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ScienceDirect
Energy Procedia 1 (2009) 2397–2404
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

A field laboratory for monitoring CO_2 leakage

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Abstract

The long-term safety of future CO_2 storage projects in aquifers will not only rely on a comprehensive geological characterisation of the formation and capillary seal, but also on the ability to effectively monitor the underground migration of CO_2 to allow immediate and effective remediation to prevent CO_2 from escaping to the atmosphere in case of leakage. To achieve such effective remediation it is necessary that deep-probing monitoring tools can detect any leakage at an early stage long before CO_2 has reached the surface. It will also be necessary to conduct shallow monitoring, at the perimeter of the storage system, where leakage to the atmosphere or ocean is imminent. Field-scale experimental observations have been designed and planned to study the sensitivity of various existing monitoring systems as a mean of monitoring CO_2 leakage. Two onshore geological formations in Norway have been identified as suitable for systematic studies of detection limits for monitoring technologies in a well-controlled geological environment. One of the sites consists of Quaternary unconsolidated sand with a high porosity and permeability, allowing fast CO_2 plume rise and the possibility of creating chimney-like plumes. The other site is a low-permeable Permian consolidated sandstone, where viscous forces will be stronger during the injection phase, thus permitting more variations in the plume shape depending on the injection rate. At both selected sites, small amounts of CO_2 will be injected into the geological formations, which have no seal that will prevent the CO_2 upward migration through the underground strata. The CO_2 plumes will therefore mimic a potential leakage from an actual storage site and, by frequently repeating monitoring measurements, the performance of different methods will be tested. These monitoring measurements will include geophysical, down-hole, ecological/environmental, chemical/geochemical, atmospheric, and satellite methods. The results of the project will illustrate the performance of different monitoring technologies and provide reference for further developments of the methods, if needed. Various research organisations from United Kingdom, France and Norway will participate in the design and implementation of this project along with the project's industrial partners.

CO_2 storage; leakage; monitoring; field laboratory; CCS

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doi:10.1016/j.egypro.2009.01.312

1. Introduction

Monitoring will be a crucial part of demonstrating that CO_2 storage sites perform to required standards [1]. The testing and demonstration of storage monitoring technologies have until now fallen into two broad areas:

1. Industrial-scale demonstration projects (e.g. Sleipner, Weyburn and In Salah) or pilot-scale research projects (e.g. Nagaoka and Frio) have allowed research consortia to develop and demonstrate the application of monitoring techniques to track CO_2 plume movement in the deep subsurface and determine geochemical processes within the reservoir
2. Natural CO_2 systems, typically in volcanic terrains, allow surface- and, more recently, airborne-based monitoring techniques to be developed and the responses of ecosystems to prolonged CO_2 exposure to be evaluated.

However, with the exception of very shallow and small-scale experiments, there remains a gap in developing monitoring techniques to detect and measure CO_2 should it migrate from the primary storage reservoir upwards through the overburden to the land surface. The physical and geochemical processes that may lead to CO_2 attenuation en route to the surface have yet to be investigated experimentally.

As industry across Europe begins to implement a range of demonstration projects, recent developments in the regulatory framework have identified two key areas of monitoring:

1. Deep subsurface monitoring to establish reservoir performance and provide early warning of non-conformant behaviour in order to implement early remediation. This requires a robust understanding of the capability (and limitations) of monitoring systems to detect small amounts of migrating CO_2 in a range of geological settings.
2. Shallow monitoring to including detection of environmental impacts of a failed storage system [2].

Regulators in Europe are drafting regulatory frameworks to enable these demonstration projects to be implemented and environmental protection is emphasised.

In order to study the performance of monitoring systems to detect leakage, a field laboratory is being established in Norway where CO_2 can be injected in permeable rocks in a well-controlled and well-characterized geological environment. CO_2 will be injected to obtain underground CO_2 distributions that resemble leakages in contradistinction to those projects where the CO_2 is injected under a seal for storage purposes. Various monitoring technologies will be studied with respect to their performance to detect known amounts of CO_2.

The field laboratory is chosen as the optimal environment and scale for a number of reasons. The quantities of CO_2 escaping from the current and upcoming demonstration sites are expected to be small because these sites were selected on the first place for the sufficient sealing capacity of the storage formation. It will therefore take too long time for practicable purposes before any detectable amounts of CO_2 will reach the surface. However, because regulations for storage are being devised now, such data is urgently needed to assist this process. Controlled leakage by a penetration of the seal, in order to induce migration of CO_2, would be difficult to control in a deep large scale setting and most probably will not be permitted. The smaller scale field laboratory, with an injection depth of several tens to hundreds of meters, does give a controlled environment where measurable migration and leakage can be induced within a short time span. Permitting issues will be less severe because the quantities of CO_2 involved will be small and no long term storage is intended. Therefore, the smaller scale field laboratory enables a better knowledge of the specific geology and a denser monitoring instrumentation.

In case of shallow injection, the field laboratory for monitoring CO_2 leakage will be clearly suited to investigate shallow monitoring. Scaling is needed when conclusions for deep monitoring are deduced from these shallow experiments. At several hundreds of meters of depth the CO_2 will be in the gaseous phase and conclusions about the sensitivity of certain monitoring tools are not directly applicable to the dense phase depths.

2. Site selection

From August 2006 until January 2007 a feasibility study was conducted with the objective to scrutinize the possibility of establishing a field laboratory in Norway for monitoring the movement of small amounts of injected CO_2 in underground formations that resembles a potential leakage from an actual CO_2 storage site. The study was conducted by nine Norwegian partners: SINTEF Petroleum Research, the Institute for Energy Technology (IFE), the International Research Institute of Stavanger (IRIS), the Norwegian Geotechnical Institute (NGI), the Norwegian

Institute for Water Research (NIVA), the Geological Survey of Norway (NGU), the University of Bergen / UNIFOB, the University of Oslo and the Christian Michelsen Research (CMR). This feasibility study was coordinated by SINTEF Petroleum Research.

Nine different Norwegian locations with consolidated or unconsolidated sediments have been evaluated for possible use as sites for establishing a field laboratory for underground monitoring of migrating CO_2. Seven of these sites have been given a more comprehensive review and evaluation namely, Svalbard, Andøya, Brumunddal, Svelvik, Gardermoen, Finneidfjord and Storfjorden [3]. Two of these seven sites have been found particularly interesting for the creation of an actual field laboratory; the unconsolidated Quaternary sand deposit at Svelvik and the Permian sandstone at Brumunddal. Important criteria for the site selection have been (a) the detailed knowledge of the formations' petrophysical properties, (b) the formation accessibility permitting its comprehensive instrumentation, (c) the formation depth allowing optimal time-length of the planned experiments and (d) the potential for conflicting use of the sites. Øyern, Moelven and Gardermoen were excluded due to limited formation depths, but the most prospective of these sites, Gardermoen, was still considered because it was evaluated as representative of all the three Quaternary sand deposits and due to the availability of comprehensive formation data. The Øyern site was also excluded due to its proximity near a lake and a popular recreational area. A summary of the sites considered is listed in Table 1.

Table 1 Brief summary of geological and physical properties of the sites

Site	Formation type	Thickness of water saturated zone, m	Permeability, mD
Svalbard	Cretaceous and Triassic		Unknown
Andøya	Jurassic to Early Cretaceous		Unknown
Brumunddal	Jurassic sand	300	65 - 195
Svelvik	Quaternary sand	300	High
Gardermoen	Quaternary sand	14 – 40	High
Moelv	Quaternary sand	35	High
Øyern	Quaternary sand	35	High
Finneidfjord	Marine Quaternary sediments	60	Unknown
Storfjorden	Marine Quaternary sediments	100?	Unknown

Some details of the Svalbard, Svelvik, Brumunddal and Gardermoen sites are provided in the sections below.

2.1. Svalbard

Porous sedimentary rocks with potential for storing CO_2 is not present on mainland Norway, however, the Svalbard Archipelago are formed by such rocks. A general W-E profile of the sedimentary succession is shown in Figure 1. Cretaceous rocks form the exposed rocks of central Spitsbergen and the Longyearbyen area while Mesozoic rocks are exposed further east, but are also underlying the Longyearbyen area. The western fold belt rocks of all ages are exposed, but no reservoir closures are present.

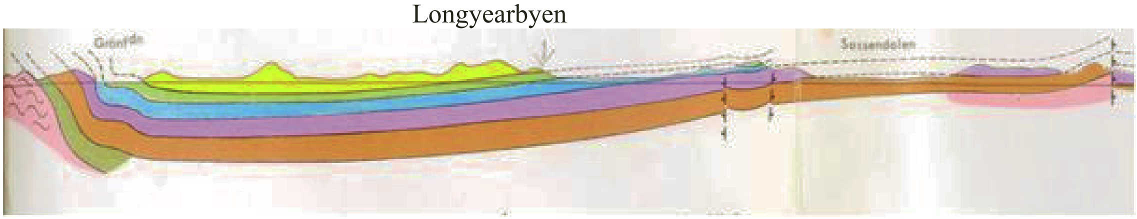

Figure 1 A 135 km cross-section through central Spitsbergen. Yellow: Tertiary, Green: Cretaceous (Helvetiafjellet, Carolinefjellet Formations), Blue: Lower Cretaceous-Jurassic (Janusfjellet Subgroup), Lilac: Triassic (Sassendalen, Kapp Toscana groups), Brown: Middle Carboniferous-Permian (Gipsdalen, Tempelfjorden groups), Green: Lower Carboniferous (Billefjorden Group), Red and pink: basements

The Longyearbyen site at Svalbard has sedimentary rocks at suitable depths (800 to 1200 m). The Helvetiafjellet formation (Cretaceous sand) and Kapp Toscana formation (Triassic sand) were identified as possible candidates. Following the drilling of two exploration wells in 2007, the Helvetiafjellet formation has proven to have too low porosity to be of interest for this project. However, the Kapp Toscana formation encountered at 900 to 1100 m depth may still be a feasible candidate if sufficient porosity can be proven.

There exist good technical and scientific facilities in Longyearbyen, which despite its northern latitude of 78ºN hosts an airport, a harbour, a coal based power station, a coal mining company with extensive experience in rock coring and the University Centre of Svalbard (UNIS). For logistical reasons the vicinity of Longyearbyen will first be evaluated. There are also other good localities on Svalbard, but going away from Longyearbyen the logistical operations will be much more complicated and costly.

Longyearbyen is the “capital” of Svalbard and has a population of approximately 2 000. Although it was started as a mining town, this activity is reduced successively with more focus on tourism, science and education.

Test drilling in Longyearbyen may take place at site conveniently localised in the coastal area where all technical facilities are available. The mining company yearly performs test core-drilling having all such facilities available. The test drilling only takes place from late winter to early summer, making the equipment available for scientific drilling during the remaining part of the year. In 2006 the drilling equipment was designed to drill down to 1250 m below the surface, but it may be extended to 1500 m.

There is a road along the shore up the Advent Valley which may be ideal for running seismic surveys. In addition there are good possibilities to conduct seismic studies during the time of the year when the ground is frozen. Such surveys may be quite economic by using snow streamers

2.2. Svelvik Ridge

The Svelvik ridge is located about 50 km south of Oslo in the outer part of the Drammensfjord, forming the sill of this main fjord basin (Figure 2). The central ridge is aerially exposed with the top plateau about 70 m above sea level, while the distal part is sub-aqueous (shallow sea bottom); both parts are easily accessible. The proximal part, also covered by clays, is deeper (≈ 117 m water depth). The central part of the ridge constitutes a phreatic aquifer, while the seaward part is partly confined by the overlying silts/clays. Sand has been excavated in the central aerially exposed part of the ridge, but there is still sufficient thickness of the unsaturated zone left. The dipping units in the glaciofluvially sand and gravel may be used for experiments to investigate up-dip migation of gas. The basin provides locations with and without upper formation seal. However, in order to find the most suitable injection places more detailed investigations are needed.

Figure 2 - Air photo looking northwards on the Svelvik area at the outlet of the Drammensfjord. The ridge out in the fjord is formed by deglaciation deposits. The photo shows the sand excavation on the ridge and also the dredged channel, Svelvikstraumen, on the west side. The laboratory site is indicated by the white rectangle

Reservoir characteristics have not been studied in detail. However, the porosity and permeability are expected to be close to those known from similar late Quaternary/Holocene deposits. Grain size analyses of samples taken from cores indicate a permeability range from 1 to 100 Darcy for the gravelly sand and sand, while siltier units display permeability values in the order of few mDarcy. A dipping anisotropy parallel to bedding is expected to greatly control the injected CO_2 flow behaviour. Deeper wells are required to be drilled to study the sediments and its reservoir properties as a function of depth.

The Svelvik ridge has been a subject to sedimentological and geophysical studies, and a profile from Hyggen/Hernes through the Svelvik ridge was constructed (Figure 3).

There are few permanent residents and some seasonal visitors who make use of the groundwater resources at the Svelvik ridge. However, the well directory at NGU indicates the presence of only one 27 m deep groundwater well in the site's deposits. Injection/monitoring wells should be located in the central cross-section of the ridge, avoiding any potential conflict with drinking water wells.

From drilling point of view, younger and non-compacted unconsolidated glaciofluvial sand and gravel of the Svelvik site pose many challenges. The main concern is a formation which is less competent and stable than the deeper and/or older formations and boulders that are observed in the deposits. Several drilling methods are able to penetrate the entire profile down to bedrock, approximately 300 metres of depth, but only the reverse mud rotary drilling with an open borehole during drilling, logging and installation of wellbore casing will fulfil the requirements of the project. To perform geophysical borehole logging, the minimum open hole diameter should be 6". Continuous coring in unconsolidated sand and gravel is a problem. The acquisition of some sediment cores could be possible, but coring 100 % of the drilled well is unrealistic. Less representative continuous samples are expected to be recovered from the mud flow-line.

Figure 3 displays a possible well configuration as well as a set-up for marine electromagnetic measurements.

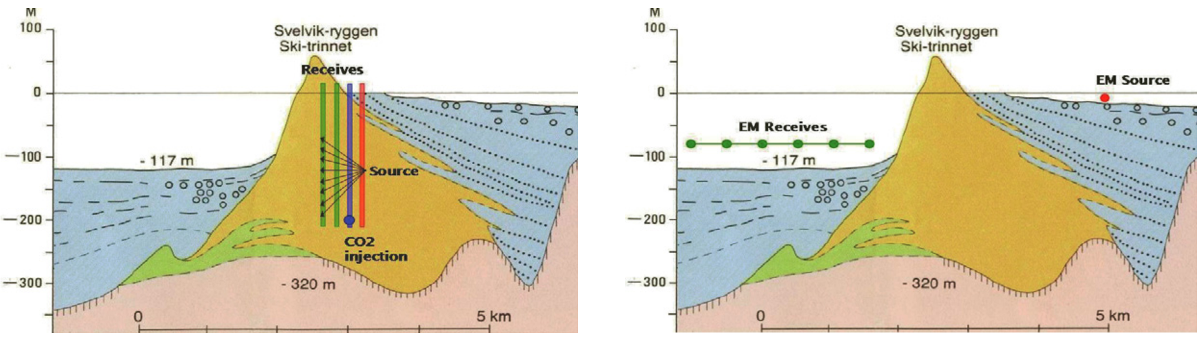

Figure 3 – Two identical north-south profiles through the Svelvik ridge with a possible well configuration (left) as well as a set-up for marine electromagnetic measurements (right).

2.3. Brumunddal sandstone

Brumunddal is situated 140 km north of Oslo, just north of Hamar. The sandstone is preserved as the uppermost sedimentary formation in the Oslo Rift, formed in a down-faulted half-graben in the northern part of the Akershus Graben. The depositional environment in the Brumunddal sandstone is interpreted as continental and consists mainly of eolian deposits, but also fluvial/wadi, lacustrine and sabkha deposits, Figure 4. The whole Brumunddal sandstone has been estimated to be up to 800 m thick in the central trough. The studied basin fill constitutes an an area, approximately 6.5 km long and 2.5 km wide. It is preserved in a half-graben, delineated to the east by the NNE-SSW striking and WNW-dipping Brumunddal fault. The sedimentary layers have a dip of around 40 degrees towards east-southeast. The sandstone has up to 24 % porosity, but porosities around 15 % and permeabilities in the range 65-195 mD are expected. The sandstone constitutes an important aquifer and groundwater occurs throughout the whole area.

The Brumunddal sandstone may in many respects be comparable with an offshore oil field, both volumetrically and formation-property wise (porosity/permeability conditions). The depositional environment shows strong similarities with Rotliegend in the northern Permian basin. The thickness, facies distribution and structural setting suggest that this is a remnant of an originally thicker and wider deposit.

Figure 4 - The Brumunddal sandstone at the quarry close to the Mauset school. The picture gives a general impression of the relatively homogeneous red sandstone, the bedding and the fracture system.

2.4. Gardermoen ice-contact delta

The Gardermoen ice-contacted delta is located in the upper Romerike area, about 40 km north-east of Oslo. The Oslo international airport is situated centrally on top of the western delta unit, the Trandum delta. However the total Gardermoen delta complex covers a much wider area. It is a terminal glaciofluvial-glaciomarine delta deposit formed during the Hauerseter stage of Holocene ice-recession in Southern Norway..

The delta complex constitutes a 40-80 m thick sediment accumulation overlaying irregular bedrock topography, and can be divided into the classical bottom-set, fore-set and top-set units.

The Gardermoen delta-complex is the best studied such deposit in Norway, due both to planning and building the Oslo airport and its railway system there, and not least through the large hydro-geological effort over a period of 30 years. Sediment distribution within the deposits is well known based on surface mapping, shafting and core samples, complemented with geophysical mapping (refraction seismics and ground penetrating radar) and geotechnical soundings. Thus, a well constrained geologic model has been constructed. The physical flow characteristics in the deposit is well known, based on aquifer pumping tests, tracer studies and estimated hydraulic properties from sediment samples. Hydraulic conductivity, water binding characteristics relative to air/gas (pF-curves) and anisotropy relations are well studied. There are numerous wells in the Gardermoen aquifer and a large number of those wells are used for monitoring purposes.

3. The CO_2 Field Lab project

Two of the sites that have been investigated are particularly feasible for a field laboratory; the unconsolidated, Quaternary sand deposit at Svelvik and the Permian sandstone at Brumunddal. Therefore, these two sides were chosen for the follow-up project named, "CO_2 Field Laboratories for Monitoring and Safety Assessment; Phase Zero". Conducted from December 2007 until the end of April 2008, the work consisted of the preparation and negotiation of the Project Agreement, planning and risk analysis, definition of the internal project organisation and division of responsibilities for the various work elements, liaison with landowners, preparation of the permit applications for the first phase of site work and specification and contract preparation for external services including drilling. In addition, there is an element for co-ordination with the current drilling under the "CO_2-Free Longyearbyen" initiative.

3.1. Communications

Initial contacts (phone calls, electronic messages and personal visits) with both the Hurum municipality, for Svelvik, and Ringsaker municipality, for Brumunddal, were made from the very beginning of the project, and the same was also true with the landowners of the two sites. This was considered crucial in order to exchange mutual information and establish good working relations. Contact with the local community, in addition to the landowners, through community organisations was also taken to arrange local information meetings regarding the planned project activities.

Through contacts with the environmental division at the county level of both sites it was established early on that the local authority at the municipal level should handle all permissions regarding the planned field activity. The initial contact at Hurum municipality (Svelvik ridge site) was the technical chief, while at Ringsaker municipality (Brumunddal site) the main contact was the head of the water works. The project had several meetings with the local authorities where the project and the planned activities were presented. Based on discussions on draft permit versions, and also helpful advice from the local authorities, permit applications were finalized and submitted.

Hurum municipality assisted the project in contacting neighbouring landowners and the local community group, and an information meeting was arranged. This meeting led to local newspapers coverage resulting in a press release from the project. People from the area were interested and generally positive. The local community organization was also contacted in Brumunddal, but the information meeting has yet to be arranged.

3.2. Permits

The permit applications for Svelvik and Brumunddal describe the entire project from the appraisal phase to the injection and monitoring phase. The permit applications have been composed based on input and advice from the local authorities. The project also gathered information from various providers of seismic and drilling equipment in order to describe the planned operations as detailed as possible.

It has also been necessary to perform some preliminary simulations of the planned CO_2-injection. The simulations have helped to make rough estimates of the total amount of gas needed, how fast the injected gas could migrate to the surface as well as the amount of gas that could possibly leak out to the atmosphere. These studies have been necessary in order to answer important, and highly, relevant questions from the local residents and authorities.

The two proposed field sites have different benefits for the intended use and potential conflicts associated. This caused differences in the permit applications. The Svelvik ridge site is located in a large sand excavation pit, and from the Hurum municipality point of view, only dispensation from the current use of sand extraction in the area and dispensation of the regulation plan were needed. The permit application was for the entire project, i.e. including CO_2 injection. For the Ringsaker municipality, the main potential conflict is related to the groundwater in the Brumunddal area, where the Brumunddal sandstone aquifer is a source of drinking water. For this reason, also the regional Food Safety Authority office was contacted and involved in the process. Ringsaker municipality requested a permit application in two stages; first only for the pre-injection phase, *i.e.*, a permit to carry out geophysical exploration and drilling.

Hurum municipality has granted a permit to establish a field laboratory at Svelvik. Brumunddal has declined the application for a permit which would cover the pre-injection investigation phase. Because of Brumunddal's concern about possible consequences on the ground water quality due to the CO_2-injection it was deemed that conclusions of a pre-investigation would not change their position. However, the Brumunddal municipality is open for a new application where air is proposed as an injection gas instead of CO_2. By injecting air the consequences on the ground water quality should be negligible and there is no need for transportation and storage of CO_2 at the surface.

3.3. Establishing a field laboratory

Since a permit has already been granted it is planned to establish a field laboratory at the Svelvik site during the following project phases:

- *Phase 1: Initial site appraisal and pre-injection permit*. In Phase 1 an appraisal well will be drilled and sufficient data will be acquired to establish a geological description for flow modelling and geophysical modelling. The result of these studies will determine if the Svelvik site is suitable and provide information for the detailed planning of subsequent site operations. Continued effort on informing the local community and government will also be an important activity.

- *Phase 2: Full site appraisal and Quantitative Risk Analysis*. In Phase 2 a more extensive site appraisal is planned, including a 3D seismic survey, a modelling update of the CO_2 plume migration and a subsequent Quantitative Risk Analysis.
- *Phase 3: CO_2 injection and monitoring*. In Phase 3 additional observation wells and other necessary instrumentation will be added to the sites to allow observation of the CO_2 saturation distribution underground. CO_2 will then be injected and monitored by the various tools. Iterative observations and flow modeling will provide frequent updates of the CO_2 distribution. CO_2 injection is planned for the summer of 2011.
- *Phase 4: Abandonment and post-injection monitoring*.
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The deep and shallow monitoring comprises of geophysical, downhole, chemical/geochemical, ecological and atmospheric methods. A decision will be made after the appraisal phase which monitoring tools will be chosen. The focus is on determining the sensitivity of the tools and systems to CO_2. Because the injection amount is known it is attempted to make an accurate mass balance with the help of modelling tools.

The depth of injection is anticipated to be between 200 and 300 meters. Next to this larger experiment, it will also be investigated if a shallower experiment could be conducted at Svelvik. This experiment will focus on near surface leakage impacts and monitoring both onshore and offshore. These experiments would be simpler, conducted faster and at lower cost. Onshore shallow experiments could also be conducted at Gardermoen where only a thin sedimentary layer is present.

At Svalbard the opportunity exists, depending on the progress in the CO_2-Free Svalbard project, to conduct deep monitoring of CO_2 in liquid phase.

The Brumunddal site is interesting as a drinking water aquifer, but has the disadvantage that CO_2 can not be used as an injection gas. Alternatives are air or nitrogen as substitutes. These would have similar physical properties as CO_2 gas, but the geochemical aspects of CO_2 would be not be tested. On the other hand, for CO_2 storage, drinking water concerns are very prominent. The project is still investigating how a non-CO_2 Brumunddal site could be of a scientific relevance.

4. Conclusions

Several site locations in Norway have been investigated for their suitability as a field laboratory for monitoring CO_2 leakage. Of these sites, Svalbard, Brumunddal, Svelvik and Gardermoen, were the most promising ones, with each having a different scope of application. One site, the Svelvik one, has been advanced the furthest by obtaining a permit for site activities, which will commence as soon as the agreement with the site owners is finalized (?) and additional funding from industrial partners is secured.

Acknowledgements

We would like to thank Jonathan Pearce and Andy Chadwick from BGS, and Hubert Fabriol from BRGM for supporting this project. We would also like to thank Gassnova for funding the feasibility project, Gassnova and StatoilHydro for funding the Phase Zero project, as well as Schlumberger and PGS for providing technical input.

References

1. Pearce J., A. Chadwick, G. Kirby, and S. Holloway. The objectives and design of generic monitoring protocols for CO_2 storage. In *8th International Conference on Greenhouse Gas Control Technologies (GHGT8)*, 2006.
2. Pearce J., A. Chadwick, M. Bentham, S. Holloway, and G. Kirby. Technology status review - monitoring technologies for the geological storage of CO_2. Technical Report COAL R285, British Geological Survey, March 2005.
3. SINTEF. CO_2 field laboratories for monitoring and safety assessment; a feasibility study. Report 54.5882.00/02/07, 2008.