, there is great benefit from detecting breaches of the primary containment, as CO_2 will be at high concentration and monitoring can focus on the known potential weak-spots of a store (ie abandoned wells and faults). There is also the possibility of early remedial action.

It is worth stressing an issue of language at this point. As illustrated in Figure 1, the term **'leakage'** only refers to the point where CO_2 enters the environment, ie comes up through the sea bed. Lateral movement, penetration through the cap rock and movement through the overburden all classifies as **'migration'**.

MMV Legislation

Legislation for CO_2 storage is developing at the current time. The key pieces are:

- **OSPAR Guidelines for Risk Assessment and Management of Storage of CO2** in Geological Formations, published in 2007. This first established a framework for risk assessment and management of stores.

- **EC Directive on the geological storage of CO2**, published in 2009, provides a regulatory framework for permanent CO2 storage where the intended storage is above 100 kilotonnes. It develops the principles defined by OSPAR and provides more detail of the practical implementation of a licensing regime. The EC storage directive specifically addresses monitoring for the purposes of assessing whether injected CO2 is behaving as expected, whether any migration or leakage occurs and if this is damaging the environment or human health.

- **EC Monitoring and Reporting Guidelines (MRG)**. This is an extension of the European Trading Scheme (ETS) and cover some similar ground to the above, but in addition calls for accounting for the CO2 throughout the CCS system and demonstrating that there is 'zero leakage' from a site or measuring leakage rates if there is any.

UK legislation is likely to largely follow the EC approach: there is currently active consultation.

A key issue for legislation is how to define the 'storage complex' which will be licenced to an operator. For a fully confined store, it is relatively simple to define the volume which comprises the storage complex (although even here the pressure field caused by injection can extend way beyond the volume where storage is occurring). Where significant lateral migration might occur, it becomes more problematic (eg What happens if CO2 migrates into a neighbouring store? How much migration might be acceptable?)

Legislation allows responsibility for a site to be returned to the after injection has ceased and a suitable stabilisation period (a few 10's of years) has elapsed. Any operator will need to be clear about what its exit strategy will be and where the risks might occur. Insurance companies are already engaged with CO2 storage and it is likely that operators will be backed by soem form of insurance against the risk posed by a site.

MMV Requirements

A monitoring scheme will have two basic components: a Core Monitoring Programme and a contingent Additional Monitoring Programme.

The **Core Monitoring Programme** is designed to meet the regulatory requirements of a conforming site (i.e. one that behaves as expected). It is aimed at performance verification, the monitoring and management of any site-specific containment risks and the detection of performance irregularities including early warning of potential leakage.

The **Additional Monitoring Programme** is designed to address the requirements of a storage site that does not perform as expected. It comprises a portfolio of targeted monitoring tools held in reserve to meet the possible range of significant irregularities and the needs of any associated remediation actions. It also includes any requirement for emissions measurement under the ETS.

In relation to monitoring, an injection project can be split into four stages:

- Pre-injection - establishing baselines against which any changes can be monitored;
- Injection – ensuring that the site is behaving as expected, identifying any irregularities and informing and tracking any mitigating actions;
- Post-injection - monitoring leading to transfer of responsibility, aimed at demonstrating that the site is in (or predictably moving towards) a stable state;
- Post-transfer - monitoring after transfer of responsibility.

Each stage has its own monitoring requirements, with the injection phase being the most intensive: current assumption is that post-transfer requirements will be minimal.

Monitoring Technologies and State of Development

Monitoring techniques can be split into four basic categories. A top level summary of the techniques and requirements are shown in the table below.

Monitoring Type	Description of Techniques	State of Development
Deep focussed techniques	These are techniques such as seismic which can track CO2 presence and movement either in the reservoir itself or in the overburden. Generally these are ship-mounted. Deep focussed techniques will form a major part of almost all Core	These techniques are by and large very mature, and there is ongoing, incremental development driven by the needs of oil & gas exploration. They have mostly been tested and to a lesser or greater extent proven for

	Monitoring Strategies and Additional Monitoring Strategies (eg detecting migration of CO_2 out of the primary containment)	CO_2 monitoring.
Down hole monitoring	Measurement of a range of parameters down either dedicated monitoring wells or existing abandoned wells can provide complementary information to deep focussed techniques for both Core and Additional Programmes.	Techniques exist for pretty much any parameter (eg temperature, pressure, pH, seismic stress, fluid sampling etc etc) but there appear to be common issues around robustness, reliability and the ability to integrate sensors, both physically and analytically (data fusion).
Shallow focussed techniques	These are the techniques to detect and measure CO_2 at or near the seabed. These would usually be deployed as part of the Additional Monitoring Strategy, once an irregularity has been detected. However, baseline imaging is also likely to be needed to ensure that any 'leakage' detected was not there before injection occurred.	Some (eg seabed imaging) are mature and can be readily and cost-effectively integrated with seismic surveys. Others (eg bubble stream measurement, seabed gas sampling) are at an earlier stage of development and performance has not been fully established, particularly where quantitative measurements are required (eg measurements for ETS).
Ecosystem Modelling	This involves monitoring of flora and fauna in the marine environment to detect any effects arising from leakage. Potential requirements here are much less clear, although reference is made to this in EU legislation.	Limited work has been done to date. A key (short term) issue is that baseline monitoring will need to cover several seasons before injection commences. This was not covered in any depth in the current study.

Opportunities and Challenges for the ETI

Taking the above four areas, the opportunities can be summarised as follows.

Deep Focussed Techniques are very mature and incremental development is being driven by the oil & gas exploration industry, so opportunities for the ETI to add value are small.

Downhole Monitoring is an area where the ETI could potentially add value. Many techniques exist, but major issues remain about their operation in the required environment, with development opportunities such as increasing lifetime (to 10's of years), miniaturisation and integration of multiple probes. The key issues for the ETI are to prioritise which techniques might be best addressed and what a project might comprise: it is likely that this will require downhole testing in a real injection project, which in the medium term (ie until the DECC and other potential demonstrators become operational) would mean non-UK.

Shallow Focussed Techniques in principle offer great opportunities for development, with a range of potential techniques. However, it appears to be a busy playing field, so the question is whether there is high opportunities for ETI additionality. There is also a real issue on the requirements for these techniques. The ability to detect a diffuse leak, and discriminate from background events remains questionable, let alone get a quantified measurement for ETS. If a leak is detected from a source which has not been identified in deep focused monitoring, it might be argued that this is a failure of the latter. The ETI is now in a good place to lead the debate in this area and engage relevant stakeholders, but not commit to any projects in the short term.

Ecosystem Monitoring. This area is clearly underdeveloped: the ETI should give further consideration to this area.

Further work

Chapter 9 of the Report provides recommendations on which technologies should be considered for further development. The ETI does not fully accept these recommendations, but is using the output of the study to inform a strategic analysis of priorities for MMV technology development.

References

Measurement, Monitoring & Verification of CO2 Storage: UK Requirements - Final Report, Volumes 1 & 2. November 2010

Appendix 1: MMV Report Executive Summary

This report was prepared for a study commissioned by the Energy Technologies Institute on: Measurement, Monitoring and Verification (MMV) of CO_2 storage: UK requirements. The project was led by the British Geological Survey (BGS) and involved the Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek (TNO) and Quintessa Limited. The report consists of two volumes. Chapters 1 to 9 form the first volume, whilst Chapter 10, a review of existing technologies, is presented in Volume 2.

The main aim of the study was to identify priority technologies and methodologies which ETI could consider funding to enable effective MMV programmes to be implemented in the UK. A secondary objective was to improve understanding of MMV strategies relevant to UK offshore storage. The approach taken was to review existing monitoring methods and examine potential developments. This was done in the light of developing legislation and in the context of the range of offshore storage options available for the UK.

Chapter 2 presents an overview of the status of the regulatory requirements for monitoring storage sites in the UK. The most relevant documents are the OSPAR Guidelines, the European Commission Storage and Emissions Trading Scheme (ETS) Directives, and two Consultation Documents from the Department of Energy and Climate Change (DECC).

The OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 in Geological Formations, published in 2007, place emphasis on monitoring through all stages of a storage project from collation of baseline data to long-term post injection monitoring, for the dual purposes of detecting potential leakages and verifying that such leakage does not occur. Central to the guidelines is a Framework for Risk Assessment and Management (FRAM) which is progressively updated as new information becomes available to reduce uncertainty in site performance. Several performance criteria are also defined, largely focussed on environmental protection. OSPAR states that no storage may take place without a licence and that this requires a risk management plan. The plan should include monitoring and reporting requirements, mitigation and remediation options and a site closure plan. In terms of site closure, the guidelines also stipulate that monitoring shall continue 'until there is confirmation that the probability of any future adverse environmental effects have been reduced to an insignificant level'. Ongoing review of monitoring results is central to continued permitting.

The EC Directive on the geological storage of CO_2, published in 2009, provides a regulatory framework for permanent CO_2 storage where the intended storage is more than 100 kilotonnes. It develops the principles defined by OSPAR and provides more detail on the practical implementation of a licensing regime. The EC storage directive specifically addresses monitoring for the purposes of assessing whether injected CO_2 is behaving as expected, whether any migration or leakage occurs and if this is damaging the environment or human health.

We follow the EC Directives in defining migration as movement of CO_2 within the 'storage complex' i.e. the primary storage reservoir (the storage site) plus any surrounding secondary geological containment. Leakage is defined as the release of CO_2 from the storage complex. The ultimate expression of leakage is, therefore, emission to seawater or the atmosphere.

In the EC Storage Directive a designated 'Competent Authority' is responsible for ensuring that the operator monitors the site according to the approved monitoring plan. The monitoring plan must include continuous or intermittent monitoring for certain specified items. Monitoring results should be reported to the Competent Authority at least once a year and routine inspections are also required at least annually. To enable site closure and transfer of responsibilities, the operator should submit a post closure plan for approval by the Competent Authority. This must include a demonstration that the actual behaviour of the injected CO_2 conforms to the modelled behaviour, the absence of any detectable leakage and that the storage site is evolving towards a situation of long-term stability.

The EC Monitoring and Reporting Guidelines (MRG) (in the draft amendment to the EC directive on the ETS) cover greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide. The MRG state that a monitoring plan should be established, which should include detailed documentation of the monitoring methodology for a specific installation, including the data acquisition and data handling activities, and quality control. Emissions are taken as zero if there is no evidence for release of CO_2 to the seabed or seawater on the basis of monitoring results. However, if leakage from storage is detected, monitoring techniques should be deployed which are capable of quantifying the leakage to a specified level of uncertainty. This is the only case where the MRG demands monitoring additional to that already required by the Directive and OSPAR.

Following the publication of the EC Directive on CO_2 storage, the UK government has issued two consultations documents. The first of these was 'Towards Carbon Capture and Storage' for which responses were published in April 2009. They indicate that monitoring would be required to cover the subsurface volume affected by the CO_2 storage, rather than just the volume occupied by the CO_2 plume itself. The period before transfer of responsibility will be determined for each project individually, depending on the behaviour of the store during operation, (based on evidence from the monitoring programme). The monitoring programme will be used as the evidence base for deciding on the duration and type of post-transfer monitoring, for which a 'transfer fee' may be imposed.

The second UK consultation document, 'Consultation on the proposed offshore carbon dioxide storage licensing regime', was released in September 2009. It presents a description of how the UK CO_2 storage licensing scheme is intended to work, and seeks views on a draft of the proposed regulations for implementing the EU storage Directive and a draft licence. The Consultation proposed that the applicant must provide a proposed monitoring plan and that responsibility for the site remains with the operator during the post-closure phase of the licence until DECC is satisfied, on the basis of the monitoring reports and inspection, that the carbon dioxide within the storage site has stabilised as predicted and that permanent containment has been achieved. This suggests that closure of the site, with removal of infrastructure and sealing of the wells, would occur before handover to the authorities. Such action would restrict subsequent monitoring as wells would no longer be accessible. However, recent discussions with DECC indicate that they are considering an option to maintain monitoring wells if appropriate. Following this consultation, guidance on applications for storage licences will be issued by DECC. It is expected that this will provide further detail on the kind of information required, including plans for monitoring.

Significant gaps remain in understanding how the high-level principles set out in the regulations will be implemented at real sites, particularly involving transfer of liability following site closure.

Chapter 3 comprises a detailed examination of three actual or proposed offshore CO_2 storage sites most relevant to the development of storage in the UK offshore area. Confidential information on the proposed monitoring plan for Miller was also considered. Although details of the Miller plan are not included in the report, some aspects are reflected in the generic plans presented in Chapter 8. There is a comprehensive description of each storage site, providing:

- Background information on the site history and reasons for its selection and development.
- A description of the geological setting, the properties of the reservoir, seal and overburden and the baseline surveys carried out or proposed.
- An analysis of the risk profile, considering migration through the seal, migration into well bores, migration outside the site's licence block, and the public relations aspects of the work.
- A description of the monitoring programme put in place or proposed, covering all the monitoring methods used and highlighting any site-specific requirements.

The monitoring programme is then assessed in terms of how well it addressed the identified risks, the overall effectiveness of the methods employed in meeting other monitoring objectives, such as management of the reservoir and the injection process, and finally how well the monitoring programme would stand up in the context of current and planned regulatory requirements. Finally, consideration is given to any additional work that could have been undertaken with the benefit of hindsight.

The Sleipner storage site is located in the Norwegian sector of the North Sea and is the oldest production-scale test CO_2 storage site. Operation began in 1996 and is still active with over 11 Mt of CO_2 injected into a saline aquifer. Because operations began well before the current regulations were developed, much of the monitoring and verification framework grew out of the research experience of operating the site. The geology is well-understood from the development of the Sleipner West gas field, which provided extensive details of the reservoir properties and baseline surveys. Monitoring was designed primarily to meet a risk profile based on understanding the subsurface migration of injected CO_2. The monitoring programme uses non-invasive technologies: 2D and 3D surface seismic, seabed imaging and gravimetry, electromagnetic surveys and pressure measurement. 3D seismic and gravimetry surveys were repeated to provide time-lapse data, and pressure is monitored continuously at the wellhead. The seismic and gravity surveys were particularly effective and provide useful research insights for storage site monitoring elsewhere. It is concluded that the monitoring objectives and programme would be largely compliant with current regulatory requirements apart from explicit emissions accounting. However, as there are no indications of leakage, such monitoring would not be needed under the regulations, although it would have to form part of a monitoring plan.

The Miller Oilfield lies in the UK sector of the North Sea about 240 km north east of Peterhead and was proposed as a storage site with the injected CO_2 also providing for enhanced oil recovery (CO_2–EOR). The geological setting is well-understood from exploration and development of the oilfield. Some baseline surveys were available; however, it was proposed to carry out additional work to characterise the seabed to provide a basis for leakage and environmental monitoring. As the site did not progress beyond the proposal stage the risk profile and monitoring plans remained incomplete. The main risks considered were vertical migration and leakage around existing wells, and lateral migration into adjacent oilfields. It was intended to use reservoir simulations of injection, with the monitoring programme, to address risk mitigation and to manage the EOR. An important factor was to be co-operation with the operators of adjacent fields. The planned monitoring was more extensive than at Sleipner, with use of invasive (downhole) methods including geophysical logging, downhole pressure measurement, well fluid and geochemical logging (with tracers).

The first CO_2 storage test site in the Netherlands is at the K12-B natural gas field, in the Dutch sector of the southern North Sea. Injection tests started in 2004, and injection continues at about 20 kt per year into a depleted reservoir. The sandstone reservoir is capped by mudstone and salt – a geological setting characteristic of this part of the North Sea. Good baseline data is available and reservoir modelling has been undertaken. The risk profile acknowledges the effectiveness of the cap rock and considers upward migration to be a low risk, with any leakage restricted to loss of well integrity. The research-oriented monitoring programme was designed on this basis, with the additional objective of providing information on CO_2 flow and mixing (with methane) within the reservoir. Integrity monitoring was based on well imaging technologies and well pressure and temperature gradient profiling. Gas migration and mixing were monitored using gas and water analysis, chemical tracers and pressure profiling, with further reservoir modelling based on this data. A significant difference with other monitoring regimes was the omission of seismic surveys for reservoir imaging. These were deemed unlikely to be effective due to the small quantities of CO_2being injected into a deep reservoir below a salt caprock. The monitoring regime was assessed as good for research purposes, with a useful test of the application of reservoir modelling in the context of regulatory requirements to predict future site behaviour.

Finally the P-18 (and P-15) sites are also gas fields in the Dutch sector of the southern North Sea. They are located a few tens of kilometres offshore, are nearly depleted and could thus represent a cost-effective option for production-scale CO_2 storage. The geological setting has some similarities with K12-B, with a sandstone reservoir capped and sealed by mudstones, although here there may be more faulting. The caprock is known to be gas-tight for methane and the risk of upward migration of injected CO_2 through it is regarded as very low. Existing wellbores are however a leakage risk and there is also a possibility of fault reactivation providing leakage pathways. Unwanted lateral migration is regarded as low-risk as the structure seems to be well constrained. Monitoring plans are at a very early stage, but are being designed using current best-practice around the risk profile and within the regulatory framework. Some of the existing wells will be converted to observation wells, using a variety of downhole physical and chemical measurement methods to monitor both migration within the reservoir and to detect leakage; the observation wellbores themselves will also be monitored for leakage. Similar measurements will be made at the injection wells, as far as injection operations permit. Seismic surveys will be used to monitor migration and image the injection plume. Seabed imaging, with geochemical sampling backup, will be used to detect any subsea leakage.

Chapter 4 presents modelling work examining CO_2 leakage parameters at four different generic North Sea sites and a review of CO_2 leakage parameters from the literature.

Modelling work examined CO_2 scenarios for migration out of the main storage container at four hypothetical sites designed to cover the range of likely storage options in the UK North Sea. The site types are similar to those considered in Chapter 3 and form the basis for preparing monitoring schemes in Chapter 8. The study provided estimates of the limits and ranges of parameters that could be monitored at future CO_2 storage sites, using the results from simplified systems-level models. Parameters derived from modelling plausible scenarios can help to prioritise suitable monitoring tools and determine monitoring strategies. The sites were specified to represent the key Features, Events and Processes (FEPs), including potential migration paths likely to be encountered.

Scenarios were investigated for each site type using Quintessa's QPAC-CO_2 computer code. Important processes that can be modelled with this code include the advection of groundwater and CO_2 due to pressure and density variations, state changes caused by pressure and temperature variations, and CO_2 dissolution in groundwater. Rapid simulations at the full system scale were possible which allowed different parameter sensitivities to be explored. Values for formation water pH were calculated separately using the geochemical modelling code PHREEQC. In each case, the hypothetical leakage paths were specified to occur at the same distance from the injection well, in order to allow comparison of the results. The simulations were run for 500 years in order to cover any likely period for which monitoring might be required. The results suggested that if the leakage pathway is reached by the CO_2 during injection then leakage will be more significant than if it arrives after injection has ceased. However, while breakthrough times to the leakage pathway can be relatively short, simulations showed that peak CO_2 fluxes may not have had sufficient time to develop over the simulation run period in under-pressured or hydrostatic scenarios.

Simulation results suggest that initial reservoir pressure conditions influence where and when monitoring is appropriate. Underpressured sites present significantly lower leakage risks. For all site types wells were the main CO_2 leakage pathway considered, although leakage through a fault or through a zone of overburden with enhanced permeability was also considered. Results suggested that chemical monitoring of a typical cap rock would be unnecessary because of the small amount of CO_2 involved and the very long timescales. Leakage that occurs via a fault or through enhanced-permeability overburden was found to discharge much more significant volumes of CO_2, for the cases studied, than when it occurs via a borehole, despite the time for the borehole to leak being typically much shorter. Seawater pH changes above a leakage pathway were found to be extremely small if only CO_2-charged water discharges, but much more significant (1 pH unit or more) if free CO_2 discharges. However, these changes are very much controlled by the rate of mixing of seawater at the discharge point. The aquifer scenario simulation results suggested that if migration occurred along a wellbore, additional storage might be found in unbounded aquifers above the main storage reservoir and these aquifers would be the most appropriate monitoring target to assess whether the borehole was providing a leakage pathway.

Leakage parameters assessed by the literature review included CO_2 flux, concentration, distribution and duration both from observations and simulations. Leakage parameters were calculated from a variety of methods, including direct field measurements. Scenarios were divided into the following categories; natural CO_2 releases; CO_2 injection sites; CO_2-EOR sites; experimental sites and numerical models.

Natural CO_2 releases exist mainly in volcanic or hydrothermal areas, where deep sourced CO_2 is released to the surface. This allows investigation of potential CO_2 pathways, fluxes and environmental impacts. Flux rates range typically from background values (10^{-3} tonnes/m^2/year) up to a few tonnes/m^2/year. CO_2 injection sites at both the pilot and commercial-scale have, in almost all cases, not detected leakage, as they were chosen carefully as secure containers. Methods including tracers and isotopic CO_2 signatures have been used to determine if any CO_2 detected originates from the stored CO_2 or comes from unrelated biogenic sources. A low flux rate leak was detected from West Pearl Queen, a small-scale storage test in a depleted oil field. CO_2-EOR sites have been operating in some cases since the 1970s and as such data on gas releases experienced at these sites can aid estimation of CO_2 leakage parameters. Expected leakage rates are very low; for example, at Weyburn, only about 0.001 % of the predicted total CO_2 stored at cessation of injection is expected to leak over 5000 years. Research at these sites indicates that old wells not designed for CO_2 contact present the most likely risk of leakage. Experimental sites have been specifically designed to monitor leakage parameters from CO_2 injection into the shallow subsurface to assess the effects and rate of leakage. Release rate and location can be controlled to mimic, for example, potential diffuse leakage or sudden leakage from a point source such as a fault. These experiments also suggest that CO_2 releases become concentrated into ‘hot spots’ which incidentally may aid detection of low level releases. Numerical models have been developed to investigate CO_2 migration and leakage from a variety of storage scenarios and over a variety of timescales.

Chapter 5 synthesises the findings of earlier chapters in order to assess the measurement requirements for UK offshore MMV and to outline the efficacy of existing measurement technologies. By examining the capabilities of existing tools, used individually or in combination, key technological and methodological gaps are identified. These are assessed further in subsequent chapters.

The regulatory requirements for monitoring at CO_2 storage sites define high-level objectives. Consideration is made of more specific requirements, and how those might be met, when large-scale storage takes place in future. This is weighed against the MMV schemes proposed or deployed at actual North Sea sites and the likely range of leakage parameters.

The efficacy of existing monitoring tools (fully documented in Volume 2) is then examined in the light of regulatory requirements and actual or proposed practice.

The purpose of this chapter is to identify where existing MMV technologies are likely to fall short of what is needed to satisfy the requirements for demonstrating storage performance and detecting and quantifying leakage. This leads to a definition of the extent to which improvement is needed to help focus investigation of technological developments in the following chapters of the report.

With some specific exceptions (discussed in later chapters) deep focussed monitoring techniques, based on decades of continuing development in the oil and gas industry, are largely considered relatively mature and adequate to meet requirements. While leakage is not expected at any storage site that has been suitably characterised and designed, regulations place significant emphasis on monitoring leakage and its impact. Our review indicates that current technologies for assessing and quantifying leakage require more development.

Chapter 6 complements Chapter 5 by presenting gaps in monitoring technologies as identified by service companies, R&D teams and those involved in CCS projects, and indicates how such organisations see developments addressing these gaps.

Some sixty organisations were canvassed for their views. Most CO_2 monitoring is carried out using existing tried-and-tested oil and gas field monitoring technologies, but there are some methods or adaptations specific to CO_2 monitoring either newly available or in development.

Joint interpretation methods represent a gap, which is also a major focus of the oil and gas industry for its reservoir monitoring, modelling and reservoir simulation programmes.

The lack of a robust strategy for dealing with abandoned wells was identified as an important gap. It was felt that technologies existed to address the monitoring issues, but there were significant risks in deployment (e.g. damage to a well completion during installation subsequently forming a CO_2 migration pathway).

The gaps identified from discussions with third parties were then cross-referenced to the gaps identified previously in Chapter 5. A full catalogue of gaps is presented in Appendix 5 (Volume 2) under six themes: monitoring strategy; monitoring large areas with non-invasive techniques; monitoring in and around wells; leakage and shallow monitoring; monitoring injection at the well head; environmental impact assessment. Within each theme the gaps have been prioritised according their importance for production-scale CCS.

This analysis allowed collation of an inventory of novel technologies. For each, we present a summary of the developments identified followed by more detailed descriptions. These are grouped according to the basis of the technology and the drivers for development. Descriptions are cross-referenced to relevant material elsewhere in this report, mainly in Chapter 10 (Volume 2), which can be regarded as providing essential background on technologies and their application. The methods and developments included in the inventory can be summarised as:

Seismic methods: there is potential for permanent installations for example using Ocean Bottom Cables (OBCs) and scope for multi-component monitoring system data. Improvements are also foreseen in: hardware (wireless, improved sensitivity, Micro Electro Mechanical System (MEMS), optical sensors, continuous recording, improved sources); processing (improved imaging, joint inversion); interpretation (data assimilation, visualisation). Inversion of pressure and saturation are envisaged from Amplitude Versus Offset (AVO) or multi-component data.

High-resolution sea-bottom imaging and bubble detection: forward-looking sonar instruments, can survey over 100 m ahead of the survey ship, and downward looking systems (e.g. sidescan sonar and multibeam echo sounding) can map seabed features with increasing resolution and detect bubbles. However, most experience is with methane or water and not with CO_2. Development is needed to establish detection limits for bubble streams, quantification potential, whether bubble composition can be determined and development of permanent detectors for critical locations (e.g. near old wellbores).

Geophysical logs: this is a mature technology, but more experience with CO_2 is needed. New concepts for well integrity logs include electro-chemical techniques. Integrity logs need more testing to establish threshold values for detectable leakage in wellbores. Custom completions for monitoring at different levels, such as the Westbay System, need further evaluation.

Downhole P/T: distributed temperature sensors seem to be a mature technology.

Chemical methods: developments are needed for downhole fluid chemistry and for new sampling devices. Permanent and robust downhole pH sensors are not yet available. Improved sampling devices and CO_2 detectors are under development. Microbial monitoring and developments in biogeochemical methods are also ongoing.

EM or resistivity based methods: there is potential for joint inversion with seismics for CO_2 monitoring.

Gravimetry: developments in gravity gradiometry have not been considered for CO_2. Borehole applications have not yet been explored sufficiently.

Other techniques: ecosystem impacts are being examined in new European and UK projects, including the use of a benthic chamber, and progress in developing biomarkers has been made by Statoil. No real development in tiltmeters is foreseen. New tracers are being tested. Drill cores which maintain the pressure of seabed samples could potentially be used to sample shallow (up to 500 m below seabed) sediments for CO_2. The acoustic signal (sound) of CO_2 bubbles in the water could also be detected at short range (up to 15 m) from a fixed monitoring position or an ROV, using directional microphones. Noise logging in boreholes is experimental for CO_2. Fixed underwater cameras may have the potential to detect bubbles.

Each novel technology identified in the inventory has been assessed in terms of its maturity, limitations and the improvements foreseen from current developments. Many developments are incremental and the main need is for more testing with CO_2. Shallow-focussed monitoring is, in general, in need of more developmental effort than deep-focussed techniques.

Chapter 7 describes the potential for integrating two or more monitoring technologies. Here we consider the integration potential from two aspects: the potential for joint interpretation of the outputs from a range of technologies, and/or the joint acquisition of monitoring data via simultaneous deployment, for example in a borehole or on a ship. The benefits of integrating monitoring technologies include: optimising detection and quantification of CO_2 migration and leakage, reducing deployment costs and improving understanding of reservoir processes such as dissolution. Typical monitoring techniques suitable for joint interpretation are injection well and monitoring well data and geophysical measurements such as seismic (including vertical seismic profiling - VSP), microseismic, gravity and controlled source electromagnetic (CSEM). Joint interpretation leads to better constrained models of the storage system. Improved understanding of the reservoir over time will reduce uncertainties in the future behaviour of CO_2 in the reservoir. Combinations of methods covering wide areas for detection, with local methods for measurement can be used to detect and characterise migration or leakage.

Selection of tools to be integrated will be based on providing complementary monitoring capabilities which improve detection and measurement both spatially and temporally. For example, geophysical methods providing detection of migration and leakage over large areas may be integrated with more direct measurement techniques deployed in wells or at the seabed which are more spatially constrained but provide higher measurement frequency and/or resolution. Further integration could include more detailed analysis to quantify rates of movement (especially flux to seabed if leakage is occurring), composition and source of CO_2. One example described in this chapter is the integration of multibeam echo sounder imaging to detect a potential leakage feature on the seabed combined with subsequent analysis of headspace gas taken from sediment cores to confirm the composition of the gas (in this case naturally-occurring methane). Similar integrated approaches with 2D seismic have been successfully used to explore for shallow gas fields in the Southern North Sea. Joint interpretation of a range of shallow geophysical technologies has showed their potential to monitor shallow CO_2 movement onshore whilst individual techniques were not able to provide a definitive interpretation in isolation.

Joint interpretation of seismic and gravity data has been demonstrated at Sleipner. The combined use of gravity with seismics (as partially tested at Sleipner) could, in specific circumstances, reduce the cost of monitoring. For example borehole-gravity measurements could be used in conjunction with pressure-test data and/or surface seismic data to enable a statistical interpolation of predicted changes in the saturation of CO_2 at a lower cost than simply using 4D seismic. Specific examples of joint acquisition are provided to illustrate the benefits for integration. Permanent well and seabed geophone installation has high installation costs but provides significant benefits in terms of continuous passive microseismic monitoring and for regular or periodic active seismic surveys. Similarly, down-hole receivers can be integrated with conventional 2D/3D surface seismics to significantly reduce costs. Downhole permanent sensors can now include geophones, temperature and pressure sensors, with noise sensors becoming available to provide more continuous real-time monitoring of events. Assessing well integrity requires the joint deployment of a number of technologies, such as multifinger callipers and electromagnetic tools, to confirm that results from individual technologies are indicative of material degradation.

Monitoring plans for UK offshore storage sites are a regulatory requirement. They will need to demonstrate appropriate site performance, to monitor and evaluate deviations from expected performance and to measure CO_2 emissions should leakage occur. In Chapter 8 we consider monitoring methodologies for four generic storage site types, which cover the likely range of storage scenarios in the North Sea. They comprise: depleted gas fields beneath the Zechstein Salt in the southern North Sea; saline aquifers and depleted gas fields above the Zechstein Salt in the southern North Sea; depleted hydrocarbon fields in the central and northern North Sea and saline aquifers in the central and northern North Sea. The generic monitoring methodology comprises two distinct elements: a core monitoring programme designed to meet the regulatory requirements of a conforming site (i.e. one that behaves as expected during its lifetime) and an additional monitoring programme designed to address the requirements of a storage site that does not perform as expected. The core monitoring programme will be defined as part of the storage licence. It is aimed at performance verification, the monitoring and management of any site-specific containment risks identified in the Framework for Risk Assessment and Management (FRAM) and the detection and evaluation of performance irregularities including early warning of potential leakage. The additional monitoring programme is contingent upon the development of a significant performance irregularity. It comprises a portfolio of targeted monitoring tools held in reserve to evaluate and manage the range of possible irregularities and meet the needs of any associated remediation. The additional monitoring programme includes any requirement for emissions measurement under the ETS.

Specific methodologies for the core monitoring programme depend on storage site type. Depleted hydrocarbon fields are assumed to have secure geological seals, so monitoring emphasis is on possible migration and leakage along wellbores. Saline aquifers have geological seals whose properties are less well understood and there will be a greater emphasis on non-invasive monitoring tools providing wide spatial coverage. For all site types, the priority is to deploy pre-emptive deep-focussed monitoring systems targeted on the primary storage reservoir and its immediate surroundings, with the aim of identifying irregularities as soon as possible, and before they become too serious to be remediable. Shallow-focussed systems, deployed at the seabed or in the seawater column, aim to provide additional assurance that leakage is not occurring. Fit-for-purpose baseline data is essential and, for shallow-focussed systems, must be sufficiently robust to allow quantitative measurement of emissions should the need arise.

Key technologies for deep-focussed monitoring include downhole pressure and temperature (P, T) measurement on the injection well and 3D (in some cases 2D) surface seismic. If suitable wellbore infrastructure is available, remote (from the injection wells) P, T monitoring, saturation logging and downhole fluid sampling may be appropriate. With the exception of CO_2 saturation logging these are generally mature technologies with ongoing improvements driven by the oil industry. Key technologies for shallow-focussed monitoring include multibeam echo sounding, sidescan sonar, bubble stream detection and seabed measurements and/or sampling. These technologies are less mature than the deep focussed tools particularly in terms of accepted practice for effective integrated deployment.

Methodologies for the additional monitoring programme depend very specifically on the nature of the irregularity. They may require further deployment of tools already used in the core programme or the use of specific new tools such as seawater chemistry or cross hole seismic. Such tools may however be relatively developmentally immature, have unproven longer-term reliability or have stringent wellbore infrastructure requirements. For emissions quantification the ability to integrate spatially extensive information from non-invasive surveys (e.g. sonar imaging) with local detailed sample measurements will be required.

Chapter 9 identifies where gaps exist in current monitoring technologies that should be addressed to meet the anticipated monitoring requirements for UK offshore storage. It builds on the findings and conclusions of previous chapters: summarising the regulatory requirements for monitoring, defining the likely monitoring needs for four generic offshore storage types and reviewing existing monitoring technologies and future developments including a review of new technologies that might offer increased or improved monitoring capabilities

We conclude that current technologies are likely to meet most expected monitoring requirements, especially in the areas of deep-focussed monitoring since this will largely utilise mature technologies widely developed and tested in the hydrocarbon industry. No significant gaps have been identified that require the development of completely new technologies. Further, no completely new technologies are expected to be developed in the near future that will either supersede any current technologies or address the gaps identified. It is expected that incremental advances in current technologies, driven largely by market demands in the hydrocarbon and marine surveying industries, will provide beneficial improvements in monitoring capabilities for CO_2 storage.

Nevertheless, some monitoring requirements have been identified for which current technologies have yet to be demonstrated as providing the necessary capability. These requirements are in the following areas:

1. Leakage detection and measurement (emissions quantification) technologies including both spatially extensive survey and continuous data collection. This may be achieved through finding and measuring bubbles acoustically and by measurement of gas concentration and flux. Testing of the latter could provide much needed natural background values for offshore environments
2. Continuous monitoring technologies, primarily monitoring geochemical processes, in boreholes.
3. High resolution time-lapse monitoring for detailed assessment of plume migration via borehole instrumentation
4. Well integrity monitoring using noise logs and establishing detection thresholds for well bore leakage using existing or refined techniques

A range of needs has therefore been identified to address these requirements, which mainly involve development and testing of existing technologies to establish their efficacy.

We recommend that consideration be given to developing UK test facilities for permanent and continuous borehole monitoring and for developing and testing CO_2 geological emission detection and measurement technologies. Alternative approaches would be to establish partnerships with existing international facilities and to work in collaboration with European and UK projects.

We also recommend dialogue with service companies and projects to help foster development in assessing well integrity, especially in plugged and abandoned wells.

Further assessment is suggested of the potential for integrated permanent monitoring technologies for specific UK offshore requirements.

Consideration should also be given to joint development with planned UK CCS demonstration projects, through discussion with DECC and project participants.

The second volume of this report (Chapter 10) presents a review of existing technologies with examples of their application and serves as a resource on the range of available techniques, which can be referred to when reading other parts of the report. Appendices related to all chapters are also to be found in Volume 2.