The objectives and design of generic monitoring protocols for CO_2 storage.

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Abstract
CO_2 storage projects are likely to comprise a typical workflow of site characterisation, injection, decommissioning and site closure. Here we describe a generic monitoring programme that supports this project evolution and identify some of the issues that should be considered when designing site-specific programmes. Monitoring programmes will need to fulfil two principal aims of (1) demonstrating that site performance meets defined standards and (2) that leakage to the surface is not occurring. Pre-injection monitoring will acquire baseline datasets against which future performance can be compared. During injection, reservoir simulations will be refined through history-matching with monitoring data. Post-injection monitoring will be required to further validate predictive models of long-term site performance. The timing of site closure is also discussed. Although careful planning is a prerequisite, flexibility will be needed to respond to changes in project development or unforeseen events.

Keywords: CO_2 geological storage, monitoring, regulation

Introduction

While the need and scope for specific regulations for CO_2 storage have yet to be agreed, it can be assumed that successful storage must be verified both for accounting purposes within national emission inventories and to protect local health, safety and environment [e.g. 1]. In order to provide assurance that storage sites are performing effectively, they will need to be monitored to verify that CO_2 remains safely trapped in the short-term and to provide confidence in predictions about its future behaviour over a period of several thousand years. Here we discuss the requirements and workflow of a generic monitoring protocol that should enable projects to operate within the European emissions trading scheme (ETS) or international agreements, as well as responding to local safety issues should the need arise. Current demonstration projects have enabled recent reviews [e.g. 2, 3] to identify appropriate monitoring techniques and make cost estimates. Previous discussions have focussed on many aspects of this approach; including identification of potential technologies [e.g. 3, 4] and the rationale and aims of monitoring programmes [e.g. 1, 5 and 6].

The rationales for developing monitoring protocols are varied. Most CO_2 storage projects will need to establish baseline conditions, characterise the storage site and develop an understanding of site performance. A carefully planned monitoring protocol will support the decision-making process during the design, commissioning, operational and post-operational stages. In addition, monitoring should also be able to demonstrate compliance with international and national guidelines and regulations, helping to verify storage for accounting and fiscal purposes. Through history-matched simulations, when reservoir models are compared to datasets acquired during and after injection, monitoring data should also improve confidence in site performance in order to refine the safety case. Potential environmental impacts of the storage site may also need to be monitored and operators will need to provide evidence of a safe working environment.

Our definition of a suitable monitoring protocol is a planned, flexible and responsive programme of monitoring activities that provides clear, traceable and appropriate data to inform all relevant stakeholders of the project evolution. These stakeholders will be the site operator and their customers, national authorities (including regulators), investors, and possibly local residents.

A suggested regulatory framework for monitoring geological storage

An outline regulatory scheme could comprise a series of staged licence applications, each allowing a storage operator to move to the next stage of the process and would comprise:

- A licence issued to explore for potential storage sites.
- A licence issued to construct infrastructure and inject CO_2, subject to:
    - Comprehensive site characterisation (including baseline surveys)
    - Risk assessments (appropriate environmental impact assessments)
    - Monitoring programmes
    - Remediation contingency plans
    - Continued satisfactory site performance (failure on this point could lead to licence revocation)
- A final licence issued for site closure.

The regulator could grant permission to the operator to close the site subject to the fulfilment of an appropriate performance assessment, which would be accompanied by documented evidence that the long-term behaviour of the site will meet the pre-defined performance criteria. At this point, the national authority may assume liability. Although current practice regarding oil and gas decommissioning is that any residual liability rests with the operator, the required storage times of several thousand years or more create significant obstacles to this.

Monitoring Programme

Monitoring is likely to have two main objectives. The first is to show that the site is performing according to a predicted specification. This may include quantifying *in situ* amounts of CO_2 where storage conditions are suitable. The second is to show that potentially hazardous leakage to surface is not occurring. Monitoring will continue after injection to confirm the system is continuing to behave as predicted, through further history-matching, which will lead to greater confidence in predictions of the long-term evolution. Monitoring activities are intimately associated with the site operation and will effectively form the basis for decision-making throughout the project. Thus, at any point where monitoring results deviate from expectations, information will be fed-back into a revised predictive site model. A well-designed monitoring programme will evolve through the project and will fundamentally support the operational decision-making process, particularly as the project evolves from one stage to the next.

The evolution of a storage project can be summarised as a “workflow” for a number of scenarios (Figure 1). A project will comprise initial site characterisation, followed by baseline and repeat monitoring surveys (in Europe this could be on a five-yearly cycle to coincide with the European ETS). On completion of injection, monitoring would continue for a period until the required site performance was confirmed. In Figure 1, different scenarios reflect degrees of departure from the ideal, as migration and leakage occur. In some cases migration or leakage may be acceptable within pre-defined performance criteria, enabling injection and site closure to proceed. However, in other scenarios, leakage may not be accepted and injection must be terminated. Scenarios that deviate from agreed and licensed plans may require more frequent or additional types of monitoring, consideration of appropriate remediation, plus revision of storage estimates and of the predictive system model. Regulators may wish to submit the project to independent technical review at two points: after the application for a licence to inject, and for site closure.

Monitoring activities may, in themselves, also have implications for site safety, either over the short or long-term, which should also be considered. A poorly designed monitoring programme may delay site closure and the long timeframes for storage mean that the aims of post-injection monitoring must be clearly defined to ensure an appropriate closure strategy can be implemented.

Baseline surveys
Baseline conditions can be defined as the site-specific conditions prior to injection of CO_2 against which future site performance can be compared. The acquisition of baseline datasets will be very closely linked to project design and site characterisation. Secondary baseline datasets for specific parameters could be established at appropriate points, for example following site closure. Near-surface baseline datasets should be conservatively designed to cover all areas of potential future leakage, so that issues not anticipated at the pre-injection stage can still be evaluated in the future. Such baseline data need not necessarily be acquired prior to injection, if modelling suggests that potential leakage could only occur at some future point after considerable migration. Not all surveys need to be repeated during the project lifetime, although surveys may be repeated during the site closure phase to demonstrate that the site had been decommissioned appropriately as defined by the environmental impact assessment.

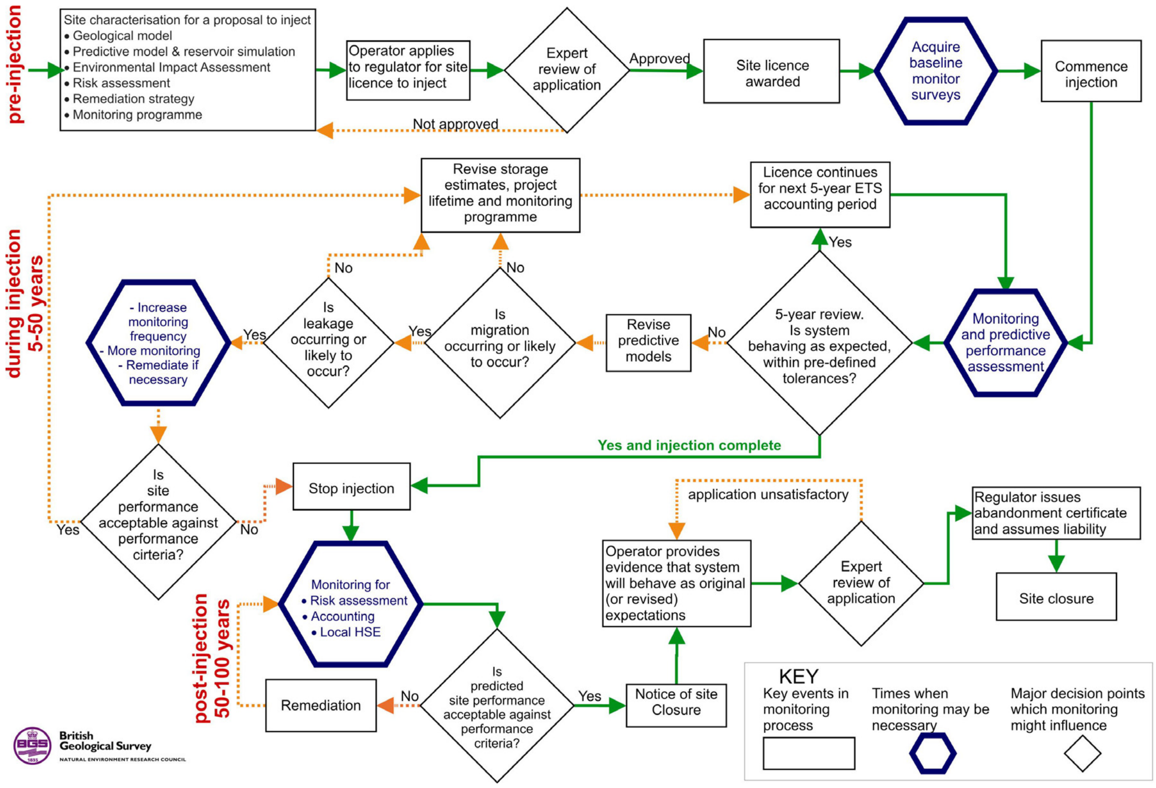

Figure 1 A conceptual diagram of the possible evolution of a CO_2 storage project and the key points when monitoring may be required. The green, solid line represents a normal 'incident-free' site evolution.

Migration and Leakage
Clearly, migration and leakage will remain the primary foci of most monitoring regimes during the project. Migration out of the target reservoir or trap, anticipated or otherwise, may trigger additional monitoring, both to track and refine understanding of the movement of CO_2 and to help define appropriate remediation plans. Similarly, leakage would also trigger intensification of the monitoring operation. In many storage sites, especially onshore in mature hydrocarbon fields, wells represent the biggest potential pathway for CO_2 to migrate out of the reservoir and possibly leak to the atmosphere. Hence these would naturally be the focus of careful assessment during baseline surveys and ongoing monitoring during operational phases. In contrast, offshore saline aquifers may have fewer wells providing shortcuts to the surface. However, the amount of data available for site characterisation may be lower due to the lack of data acquired during oil or gas exploration and production. Therefore, natural pathways such as faults may represent a more significant risk for CO_2 migration and leakage. If leakage did occur, then additional monitoring may include the assessment of impacts on near surface ecosystems, which could be compared to similar baseline datasets and would enable appropriate remediation actions to be defined.

Remediation

The monitoring programme should be intimately linked with remediation plans, since appropriate remediation action cannot be taken without supporting monitoring data. The success of any actions taken must also be measured. Benson and Hepple [4] have discussed possible remediation options, focussing on the onshore storage case. One important aspect of the remediation plan is the definition of appropriate thresholds or events that require some remediation. Accurate, comprehensive baseline monitoring data is crucial in establishing appropriate safety levels or trigger thresholds. Thresholds can be applied to a wide variety of parameters including, *inter alia*, annular well pressure, microseismicity, soil gas CO_2 concentrations, atmospheric CO_2 concentrations, fluid geochemistry (pH or pCO_2 are obvious choices but other groundwater quality criteria could be chosen), reservoir pressure or temperature, and tracer concentration. When monitoring ecosystems, target indicator organisms could also be selected. Activities that could be implemented as a result of reaching a specific threshold or trigger event, could include increasing the frequency of current monitoring, implementing additional monitoring techniques, revising geological models and storage estimates, delay or implementation of the next stage in the project, change of operations, well workovers, instigating remediation plans and informing the regulator(s).

Site Closure

The closure phase of a project can be defined as the post-injection period leading to transfer of liability from the site owner to the national or jurisdictional authority. The initial project application is likely to have defined the amount of CO_2 to be injected and when the injection will finish, at which point the operator will prepare to close the site. This will include continuation of a number of activities from the injection phase plus others specific to the closure stage. Ongoing activities will include continued monitoring and history matching, and revisions of performance assessment and remediation plans. The closure and post-closure stages are the least well defined in terms of duration and expected activities, and will have to be addressed in any performance assessment. They have not yet been encountered in current CO_2 storage projects and, though some examples of best practice can be exploited, it is not clear if the approaches taken in other industries are appropriate for CO_2 storage. During the closure phase the safety case will be revised and finalised, so that any residual liability can be minimised and transferred from the operator to the designated national authority. The safety case for the post-closure period should not necessarily be based on the prerequisite for a continued long-term monitoring regime to guarantee the safety of future generations, since this would be placing an undue burden on future generations to continue monitoring [6]. Rather, an assessment of the safety of the site should be based on its inherent behaviour established during site selection and characterisation, and confirmed by monitoring during injection and site closure. These include caprock integrity, wellbore abandonment techniques, sealing features such as faults and fractures and operational history (injection pressures, volumes, injection point etc.). Therefore, monitoring should not be needed in the post-closure period. However, it should also be emphasised that monitoring should not be precluded if future generations required it.

Closure application

As part of a regulatory process it is likely that an operator will have to apply for permission to close a site. Decommissioning regulations within the oil and gas industry provide examples of how this might be undertaken and the scope of such a closure application. In addition, the long-term nature of CO_2 storage requires careful consideration of issues such as record keeping, data transfer and archiving, and decommissioning [6]. Predictions of future site behaviour will have been made prior to injection and will extend to include the closure and post-closure periods. During the injection period this performance assessment will evolve to reflect the increased understanding of the system, obtained by history-matching reservoir simulations with monitoring data. Monitoring will continue after injection to validate these predictive models as reservoir pressures decrease and the CO_2 plume migrates. The design of the monitoring programme, including selection of techniques, monitoring frequency and duration should specifically address these aims. For example, the operator and regulator would need confidence that the data obtained during a post-injection monitoring programme would provide confirmation of reservoir modelling predictions with minimum ambiguity. At some point a decision will be made that there is sufficient confidence in the models to predict acceptable future site performance, and monitoring will no longer be needed to validate the safety case. This may be considered a suitable time for the operator to close the site and transfer liability back to the national authority (see next section). The frequency of monitoring is likely to decrease with time during the closure phase as confidence in models increases. Clearly, if the system does not behave as predicted, then the frequency and types of monitoring may increase.

Transfer of liability from operator to national authority

The project endpoint is defined by the end of the closure phase, when the operator transfers site ownership to the designated national or jurisdictional authority. Due to uncertainties over the long-term existence of operator companies, it is generally assumed that at this point, the state, through the designated national authority, will accept liabilities associated with future site performance. Clearly, therefore, the national authority is only likely to take on this liability if the operator can demonstrate that it is as low as possible, and certainly within the terms of the injection and closure licences. For the purposes of safety assessments it has been proposed that the post-closure period, when the state retains liability for the site, will be divided into a period of active institutional control lasting 100-300 years, reverting thereafter to 'passive' control [6].

There are several ways of determining the duration of the closure phase and when to transfer liability. All have their limitations. Pearce *et al*. [5] arbitrarily suggested the closure period for a generic project to be up to 100 years, approximately twice the injection period. However other technical reasons may, on a site-specific basis, provide an indication of the appropriate length of time for which post-injection monitoring may be continued. These include, *inter alia*:

(i) The closure phase could continue until 'equilibrium' or steady-state is reached. The definition of 'equilibrium' will depend on site-specific conditions such as the rates of CO_2 dissolution, mineral trapping, plume migration and residual trapping, some of which are likely to take thousands of years to reach a steady-state, which would be impractical for monitoring. At Sleipner for example, reservoir modelling predicts that, within a few years of injection completion, most of the CO_2 will accumulate in one layer beneath the top seal and that after 250 years or so, geochemical processes dominate over lateral migration.

(ii) The post-injection period could last until reservoir pressures decline to a certain point, after which time the reservoir is secure against geomechanical failure due to internal forces. Chalaturnyk and Gunter [5] indicate that this is of the order of 100 years. At Weyburn for example, ambient pressures are reached after approximately 1000 years, though reservoirs pressures decline from when injection is stopped [7].

(iii) Post-injection monitoring could continue until a predicted event occurs, e.g. CO_2 may be predicted to migrate towards a fault with a poorly-constrained permeability and monitoring would continue until it was demonstrated that no leakage was occurring along the fault.

(iv) An arbitrary minimum timeframe could be defined, such as double the injection period. However, this seems difficult to justify from a safety or practical viewpoint.

(v) The closure phase could continue until operators and regulators are sufficiently confident that models used in predicting future site performance have been validated by history-matching to monitoring data. This time could vary significantly depending on specific site characteristics and defined tolerances in matching models and monitoring data.

Duration of the post-closure stage

The duration of the post-closure phase is defined by the estimated retention time of CO_2 and its ultimate fate (structural trapping, residual phase trapping, solution, mineral trapping and diffusion). The minimum required duration of CO_2 retention is likely to have been defined during earlier stages of the licence approval process. Currently this remains an unresolved issue and, as such, presents some difficult challenges to overcome. Prescribed or estimated minimum retention times may vary between regions or states depending on local regulations and site-specific geology. However, it is worth noting that in a suitable storage site, injected CO_2 could remain trapped as a buoyant fluid for up to millions of years, similar to some naturally occurring CO_2 fields [e.g. 8].

Summary and conclusions

CO_2 storage projects will follow a natural workflow of site selection and characterisation, baseline data acquisition, followed by injection and post-injection monitoring, and site closure. A generic monitoring protocol to support this workflow has been defined to support the project design and operational decision-making, and demonstrate that site performance is meeting stipulated criteria. The programme must initially identify relevant parameters to monitor and also remain flexible to respond to planned or unplanned changes in site evolution. We suggest that monitoring will be needed to define baseline conditions, to verify and, if necessary, refine reservoir simulations both during and after injection, to monitor for leakage, and to help define appropriate remediation plans. Programme aims will vary depending on the nature of the site, stage of project and site behaviour. Monitoring will be a key component of the site closure strategy to enable liability transfer from operator to national authority. Time scales involved in completing such workflows are likely to be exceptionally long, extending as a minimum over many generations.

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