*Exploration Geophysics (2006) **37**, 1–9*
Butsuri-Tansa (Vol. 59, No. 1)
Mulli-Tamsa (Vol. 9, No. 1)

International developments in geological storage of CO_2

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Key Words: CO_2, climate change, geological storage of CO_2, monitoring of CO_2 underground

ABSTRACT

Geological storage of captured CO_2 is a new way of reducing greenhouse gas emissions to protect the climate, but is based on the established technology associated with injection of fluids underground. The geological formations of interest for this technique include operational and depleted oil and gas fields, and deep saline aquifers. Prediction of storage performance will depend on models of the behaviour of CO_2 in geological formations; these need to be refined and verified, and methods of monitoring developed and proved. These needs can be met through monitored demonstration and research projects. Current commercial projects that are demonstrating CO_2 storage include Sleipner, Weyburn, ORC, and In Salah; research projects include West Pearl Queen, Nagaoka, and Frio. In this paper, some of the monitored injection projects are described. The reservoirs employed for storing CO_2, and the associated monitoring techniques, are briefly reviewed. It is argued that small-scale research projects, used to develop techniques and prove models, are complementary to the large-scale monitored injections that will establish the viability of this technique for mitigating climate change.

INTRODUCTION

Climate change is recognised by many observers as a potential threat to the global environment. Predicted impacts include increasing global average temperatures, rising sea levels, and changes in precipitation, with consequences for low-lying inhabited areas, agriculture, biodiversity, and human health (IPCC, 2001). The cause of these changes is the increased levels of greenhouse gases in the atmosphere due to human activities, including the combustion of fossil fuels and the destruction of forests. In recognition of these threats, many nations have agreed that action is needed. This agreement is embodied in the 1992 UN Framework Convention on Climate Change, which has the goal of "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The principal greenhouse gas arising from human activities is carbon dioxide, so measures to combat climate change tend to concentrate on ways of reducing CO_2 emissions. Until recently, it was thought all such measures would require reduction in the use of fossil fuels. As fossil fuels provide 85% of the world's energy at present (IEA, 2004), any substantial change in use, especially a rapid change, would be likely to have major consequences for the global economy. However, in the past five to 10 years there has been recognition of another option that would enable continued use of fossil fuels but with much reduced emissions of CO_2. This technique is CO_2 Capture and Storage (CCS).

CCS involves capturing CO_2 from combustion and storing it away from the atmosphere for a long time – sufficiently long that it cannot affect the climate. In view of the quantities of CO_2 which are emitted globally today – 24 Gt of CO_2 per year from fossil fuel combustion – the storage reservoirs would need to be sufficiently large that they could cope with a significant fraction of these emissions for periods of hundreds of years. The only reservoirs that have sufficient capacity are natural reservoirs (Freund, 2001), in particular geological formations such as operational and depleted oil and gas fields, deep salt-water formations that have no other uses, and unminable coal seams. Although some of these have been used for analogous purposes, e.g., storage of natural gas and disposal of acid gases, the long-term storage of CO_2 in order to mitigate climate change would be a new use for them. This will present challenges such as obtaining credible evidence about the security of storage, accurately estimating storage capacity, verifying the amount of CO_2 stored, and confirming the safety of this approach. For these reasons it is essential that practical examples of underground CO_2 storage are established, operated, and monitored, to provide evidence to scientists, governments, and the public of the safety and security of this method of addressing climate change. In recognition of these needs, several demonstration and research projects have been established around the world, initially in Europe and North America and latterly in Asia. The purpose of this paper is to provide an overview of these geological storage projects, and to put the recent developments at the Nagaoka site in perspective.

DEMONSTRATION OF GEOLOGICAL STORAGE OF CO_2

Principles of geological storage of CO_2

In a closed structure the injected CO_2 will, initially, be physically trapped at the top of the formation[1]. Even if the structure is not a closed one, the CO_2 may be considered hydrodynamically trapped, if the movement of fluids in the formation is so slow that the CO_2 will be isolated from the atmosphere for a very long time. The CO_2 may dissolve in the formation fluids (called solubility trapping) – in an Enhanced Oil Recovery (EOR) project, the aim will be for the CO_2 to rapidly dissolve in the oil; in saline water, much less CO_2 will dissolve but the denser CO_2-rich water should sink after dissolution, causing some natural dispersion of CO_2 in the reservoir. After dissolving in formation water, the resulting weak acid may dissolve the host rock, thereby constraining the CO_2 even more. Ultimately, some part of the CO_2 may be converted to stable minerals, the most permanent form of storage, but this may take thousands of years.

Types of geological reservoirs relevant to storage of CO_2

In order for a geological formation to be suitable for storing CO_2, it must have sufficiently high permeability to permit injection, with adequate capacity to warrant use for storage, and a boundary

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Manuscript received August 11, 2005; revised manuscript received September 28, 2005.

[1] Under hydrostatic pressure at depth of approximately 1000 m, the density of CO_2 is about 800 kg/m^3, making it buoyant in water.

(upper) seal that can contain the CO_2 for a very long time. Further understanding of the requirements is being gained from ongoing research.

Formations that have been used as sources of hydrocarbons (or of natural CO_2) are potentially attractive, not least because of their demonstrated ability to retain these fluids, plus the fact that they will have already been investigated and surveyed. Providing that subsequent penetrations of the sealing layer have not compromised their ability to retain CO_2, these should make good storage reservoirs. The global capacity of depleted oil and gas formations for storing CO_2 has been estimated to be approximately 900 Gt CO_2 (Freund, 2001). Injection into a depleted oil field has not yet been attempted on a commercial scale; the ORC project (offshore the Netherlands) will be the first to do this in a depleted gas field.

A much larger capacity (probably much more than 1000 Gt CO_2) is provided by deep saline formations, but these are unlikely to have been used for other purposes and so will not have been investigated in as much detail as oil and gas fields. In fact, the world's first commercial scale CO_2 storage project, the Sleipner project, uses such a formation.

Another type of geological formation that could store CO_2 is coal; for these purposes, the coal seams in question must be recognised as being unminable, otherwise the stored CO_2 might be released by subsequent mining, thereby negating the purpose of the original injection. The CO_2 is adsorbed into the coal matrix and may displace adsorbed methane so providing a valuable by-product, which could help to offset the cost of storage. This approach is quite different from storage of CO_2 as a fluid in geological formations and has limited global potential (Freund, 2001) so this paper concentrates on storage of CO_2 as a fluid rather than injection into coal.

A well established use of CO_2 is for enhanced oil recovery (EOR) – in this, CO_2 is injected into depleted oil fields to recover an additional fraction of the oil in place. This is being done at the Weyburn oil field in Canada, which is the first EOR project with monitoring of the CO_2 stored in the reservoir. Some of the CO_2 injected for EOR will be produced with the oil – it is normal practice to separate this and reinject it. The CO_2 remaining in the reservoir at the end of injection can be regarded as being stored providing the field is not re-entered. This is analogous to the use of a depleted oil field for storage of CO_2 except that the extra oil produced can help to offset some of the cost of supply and injection.

A recent development is to use CO_2 to enhance recovery from a gas field – this would be done in the early stages of development of the field, to maintain pressure in the field and hence the rate of gas production. The first practical example is at the In Salah field complex in Algeria. As gas production declines there is a danger of contaminating the remaining gas with CO_2, so the benefits and costs of injection, especially later in the life of a field, must be considered before such a project is undertaken.

Demonstrating storage of CO_2

In order for CO_2 to be injected into a formation, various regulatory and legal requirements will have to be satisfied, especially if the CO_2 is to be accepted as being stored for purposes of protecting the climate. Some of these requirements are clear – the storage must be safe and secure; it must be possible to verify the amount of stored CO_2; there must be minimal impact on the environment (both the local environment and the global climate). Because of the long time involved, especially in relation to climate impact, models of the physical and geochemical behaviour of CO_2 in the formation will be key tools in verifying that these requirements are met. Risk assessment techniques may be needed to satisfy the authorities about the safety of the storage facility. In order to calibrate and check these models, monitored data from real-life injections will be essential. This is one of the main reasons why several commercial CO_2 injection projects involve monitoring of the CO_2 in the reservoir, or may do so in future (see Tables 1 and 2). In addition, by monitoring the initial behaviour of the CO_2, graphic evidence is presented to interested parties, including

Project	Country	Storage type	Storage formation	Source of CO_2	Injection started	Injection rate (t/year)	Measurement project
Sleipner	Norway	Saline formation	Utsira (sandstone)	Separated from natural gas	1996	1 million	SACS, CO2STORE
Weyburn	Canada	EOR	Midale (carbonate)	Gasification plant	2000	1.1–1.8 million	WEYBURN
ORC (K12-B) phase 2	Netherlands	Depleted gas field	Rotleigend (sandstone)	Separated from natural gas	2004	20 000	CO2REMOVE
In Salah	Algeria	Producing gas field	Krechba (carbonbate)	Separated from natural gas	2004	1 million	IN SALAH

Table 1. Commercial projects that have injected and monitored the storage of CO_2 in depleted gas fields, EOR, or deep saline aquifers.

Project	Country	Storage type	Storage formation	Injection start	Injection rate (t/year)	Total storage planned (t CO_2)
Snøvhit	Norway	Saline formation	Tubåen (sandstone)	2006	0.75–0.95 million	23 million
ORC phase 3	Netherlands	Depleted gas field	Rotleigend (sandstone)	2006	480 000	approx. 8 million
Gorgon	Australia	Saline formation	Dupuy (sandstone)	2009?	2.7 million	Not published

Table 2. Future commercial projects that plan to store CO_2 in depleted gas fields or deep saline aquifers and may involve monitoring. This table does not include CO_2-EOR projects where no monitoring of the stored CO_2 is planned.

the media, demonstrating the storage of CO_2. Monitoring of the injection will also be done for operational reasons, and may also have to be done, later on, to verify the amount of CO_2 in store (as part of assembling a national emissions inventory) or to support claims for emissions reduction credits or carbon trading. Figure 1 indicates where some of the projects discussed in this paper are located.

Factors affecting demonstration of geological storage of CO_2

A key aspect affecting the design of the early projects is the source of the CO_2, because CO_2 currently has commercial value. This is ironic because the reason we are interested in this technique is to avoid disposing of CO_2 in the atmosphere – in other words, as a means of dealing with something that has no value. However, in order to obtain sufficient CO_2 for a research project, say 10 000 t, it is currently necessary to purchase it. This may cost around $600 000, a challenging sum for the budgets of individual research projects. However, some projects have successfully made the case for doing this, including West Pearl Queen and Frio in the USA and Nagaoka in Japan (Table 3). These are discussed below. Several more research projects are in preparation – some of these are listed in Table 4.

The reason that CO_2 costs as much as it does is largely to do with the cost of separating it from a gas stream. Thus, the first commercial CO_2 injection projects have been ones where the cost of CO_2 is met by others – for example, in natural gas production operations where the operator must remove CO_2 from the natural gas before it is delivered to market. Such a stream of CO_2 would normally be vented to atmosphere but there are now several projects where the operator has decided to inject the CO_2 underground. Examples include Sleipner, ORC, and In Salah (Table 1). Future projects of this type (see Table 2) include Snøvhit and Gorgon. A second type of project is where the cost of purchasing CO_2 is met by others – typically where CO_2 is injected underground for commercial reasons such as EOR. An example of this is the Weyburn EOR project (see Table 1), currently the only commercial EOR project with monitoring of the stored CO_2. Brief descriptions of the commercial and the research projects are presented below.

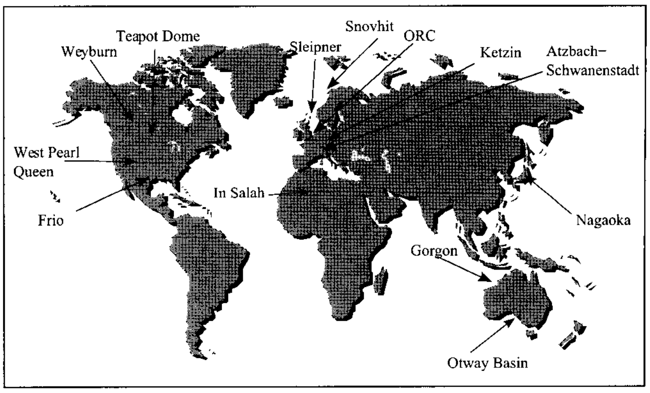

Fig. 1. Locations of the CO_2 injections described in this paper.

COMMERCIAL PROJECTS MONITORED FOR CO_2 STORAGE

Sleipner

The world's first commercial-scale project storing CO_2 for reasons of climate protection started injecting CO_2 in 1996. The Sleipner project, offshore Norway, was established in connection with gas production from the Sleipner Vest field. CO_2 separated from the Sleipner Vest gas stream is injected at a rate of about 1 Mt/y into a deep saline aquifer, the Utsira formation, about 1100 m below sea level. The Utsira formation is mainly sandstone, with porosity of 35–40%, and very high permeability (>1 D). By 2004, over 7 million tonnes of CO_2 had been injected. The CO_2 has been observed by seismic measurement (Arts et al., 2004a) to have collected at the upper boundary of the formation and to have moved in a roughly northwards direction from the injection point.

Project	Country	Storage type	Storage formation	Injection started	Injection completed	Injection rate (t/day)	Total injected (t CO_2)
West Pearl Queen	USA	Depleted oil field	Upper Queen (sandstone)	December 2002	February 2003	40	2100
Nagaoka	Japan	Saline formation	Haizume (sandstone)	July 2003	January 2005	20 - 40	10400
Frio	U.S.A	Saline formation	Frio C (sandstone)	4 October 2004	14 October 2004	approx. 160	1600

Table 3. Research projects currently storing and monitoring CO_2 in depleted oil fields or deep saline aquifers.

Project	Country	Storage type	Storage formation	Injection start	Injection rate (t/year)	Total storage planned (t CO_2)
Ketzin	Germany	Saline formation	Stuttgart (sandstone)	2006	approx. 30 000	60 000
Teapot Dome	USA	Depleted oil field	Tensleep (sandstone)	2006	2.6 million	26 million
Otway Basin Pilot	Australia	Saline formation	Waarre (sandstone)	Late 2006	approx. 60 000	approx. 100 000
Atzbach-Schwanenstadt	Austria	Depleted gas field	(sandstone)	Not yet announced	approx. 200 000 (to be confirmed)	Not stated

Table 4. Research projects that plan to store and monitor CO_2 in deep saline aquifers or depleted oil or gas fields.

An international collaborative research program was started in 1997 to take advantage of this unique opportunity to monitor the behaviour of CO_2 underground. Because of the offshore location of the project, the range of monitoring techniques that could be deployed was limited. No observation well has been used because one such well would only have provided limited spatial information and it was considered too expensive to have several observation wells (Torp and Gale, 2004). There was also concern about the risk of leakage from one observation well placed within the CO_2 bubble. Use of the injection well itself for a seismic survey was thought to be too complex technically and too costly whilst producing only limited volumetric information. Several 3D time-lapse seismic surveys have been conducted of the site – an initial, baseline survey in 1994, and three further surveys during injection (in 1999, 2001, and 2002); the results of these measurements have been used to estimate the position of the CO_2 and for testing geophysical models. Subsequently, other techniques for monitoring the CO_2 have been used (e.g., tilt and microseismic measurements). Time-lapse gravity measurement was considered to be cost-effective – it would give good areal coverage but with lower resolution than seismic. A gravity survey was run in 2002 and should provide an independent estimate of the in situ density of CO_2.

Prior to this project, some doubt had been expressed about whether seismic surveys could detect the presence of CO_2 because of the similarity in density of CO_2 and saline water in the formation but, in fact, the difference in velocity of sound makes for a very clear distinction between the two (Gale et al., 2001). Extensive analysis of the seismic results has taken place (Arts et al., 2004a). The CO_2 is observed to rise vertically from the injection point but appears to be delayed by intermediate shale layers, until (it is thought) a dynamic equilibrium is established with CO_2 permeating the shale layers in a distributed manner. Finally, the CO_2 collects at the upper boundary of the formation under the cap rock. Little geochemical activity has been detected over the duration of the project. About 80–85% of the CO_2 is thought to be hydrodynamically trapped, 15–20% solubility trapped and less than 1% mineral trapped at present (Johnson and Nitao, 2004).

The seismic results have been used to attempt to verify the amount of CO_2 in store. Arts et al. (2002) indicate that the effective detection limit for local CO_2 accumulations is of the order of 1 m or less; a later paper (Arts et al., 2004b) estimates that a volume of less than 4000 m^3 (2800 t) of CO_2 can be detected using seismic analysis. A method of verification was developed which takes account of the thin beds of CO_2, restrained by the intermediate shale layers. By making allowance for the estimated saturation of each layer, this can account for 72% of the injected CO_2 under certain assumptions about the formation temperature. A further 13% is predicted to be in the intra-layer areas (Chadwick et al., 2005).

Weyburn

The Weyburn project is a demonstration of CO_2 storage made possible by adding a research component to ENCANA's CO_2-EOR project in Saskatchewan, Canada. The CO_2 is a by-product of the gasification of coal at Dakota Gasification's plant in Beulah, USA. Injection began in the year 2000 and, currently, approximately 5500 t/d of CO_2 are injected with a further 1300 t/d of gas and CO_2 recycled from the produced oil.

The injection zone is a carbonate formation at a depth of about 1450 m and temperature of 63°C; pore pressure varies from 12.5 to 18 MPa. From an understanding of the reservoir sealing and of the hydrology of the region it was decided that this formation would be well suited to long term geological storage (Wilson and Monea, 2004). There are two geological intervals – one approximately 6 m thick with high porosity (16 to 38%) but only moderate permeability (1 to >50 mD); the other, approximately 17 m thick, has low porosity (8–20%) but higher permeability (10 to >300 mD). In the study area there are 19 well patterns consisting of CO_2 injector wells, surrounded by several vertical and (in some cases) horizontal producer wells, amounting to about 150 wells in an area of approximately 25 km^2. A schematic diagram of the wells in one pattern in this area is shown in Figure 2.

The monitoring is being conducted on the first part of the reservoir to be injected with CO_2. The objective of the Weyburn monitoring project is to predict and verify the ability of an oil reservoir to store CO_2 securely and economically. Conducting this work in conjunction with an EOR project in an existing oil field had a number of advantages, including access to large volumes of CO_2, multiple sampling points across the field and detailed information on the sub-surface. However, there were also disadvantages, such as the complexity of the storage mechanisms and the need for coordination with production operations, which made interpretation of the results more difficult.

The monitoring program has four themes:

- Geological characterisation of the geosphere and biosphere
- Prediction, monitoring and verification of CO_2 movements
- CO_2 storage capacity prediction and economics
- Long term risk assessment.

The principal measurements made included a baseline survey, geochemical fluid sampling, tracer surveys, reservoir pressure surveys, and a variety of geophysical surveys, especially 3D time-lapse seismic, passive seismic, and soil gas sampling. The results from these measurements were used to calibrate reservoir models and geochemical models.

The extent of geochemical fluid sampling (made possible by the many wells in this field) provided good insight into the movement of CO_2 including indication of incipient breakthrough of the CO_2 front. This gave information on three chemical processes – dissolution of CO_2 in brine, reaction with carbonate rock, and

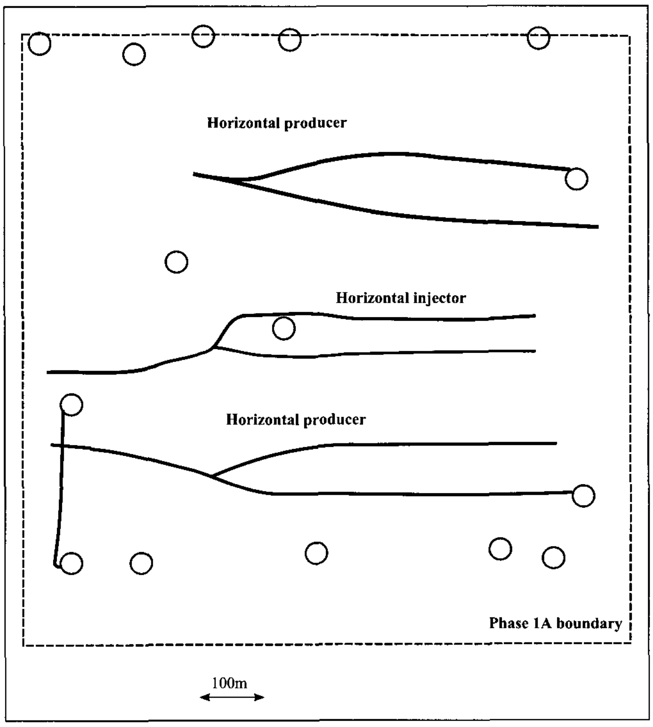

Fig. 2. Schematic diagram of one pattern of the Phase 1A area of the Weyburn project, illustrating the complexity of vertical and horizontal injectors and producers.

mineral dissolution. It was also found that not all of the CO_2 dissolved in the water or the oil – there is a CO_2 gas cap as well.

There was good but not perfect correlation between the anomalies seen in the seismic results and the pattern and volume of injected CO_2 deduced from sampling. Various reasons have been advanced for this, which are still being investigated (Wilson and Monea, 2004).

One vertical well was used for passive seismic detection but the events detected were mainly associated with changes in oil production or changes in injection; otherwise, microseismicity was low. Several measurement techniques have been used once, including 3D Vertical Seismic Profiling (VSP) in a single well, plus horizontal and vertical cross well tomography. These have not yet been repeated for various reasons. For technical and operational reasons, the tracer surveys were less successful than the other methods (Wilson and Monea, 2004).

Soil gas sampling was carried out three times between July 2001 and October 2003. No indication of CO_2 emissions different from background was found, although some anomalously high levels of higher hydrocarbons could not be explained. Isotopic analysis was not performed on the soil gas CO_2.

The minimum detectable volume depends on assumptions about the sensitivity of the seismic survey and on the physical state of the CO_2 – for travel-time delay measurements, the minimum detectable thickness would be about 1 m of CO_2 at reservoir conditions. The researchers feel that this translates into a "reasonable estimate of the detection limit" as 7500 t (Wilson and Monea, 2004), although if CO_2 were present as a free gas, this would be reduced by a factor of 8 (i.e., to 940 t); in the case of seismic amplitude measurements, a reasonable estimate of the detection limit is said to be 2500 t. Although there is no evidence of any leakage, the upper limit on the amount that could have migrated into the overlying aquitard is put at 2–3% of the total injected to date. A mass balance calculation is planned to verify the injected and stored amount but this has not yet been completed.

Risk assessment has been attempted but was constrained because it had to be done in parallel with the data collection; the results to date suggest that, for a single injector over a period of 5000 years, only 26% of the CO_2 would migrate out of the area subjected to injection, of which one third would move into the underlying aquifer and 18% migrate laterally. Only 0.02% of the CO_2 should diffuse into the cap rock and none of it should reach the overlying aquitard in this period. In addition, it was estimated that a maximum of 0.14% of the accumulated CO_2 would leak through the well bores. The potential leakage over 5000 years is estimated to be 0.001% of the CO_2 in place.

ORC

The Offshore Re-injection of CO_2 (ORC) project will eventually demonstrate full-scale injection of CO_2 (480 000 t/year) into a compartment of the depleted K12-B field offshore the Netherlands. This will be the culmination of a project initiated under the Netherlands government's CO_2 Re-use through Underground Storage (CRUST) program. This project is another significant demonstration of CO_2 storage underground although the eventual aim of the CRUST program could involve re-using the injected CO_2 for EOR.

The first phase of CRUST investigated the feasibility of re-injection and storage in an offshore, depleted gas field. This work was carried out by Gaz de France, the operators of the K12-B field. As well as the scientific and technical aspects of the project, the phase 1 work also examined the potential for significant legal or social impediments to the underground storage of CO_2; none was found in the initial assessment.

The K12-B field produces natural gas and supplies it to market after removal of CO_2. Phase 2 of the ORC project involves compressing (to 45 bar) about 60 t/day of the vented CO_2 for re-injection into the field as a test of the concept before full-scale injection takes place. This is necessary because the behaviour of the reservoir could not be predicted from theory alone (van der Meer et al., 2004). The injection is done through an existing well into a compartment of the field that is essentially isolated from the rest of the field. Injection started in May 2004.

The Rotleigend formation, part of the Upper Slochteren sandstone, is highly heterogeneous with zones of high permeability (300 to 500 mD) interspersed with low permeability regions (5 to 30 mD) and several natural, vertical permeability barriers. There are a number of blocks within the reservoir that are virtually isolated from each other, one of which is the target for CO_2 injection. The reservoir is 3800 m below sea level with formation temperature of 129°C.

A 3D reservoir simulation was developed and history-matched against bottom-hole pressure recorded during six years of gas production from this block. To establish a baseline for CO_2 injection, pressure and temperature measurements were made by wireline logging. The reservoir simulation and a well bore hydraulics model were used to predict the effects of CO_2 injection and for comparison with the first few days of injection; there was good agreement between prediction and observation in many respects although the pressure differential between reservoir and well-head was less than expected. Nevertheless, this has demonstrated the ability to inject CO_2 into the target formation at this depth. Injectivity is said to be high despite the relatively low permeability of the reservoir (van der Meer et al., 2004). It is not known what further measurements will be made on this formation when full-scale injection starts in 2006.

In Salah

Natural gas from some of the fields in the In Salah complex (Algeria) contains CO_2, which must be removed before the gas is sent to market. The operators of this project have decided to reinject about 1 Mt/year of CO_2 into this Carboniferous reservoir rather than emitting it to atmosphere. The gas-producing part of the reservoir lies about 1850 m below the surface. CO_2 injection started in 2004 through three horizontal wells, each between 1200–1500 m in length, into a water-containing part of the reservoir down-dip. An extensive monitoring program is planned although the final details will only be decided once the consortium has been formed to carry out the work (Wright, 2005).

The surveying of the reservoir for gas production purposes has provided a substantial understanding of the baseline. Other baseline measurements include gravity and soil gas. Samples will be taken of water, gas, and solids and various electric logging tools will be run throughout the injection; pressure surveys will be carried out at surface and down hole. Specific measurements to monitor the injection are likely to include microseismic and tilt meters; noble gas tracers will be injected with the CO_2. It is expected that 4D seismic surveys will be carried out but the details are yet to be decided. A monitoring well will be drilled into the saline formation, with oriented cap rock core and cuttings analysis. Down-hole gravity and geomechanical monitoring will be used. Surface gas measurements will be made using the eddy flux covariance technique to detect any CO_2 leakage. A collaborative monitoring program is now being established.

Future commercial projects

Further CO_2 injection projects are planned, several of which will be monitored (Table 2). Both Snøvhit and the Gorgon project are natural gas production projects that will inject CO_2 into geological formations under the sea. The Snøvhit project in the Barents Sea (Maldal and Tappel, 2004) will involve, amongst other novel features, a sub-sea wellhead for injection of CO_2.

RESEARCH PROJECTS INVESTIGATING CO_2 STORAGE

West Pearl Queen

The purpose of this project is to learn about the chemical and physical processes related to storing CO_2 (Westrich et al., 2001; Pawar et al., 2001). This is being achieved by injection of 2100 t of CO_2 into a depleted oil field in New Mexico, USA and subsequent monitoring and analysis. The injection took place over a 53-day period in 2002/3 into the Shattuck member of the Upper Queen formation. This is a largely sandstone formation about 7.5 m thick at a depth of about 1400 m and temperature of 35°C, with porosity of 15–20% and permeability ranging up to 200 mD. A prior core study and seismic analysis was undertaken to characterise the reservoir, together with well logs (Malaver, 2004) and a cross-well seismic tomographic survey. Additionally, analysis of lineaments and a survey using ground-penetrating radar were carried out to identify possible CO_2 leakage pathways.

The project made use of existing wells, one for injection and another, about 411 m away, for observation; other nearby wells in the field were still in active use for water injection (Figure 3). After injection, the CO_2 front did not reach the observation well (Bromhal et al., 2004). The formation pressure rose from about 2.4 to 11 MPa after which the formation was left to "soak" for approximately 6 months. Then a second seismic survey was undertaken, which has been used to delineate the plume of CO_2

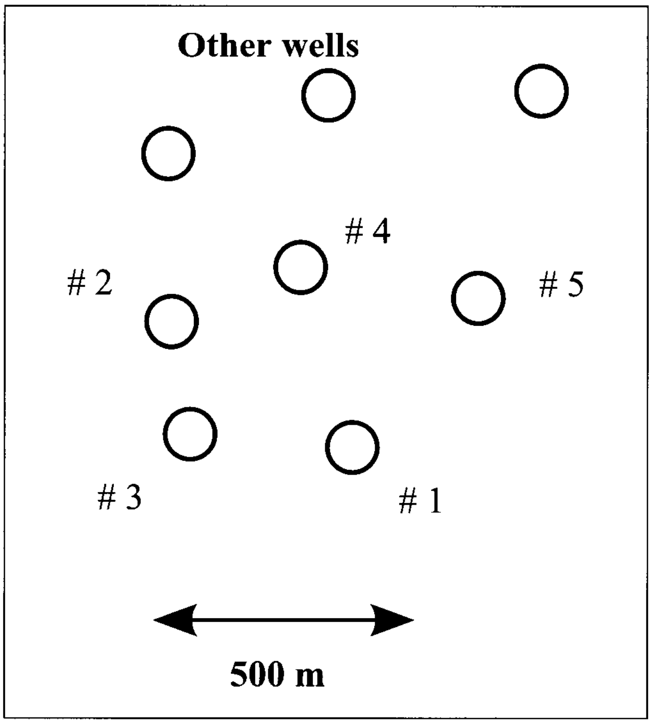

Fig. 3. Location of the CO_2 injection (#4) and monitoring (#5) wells in the West Pearl Queen field. The other nearby wells are not used for this project - #2 is plugged, #1 and #3 are waste water injectors used by the operator of the field.

(Pawar et al., 2003). The remaining free CO_2, amounting to 17% of the injected amount (J. Lorenz, personal communication), was then vented from the formation.

As part of the monitoring study, three perfluorocarbon tracers were injected with the CO_2 for three twelve-hour periods. Sampler tubes were located near the surface in a 300 m circle around the injection well to detect the presence of tracers. These were sampled at different times during the injection. There are no reports that anything was detected in the period immediately after the injection. Microseismic tests during injection did not observe any events, probably because the injection rate was too low to induce events large enough to be detectable at the observation well (J. Lorenz, personal communication).

Geomechanical, geophysical and flow models have been developed for the site. The geomechanical model has been used to help predict the deformations caused in the reservoir and surrounding rock, and to identify potential fracture zones. The flow of CO_2 and tracer has been modelled to help identify potential leakage pathways. A reservoir simulation has been used to model the flow of CO_2 in the reservoir and overburden strata; even assuming limited dissolution of CO_2 in the brine, the interaction with reservoir oil and possibly with the formation itself makes interpretation of the seismic results quite complicated. When the second seismic survey was carried out, the CO_2 was observed to have moved laterally up to 350 m from the injector but remaining within the domal structure (Malaver, 2004); CO_2 saturation in the residual oil was 40% at 200 m from the injector. Further analysis of the monitoring results is currently underway.

Nagaoka

As part of a larger program of work to research and develop underground storage of CO_2, an experimental injection was made into a sandstone reservoir near the city of Nagaoka on the island of Honshu in Japan. The target formation is a bed 12 m thick in a 60 m deep reservoir lying 1100 m below the surface, with formation temperature 48°C and pressure 10.8 MPa. Porosity is 23% and permeability, 10 mD. The site of the injection belongs to the operators of a gas field, although there is no connection between this and the CO_2 injection activities. Three observation wells have been sunk between 40 and 120 m from the injection well (Kikuta et al., 2004); see Figure 4.

The CO_2 was purchased from an ammonia plant and delivered to site by truck. Injection started in July 2003 at the rate of 20 t/day and continued until January 2005 by which time about 10 400 t had been injected. There was one 50-day interruption, during annual inspection of the ammonia plant, after which injection was resumed at the rate of 40 t/day.

Measurements to observe the behaviour of the CO_2 have included pressure and temperature measurement, geophysical logging, cross-well seismic tomography, and monitoring of induced seismicity (Xue et al., 2005). A baseline survey was carried out including geophysical logging of each of the three observation wells using induction, gamma ray, neutron, and sonic probes, and cross-well seismic tomography before and at regular intervals during the injection. Continuous pressure and temperature measurements were made at the top and bottom of the injector and at the bottom of one of the observation wells. Seismicity measurements have been made continuously at ground level and in another of the observation wells.

CO_2 was observed to migrate up-dip from the injection well. The breakthrough of CO_2 at the nearest observation well (a distance of 40 m from the injection well) was observed after 8 months injection. This was associated with a reduction in P-wave velocity of 23%. The resolution of the measurements is not stated in the papers seen to date but, given the ability of this cross-well seismic survey to produce a detailed tomographic image of 3200 t of CO_2, it seems likely that this technique will be able to resolve smaller quantities of CO_2. Further results and analysis from this project are presented in associated papers in this volume.

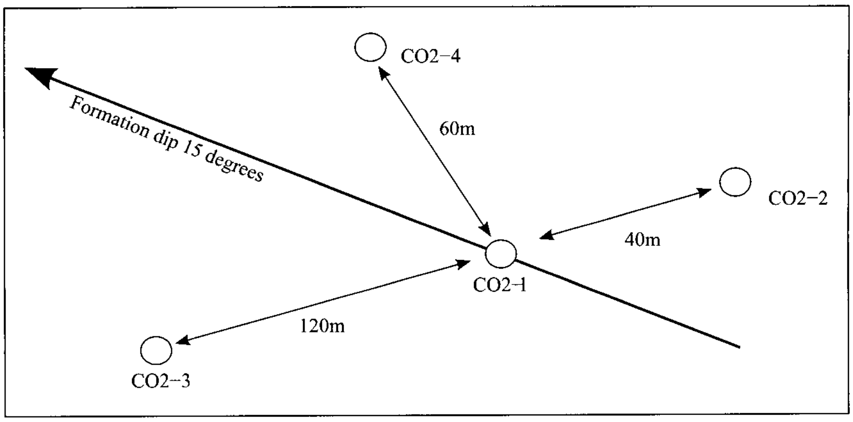

Fig. 4. The observation wells at the Nagaoka site (CO2-2, CO2-3 and CO2-4) are between 40 m and 120 m from the injection well (CO2-1).

Frio

The aims of this project are to demonstrate safe injection of CO_2 into a brine formation, to measure the sub-surface distribution of CO_2, to test models of the process and to develop experience for later injections. The site chosen for the project is onshore, on the Gulf Coast of Texas, USA. The target is a sandstone formation containing brine (but no hydrocarbons) at a depth of 1500 m; the target zone is 24 m thick with average porosity of 27% and permeability between 150 and 3000 mD as measured by neutron log (Hovorka, 2004). Formation pressure is 150 bar and temperature 30°C, so the stored CO_2 will be in the supercritical state. Injection of 1600 t of CO_2 took place during October 2004 through a well sunk for the purpose (Hovorka et al., 2005). A well, previously drilled through this formation 30 m up dip from the injector, has been refitted as an observation well; breakthrough of CO_2 to the observation well occurred 51 hours after injection started, which was earlier than predicted and in a narrower zone.

A variety of measurement techniques has been deployed to examine the behaviour of the CO_2. Pre-injection site characterization included 3D seismic, wireline logs of the wells, core analysis, and hydrologic testing. Pressure and temperature measurements were made down hole and at the surface during the injection. Brine and gas were sampled for pH, conductivity, alkalinity, major and minor ion chemistry, and stable isotope chemistry. A novel measurement device (Schlumberger's Reservoir Saturation Tool) is being used for time-lapse monitoring of CO_2 migration. Tracer gases (perfluorocarbons, noble gases, and SF_6) were injected. Geophysics measurements consist of cross-well seismic and cross-well, cased hole electromagnetic induction, and VSP. The cross-well seismic and electromagnetic induction measurements were designed for monitoring and estimating saturation whilst the VSP was designed for monitoring and imaging. Surface monitoring of tracers, CO_2, and CH_4 is being carried out in groundwater, in the vadose zone, in the soil, and at the surface. Down hole pressure and temperature gauges proved critical for interpretation of complex gas phases in the well bore. Geochemical modelling predicted the evolution of elements of the brine composition. Monitoring continues and results are now being analysed.

Future research projects

Several projects are planned, some of which are indicated in Table 4. The CO2SINK project at Ketzin in Germany will make use of an aquifer that had previously been a gas storage facility. Preparations are now underway for injection into the Stuttgart formation at a depth of approximately 700 m – in this reservoir, unlike the other projects discussed here, the CO_2 will not be in a supercritical state. The project will enable the development and testing of novel measurement techniques and calibrate existing geophysical and geochemical models. CO_2 will be purchased from a local refinery but there is possibility of receiving CO_2 in future from a pilot plant testing a novel CO_2 capture technique.

The Teapot Dome project in Wyoming, USA is to become a national test centre for developing CO_2 injection and monitoring techniques. It is adjacent to the Salt Creek EOR project and will make use of CO_2 delivered to Salt Creek by a 125 mile pipeline installed in 2004. Initial injection of a large amount of CO_2 will be into the TenSleep formation at 1700 m depth, with 10% porosity and 30 mD permeability. A structural closure has been selected for injection, which is penetrated by 33 wells, 13 of which have been cored so providing a substantial body of information on the target formation (Friedmann et al., 2004). Although there is residual oil in this field, this injection is not intended to produce substantial enhancement of oil production but to emphasise storage. Other potential injection targets range in depth from 150 m to 1700 m and could be used for later experiments. This will be a substantial opportunity for testing the sealing of such reservoirs, including use of a controlled leak from depth. This will be the largest amount of CO_2 injected in a research project, coming close to commercial quantities because of the availability of low cost supplies.

At the time of writing, limited information is available on two other projects – the Otway Basin Pilot in Australia, and injection into the Atzbach-Schwanenstadt field in Austria, which is being considered under the European CASTOR project.

DISCUSSION

At first sight, injection of CO_2 underground should be equally attractive (as a means of mitigating climate change) whether it involves injection into a deep saline formation, or into a depleted gas field or as part of an EOR project. However, when considered from the point of view of monitoring and verifying the stored CO_2, there is a substantial difference between the different types of storage reservoir. At one end of the spectrum, there is the relatively pure sandstone formation containing brine whilst, at the other end, there is the oil-bearing carbonate formation. The differences between them are exemplified by the preliminary results from Sleipner and Weyburn respectively. The more complex the formation, the more difficult it is to make accurate predictions about the fate of injected CO_2 – for example whether fingering or swelling of formation clays may affect the flow of CO_2 in the formation as has been seen at Frio and West Pearl Queen. Conducting a trial injection, as is being done at ORC, provides a means of learning more about the formation before full injection begins.

It may be possible to reconcile the amount of CO_2 injected with the amount in structural traps as measured by a seismic survey, at least in the period immediately after injection. The Nagaoka project has shown the power of cross-well tomography in imaging a relatively small amount of CO_2. However, in the longer term, as other trapping mechanisms become more important, verification of the amount of stored CO_2 will tend to rely on various types of geological model. It is likely this will have to be accompanied by near-surface measurements to determine whether any leakage is taking place.

To prove the models will require monitored injections maintained over periods of time. Isolated injections into deep saline formations, because of their relative simplicity, provide opportunities to examine different measurement techniques and to verify the models. Thus projects like Nagaoka and Frio will play a significant role in establishing confidence in the models that will be used to verify storage.

A key aspect of proving the models is obtaining (rather than inferring) data on the physical and chemical state of the CO_2 in the formation. In this respect, an onshore project has the advantage of being able to obtain more observation wells for a certain amount of money, and potentially better resolution, than an offshore project. This provides the researcher with much better opportunity to analyse the behaviour of the reservoir. Nevertheless, the opportunity for any such project is determined by circumstances, so there may be several reasons (not least access to suitable supplies of CO_2) why projects must be done offshore.

When full scale storage projects (storing tens of millions of tonnes of CO_2 per year) are eventually undertaken, the cost of monitoring and verification will be spread across much larger amounts of stored CO_2 so the unit cost (per tonne of CO_2 stored) should be very small (Benson et al., 2004). Thus, the overall cost of monitoring today's projects should not be seen as indicative of the specific cost of monitoring full scale projects.

Any rapid leakage from a store needs to be detected in case it presents a threat to human life or the local environment – appropriate detectors are built into any such injection project. However, slow leakage could, over the long term, negate much of the climate benefit of injecting CO_2 into geological formations. Such leakage may well be at a lower level than the natural CO_2 emissions at the surface, so that measurements must be taken sub-surface and/or using isotopic analysis or by use of tracers. No evidence of such CO_2 leakage has been reported to date but relatively little work is currently being put into detecting it. This presents significant challenges for future work in this field.

The most robust strategy for research in this field seems to be to develop and prove monitoring and modelling techniques onshore. Then the most appropriate techniques can be selected for large-scale projects which may be offshore. Large scale projects are also important for proving injectivity and leakage assumptions. This emphasises the need for international cooperation on research in this field with full sharing of results to take advantage of the different and still limited number of opportunities.

ACKNOWLEDGMENT

The author thanks John Lorenz for his help with information on West Pearl Queen.

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CO_2 地層貯留法の国際的な発展

ポール フロイント[1]

要 旨： CO_2 の地層貯留は、気候環境保護のために地球温暖化ガス放出を減少させるための新しい方法であるが、その基礎となる地下への流体圧入技術はすでに確立したものである。この方法の適用対象となる地層は稼動中または枯渇した油・ガス田、および深部塩水帯水層などである。貯留能力の予測は地層中での CO_2 の挙動モデルに依存する。そのモデルは今後の改善と確認が必要であり、またモニタリング手法は開発・検証が必要である。これらは、実証・研究プロジェクトを通して達成されるであろう。現在の稼動中の CO_2 地層貯留プロジェクトには Sleipner, Weyburn, ORC, In Salah;などがある。 研究プロジェクトは West Pearl Queen,長岡, Frio などで行われている。本稿では、圧入モニタリングが行われたプロジェクトをいくつか説明する。CO_2 貯留に用いられた貯留層、および関連モニタリング技術について簡単にレビューする。

本論文中で筆者は、技術開発やモデル立証のために実施される程度の小規模の研究プロジェクトであっても、気候変動緩和を目指して CO_2 地層貯留の有効性を確立するといったような、モニタリングを伴うほどの大規模圧入プロジェクトと相互補完的であると主張する。

キーワード：CO_2、気候変動、CO_2 地中貯留、地下 CO_2 のモニタリング

CO_2의 지질학적인 저장에 있어서의 국제적인 개발들

Paul Freund[1]

요 약： 포획된 CO_2 의 지질학적 저장은 기후 보호를 위한 온실가스 방출 감소의 새로운 방법이나, 유체의 땅속 주입과 관련된 기존의 확립된 기술에 근거하고 있다. 이 기술에 대해 관심있는 지층 구조는 현재 가행 중이거나 고갈된 석유, 가스층, 그리고 심부 염수 대수층이다. 저장 능력에 대한 예측은 지층구조내에서 CO_2 의 거동 모델들에 의해 좌우되는데, 이들 모델들은 정제되고 입증될 필요가 있고 모니터링 방법들도 개발되고 증명될 필요가 있다. 이 필요성들은 모니터링되어지는 시범이나 연구 프로젝트를 통해 충족될 수 있다. 현재 CO_2 저장을 시범해 보이는 상업적 프로젝트에는 Sleipner, Weyburn, ORC, In Salah 가 있으며, 연구 프로젝트로는 West Pearl Queen, Nagaoka, Frio 가 있다. 이 논문에서는 모니터링 되는 주입 프로젝트들 중 몇 개에 대해 서술한다. CO_2 저장에 사용되는 저류층들과 관련된 모니터링 기술들을 간단히 살펴본다. 모델들을 증명하고 기술들을 개발하기 위해 이용되는 작은 규모의 연구 프로젝트들이 기후 변화 완화에 이 기술들의 실행 가능성을 확립하는 큰 규모의 모니터링되는 주입들에 유용한지에 대해서는 논란거리이다.

주요어：CO_2, 기후변화, CO_2의 지질학적 저장, 지하 CO_2의 모니터링

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