Oil & Gas Science and Technology – Rev. IFP, Vol. 60 (2005), No. 3, pp. 573-582

Dossier

CO_2 Capture and Geological Storage: State-of-the-Art
Capture et stockage géologique du CO_2 : état de l'art

Monitoring Subsurface CO_2 Storage

P. Winthaegen[1], R. Arts[1] and B. Schroot[1]

1 TNO Built Environment and Geosciences, Business Unit Geo-energy, Princetonlaan 6, 3584 CB Utrecht - The Netherlands
e-mail: Pascal.Winthaegen@tno.nl - Rob.Arts@tno.nl - Barthold.Schroot@tno.nl

Résumé — Monitoring du stockage souterrain de CO_2 — Les techniques de monitoring actuellement appliquées au stockage de CO_2 sont présentées. Ces méthodes sont regroupées en 3 familles selon leur zone d'application :
– l'atmosphère et la zone souterraine proche de la surface ;
– les couches recouvrant le réservoir ;
– le réservoir et ses pièges.

Une autre façon de regrouper ces techniques peut être envisagée en fonction de la chronologie, d'abord pendant l'injection et le processus de stockage, puis à long terme (après abandon du champ). Dans cette optique, l'importance de la caractérisation et du monitoring avant injection est soulignée.

Abstract* — *Monitoring Subsurface CO_2 Storage — *An overview is given of various currently applied monitoring techniques for CO_2 storage. Techniques are subdivided in correspondence to their applicability for monitoring three distinct realms. These are:*
– *the atmosphere and the near- surface;*
– *the overburden (including faults and wells);*
– *the reservoir with its seals.*

Another subdivision can be made with respect to time, i.e. first monitoring during the injection and storage process and subsequently monitoring for the long term (after abandonment of the field). In this perspective, the importance of characterisation and monitoring before injection is addressed.

INTRODUCTION

One of the measures to reduce the emission of CO_2 into the atmosphere is to store CO_2 in the subsurface. CO_2 will be injected into subsurface structures, from which it is assumed that no leakage to the surface will take place. The CO_2 involved might be captured from industrial activities, such as the combustion of fossil fuels. In addition to industrial CO_2 also natural CO_2 is being injected. Both in offshore Norway and in offshore the Netherlands natural gas is being produced which has a high CO_2 content. During production the CO_2 is separated on the platform and re-injected into respectively an aquifer in the Norwegian case (the Sleipner gas field) and back into the gas reservoir in the Dutch case (the K12-B gas field) instead of venting the CO_2 into the atmosphere. Recently, experience in monitoring CO_2 in the subsurface has been gained by considering natural pure CO_2 accumulations. In the United States there are examples of natural CO_2 reservoirs with a 98% CO_2 concentration in the greater Colorado Plateau and the Southern Rocky Mountains region (Allis *et al*., 2004). In Europe naturally occurring CO_2 was studied in the scope of the recently completed EC-supported NASCENT project (http://www.bgs.ac.uk/nascent/).

Natural CO_2 can be the result of degassing of basaltic magmas or metamorphism or it can be dissolved in the subsurface from natural hydrocarbons.

Instead of injecting CO_2 only for the purpose of disposing, it can also be injected (primarily) because of its beneficial effects on oil or gas production. For instance, in the case of enhanced oil recovery (EOR) CO_2 can be used to release the oil from the porous rock and cause the oil to better flow to the producing wells. The Weyburn project in Canada has demonstrated how monitoring techniques can be applied in case of an onshore EOR project (Petroleum Technology Research Centre, 2004).

Depending on the lithology of the target formation in which it is injected and the quality of the seal, CO_2 might be present for thousands of years (Zhou *et al*., 2004). However due to its buoyancy effect some depletion may take place. When CO_2 comes into contact with groundwater the water becomes more acid. CO_2 is not toxic, but in large accumulations it may be suffocating, especially in low situated areas where the CO_2 gathers like a pond. Also, as a result of pressure changes in the subsurface related to injection local seismicity may occur.

Here, monitoring aspects, related to subsurface storage of CO_2, are discussed that aim at both verifying the injected amounts of CO_2 and at detecting possible leakage at an early stage. Regardless of the specific objective, the applicability of a monitoring technique in general depends on geology and surface conditions.

1 NEED FOR CO_2 MONITORING

Monitoring subsurface storage of CO_2 is being done for the following reasons:

- Health and safety reasons. It is important that after injection and storage of CO_2 it can be ensured that (human) health and the environment are not jeopardised. Monitoring must demonstrate the integrity of the geological seal. Preferential pathways for the upward migration of CO_2 to the surface such as faults and boreholes must be monitored. An early indication for leakage of CO_2 to the groundwater or to the atmosphere gives the possibility to take measures.
- Mass balance verification. The total injected volume CO_2 needs to be monitored to verify that it is stored in a controlled way and into the correct target formations. Monitoring is applied to verify that the intended injection plans are met according to permissions and legislation and that the numbers used for emission quota and carbon credits (Kyoto protocol) are correct. The stored CO_2 should equal the injected amount of CO_2 (mass balance).
- To improve the understanding of behaviour and future state of the injected CO_2 within the reservoir. If properly monitored, this will allow for improved knowledge about the subsurface. Models can be updated so that future behaviour can be more correctly predicted.
- Development of techniques and methodologies regarding subsurface storage of CO_2 and possible other future gasses to be injected.

For all of these arguments monitoring is important during the injection and storage phase of the project and considerable amounts of time and money should be spent to monitor the reservoir, the overburden, wells, injection facilities, the surface and the atmosphere.

In addition, because of the first argument on health and safety, monitoring is also important at a larger time-scale, after abandonment of the field by the field operator (*i.e.* after completing the storage process). Considering the lifetime of the injected CO_2, depending on the degree of bounding and depending on the sealing capacities of respectively the reservoir and the overburden, continuous monitoring or time-lapse measurements at strategic places can be used. These should preferably be simple, durable and not too time consuming and applicable over a long period of time. Because of the long lifetime, it is questionable whether it is realistic that monitoring is applied as long as free CO_2 gas is present within the reservoir. This underlines the importance that the reservoir and its seal are fully understood and that future behaviour can be well predicted before leaving the site successfully.

A side effect of injecting CO_2 into the subsurface may be ground movements resulting from geomechanical changes. Injection of gasses may change the stress in the reservoir and in adjacent formations. Changes in stress might cause small earthquakes. Uplift of the surface, earthquakes and subsidence due to lateral migration of the injected CO_2 may have undesirable effects, depending on the local circumstances. Subsidence and earthquakes are known to occur during gas production (*e.g.* in the northern part of the Netherlands). Hence, monitoring possible ground movement is required.

Additional monitoring might be required in case of more extensive use of the subsurface. The injected CO_2 should not harm exploration and exploitation of other accumulations of water, hydrocarbons, other minerals, ores and geothermal energy. Monitoring will then not only be focused at the CO_2 reservoir, but also at the other exploitation activity. Due to extra activity near the storage location the intensity of monitoring can be increased.

In addition to monitoring the injection and storage of CO_2, the injected CO_2 needs to be characterised. This will not only facilitate monitoring the CO_2, but also the interpretation of the monitoring data. For example, the injected CO_2 should be distinguished from other (natural) CO_2 sources. This already indicates that monitoring (monitoring CO_2 directly and the (subsurface) should start before injection, in order to obtain a baseline (or reference) measurement. Measurements acquired during and after injection can then be compared to this reference measurement.

2 PLANNING CO_2 MONITORING

In addition to the monitoring of the behaviour of the injected CO_2 in the reservoir itself, the monitoring should also be focused on seal integrity and, as a consequence, on leakage to other geological formations and the surface and atmosphere. Features, events and processes (FEP analysis) have been described that may affect the future integrity of the seal (*e.g.* Espie, 2004; Maul *et al.*, 2004; Wildenborg *et al.*, 2004). Some examples of relevant identified FEP's are (Arts and Winthaegen, 2005):

- formation damage due to drilling of a well;
- operational failure of a well;
- casing or cementation defects due to improper design or construction;
- fracturing or fault activation due to increased CO_2 pressure;
- dissolution or dehydration of the seal due to the presence of CO_2;
- unrecognised features in the seal like faults, joints or fractures;
- corrosion of casing due to CO_2;
- deterioration of cement plug after abandonment due to CO_2.

Potential leakage can occur either through seal failure (including lack of seal) or through well failure (including leakage along the bore hole). Hence, the choice of the monitoring technique depends on the geological target formation, on the site situation including infrastructure, CO_2 injection programme, duration of the project, and on the objective, *i.e.* focus of the monitoring.

It is important to have an early warning (or early detection) system which can detect low concentrations. The earlier possible leakages or migration pathways are detected, the easier it will be to take mitigating actions (for example reproduction of the CO_2 or re-plugging abandoned wells).

2.1 Geological Target Formation

The main requirement for geological CO_2 storage is the presence of a suitable reservoir rock with sufficient storage capacity and an overlying sealing formation to prevent leakage to other formations and to the surface. Any possible features affecting the sealing integrity of the cap-rock formations should be identified, *e.g.* faults and fractures, and must be avoided as much as possible while planning a storage project. Furthermore a good characterisation of the target formation (reservoir and seal) and of its properties is of crucial importance.

In case of geophysical monitoring, the changes in physical parameters induced by the CO_2 must be above the detection threshold with sufficient resolution. When monitoring of the reservoir is applied from the surface (*e.g.* 4D seismics), the physical parameters of the overburden play an important role. Accurate monitoring will be much more difficult in case of a geologically complex structure. In case other pore fluids or gases are present, the monitoring method should be able to distinguish the injected CO_2 from the original pore fluid or gas.

In case of geochemical monitoring, it is important to know if the chemical signature of the injected CO_2 can be distinguished from that of naturally occurring CO_2 in the shallow subsurface, or from other, deeper gasses and fluids present.

Since the applied monitoring techniques to a certain extent depend on the storage formation (reservoir and seal), the main options are summarised below highlighting specific monitoring aspects:

- Producing or nearly depleted oil and gas reservoirs. Produced hydrocarbons or infill water will (partly) be replaced by CO_2. In general, it is assumed that the hydrocarbon seal is also a good seal for CO_2 and has already demonstrated its integrity over geological times. Much information about the static and dynamic properties of the reservoir and data is already available because of the long production history. Calibrated reservoir models are available and can be used to predict the CO_2 migration in the reservoir. A number of existing wells can be made available for monitoring. Older abandoned wells require specific monitoring attention as a potential leakage pathway. One of the major obstacles for geophysical monitoring is probably to distinguish between the injected

CO_2 and methane. Examples are the Weyburn site in Canada and the K12b site in the Netherlands.

- Deep brine filled reservoirs/layers. The pore fluid is brine water in which the CO_2 can dissolve. Lateral migration is caused by possible flow of the pore fluid. An example of a demonstration project using a saline aquifer is the SACS project carried out in offshore Norway (most recent publications: Arts *et al*., 2003; Chadwick *et al*., 2004; Zweigel *et al*., 2004; Arts *et al*., 2004). Monitoring should focus on the sealing capacity of the cap rock since this might not be a proven seal for "free" gas. Due to the relative strong contrast in compressibility the free CO_2 can be well imaged by seismic methods.
- Cavities in salt layers/domes. Not the pore space but open cavities (filled with brine water) in the salt can be used to inject CO_2. The impermeable and plastic behaviour of salt appears highly suitable to store CO_2 (Bachu and Rothenburg, 2003), though the storage capacity seems relatively small compared to the other options. Although salt might be located at shallower depths compared to hydrocarbon reservoirs the conventional time lapse seismic imaging is not suited to monitor the injected CO_2.
- Unmineable coal seams. Injecting CO_2 into coal has the advantage that CO_2 is stored and that methane is produced (ECBM: enhanced coal-bed methane recovery). Although the CO_2 adsorbs to coal, a sealing cap formation needs to be present to avoid leakage of "free" CO_2 from the coal to the surface. An example of a CO_2 sequestration project in coal is the RECOPOL project carried out in Poland (Van Bergen *et al*., 2002). These coal layers are in general located shallower than the hydrocarbon reservoirs, but can be relatively thin and therefore difficult to image from the surface. If available, wells can be used for monitoring.

2.2 Site Situation

The site situation, including the infrastructure, climate conditions and surroundings, is of influence to the different monitor techniques, especially with respect to their repeatability and their detection threshold. Monitoring from the surface in a desert area is completely different from monitoring in an urban region or in an offshore environment. Factors like (seasonal) variations in weather or obstruction of monitoring positions due to new infrastructure can severely degrade the quality of the monitoring. Furthermore varying background noise levels such as in naturally occurring CO_2 concentrations for geochemical monitoring or ambient noise for geophysical methods, can mask the actual changes induced by the injected CO_2.

Because CO_2 is naturally occurring in the subsurface, the sea and the air, the background level of the monitoring site should be determined prior to injection (see next section).

2.3 Monitoring Focus

Monitoring can be applied from the surface, but also near the injected formations in the wells. In the latter case these are in general point measurements and do not provide a lateral 2D or 3D image of CO_2 concentrations, unless a large number of wells is available. The CO_2 sensors at the surface measure directly CO_2 concentrations in the atmosphere or in soil, while geophysical monitoring at the surface or in wells acquires data that has to be interpreted to CO_2 accumulations. In the latter case movement of the injected CO_2 in the formation is imaged and possible leaks to above laying strata can be detected.

The subsurface can be divided into 3 subsurface systems. For each subsurface system specific monitor techniques can be applied. The 3 subsurface systems and their monitor objectives are:

- Surface System: includes air, water, soil, groundwater, shallow subsurface (incl. subsurface infrastructures, *e.g.* tunnels). The objective is to monitor possible leakage into the biosphere and atmosphere and indicate safety hazards. With respect to infrastructures also seismicity as a result of subsurface pressure changes and possible heave as a result of injection are relevant.
- Reservoir System: includes the target formation, the geological seal, and local faults. The objective is to monitor the CO_2 migration within the target formation, the sealing integrity of the cap rock and possible leakage through local faults to above laying formations.
- Background System: includes the overburden formations of the target formation, faults, and wells. The objective is to monitor leakage through the overburden, leakage along faults to overlying formations and along the outside or inside of the well (annulus) to overlying formations, possible heave or seismicity as a result of pressure changes.

There is overlap between these subsurface systems *(Fig. 1)* and there will also be overlap between the covered monitor areas. However, basically each monitor technique is focused to a certain subsurface system.

Before CO_2 injection, the background CO_2 concentrations need to be determined. Other sources of CO_2 in the vicinity of the injection location and possible preferred pathways to the surface need to be determined. These sources are the result of human and industrial activities, but also of biological activities (trees, plants, bacteria). CO_2 concentrations increase during the night due to respiration and because photosynthesis can not occur, and decrease during the day when photosynthesis starts. In general, these concentrations are not constant and do vary during the day. Factors causing this variation are *e.g.* sun light, wind, and perhaps temperature and water. An example of daily variation is shown in Figure 2. The measured values of CO_2 concentration are recorded near the well locations of the Kaniow site (RECOPOL project), before injection

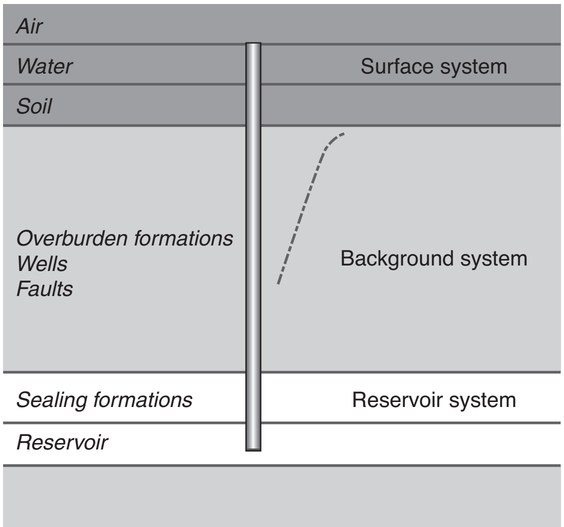

Figure 1

Subsurface profile showing the Surface System, Reservoir System and Background System. In the latter system also wells and possible faults (dashed) are included.

(Pagnier *et al.*, 2004). The CO_2 sensors are placed in 2 m deep tubes. This is done to reduce recorded variations due to biogenic activity, *e.g.* CO_2 emission by roots and organisms through respiration. Still, some variation is recorded.

Also seasonal variation will occur with an average increase during winter and an average decrease during summer (Keeling and Whorf, 2004). Moreover, based on a 46-year monitor program the authors observe an upward trend in the mean annual concentration of CO_2 in air.

Because of these variations it is important to monitor CO_2 changes over time and location in order to establish the background CO_2 concentrations and their fluctuations prior to the actual injection. After injection takes place and after correction for noise and other changes, anomalies in the measured monitor data can be inverted to occurrence of CO_2 and possible CO_2 leakage.

3 MONITORING TECHNIQUES

In general, the currently applied monitoring techniques were developed for the oil and gas industry. However as a result of various research projects also new technology is developed specifically for monitoring CO_2. The technology can be divided into the following groups: engineering, geophysical, geochemical and geodetic techniques. These techniques have a different location of application and focus at different parts (systems) of the (sub)surface. However, there is overlap between the technologies applied, not only in location of application, but also in spatial coverage. The engineering techniques are focused at the reservoir and the wells. Seismic measurements are focused at the reservoir and the overburden. Geochemical techniques can be applied in the wells (*e.g.* at reservoir level) and in the Surface System. Geodetic techniques monitor the Surface System. An overview of techniques is shown in Table 1.

A combination of monitoring techniques can be used in order to use the advantages of each individual method, *e.g.* based on monitor focus, spatial coverage, resolution and costs. Based on the measurements and changes in response over time a model of the subsurface is constructed and

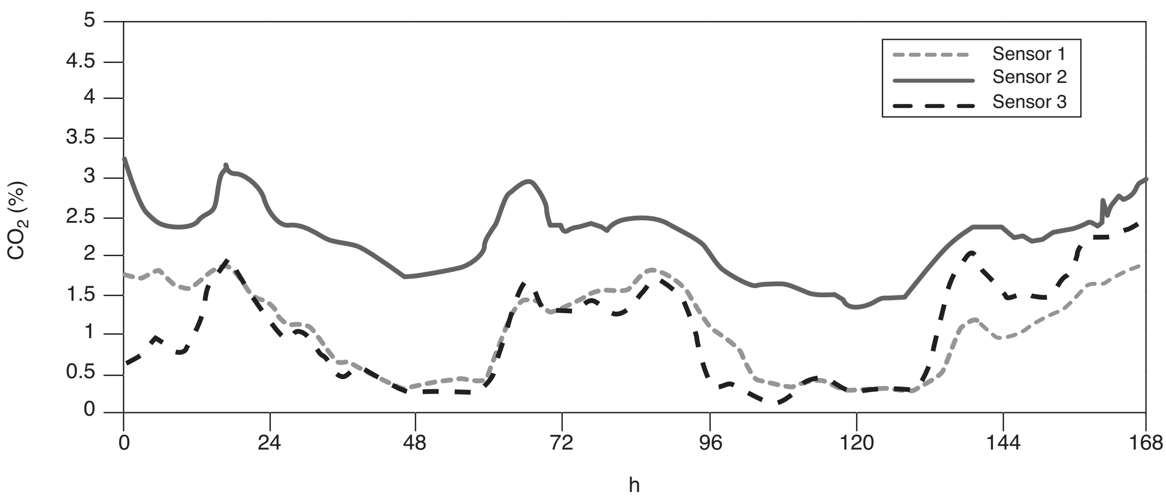

Figure 2

Raw measurements showing the variation in CO_2 concentration in soil before injection. The general trend in concentration (with exceptions) is a decrease during the night with a trough in the middle of the day followed by an increase (Van Bergen *et al.*, 2005).

TABLE 1

Monitoring techniques in relation to the subsurface systems.
The measurements are continuous or repeated in time

System	Group	Technique	Remark
Reservoir	Engineering	Pressure	Local measurement
	Engineering	Temperature	Local measurement
	Chemical	Tracers	Local measurement
	Chemical	Gas analysis	Isotope or compositional analysis. Local measurement
	Chemical	Water analysis	Isotope or compositional analysis. Local measurement
Reservoir & Backg.	Geophysical	3D surface seismic	Spatial coverage
	Geophysical	Crosswell seismic	Measurement between wells
	Geophysical	Offset VSP	Spatial coverage using 1 well
	Geophysical	Microseismicity	Monitoring well
	Geophysical	Gravity	Applied at surface or in well
	Geophysical	Electro-magnetic	Applied at surface or in well
	Geophysical	Self-potential	Applied at surface or in well
Background	Geophysical	Cement bound logs	Measurement along well
	Chemical	Overburden fluid	Local measurement
	Chemical	Well fluids after abandonment	Local measurement
Surface	Geodetic	Geodetic surveying	Spatial coverage
	Geodetic	Satellite remote sensing	Spatial coverage
	Geodetic	Tilt meters	Local coverage
	Geodetic	Airborne remote sensing	Spatial coverage
	Chemical	Soil/seabed gas	Local measurement
	Chemical	Surface fluid	Local measurement
	Chemical	Microbiology	Local coverage
Surface & backg.	Geophysical	Subbottom profiling	Spatial coverage
	Geophysical	Side scan sonar	Spatial coverage

updated when new data are added. In this quantitative process monitoring, data interpretation and reservoir simulation are combined to construct a dynamic model. This model (reservoir flow model) is used to model synthetic data that is compared to real, acquired data. The resulting model is used to predict future behaviour of the subsurface. Based on these results it can be decided to adjust the monitoring for the long term after the injection and storage process, *e.g.* by employing reduced monitoring.

3.1 Reservoir System

Downhole pressure and temperature monitoring are applied to obtain continuous or repeated measurements from the injected reservoir upwards. The sensors can be moved in the well or permanently positioned near the perforations. The data are transmitted to the surface. The measurements are only representative for the part of the subsurface close to the well. The data are used for reservoir understanding, injection performance and CO_2 breakthrough.

Reservoir tracers can be injected in one well and migrate to another well where they can be measured. An example of a chemical tracer is SF_6. With tracer tests the migration and connectivity between wells are determined. Also the volume and flow rate of the reservoir can be established. The tracer can be injected using the CO_2 injection facility. However, also a producing well is required. This method can be combined with reservoir gas and water analysis.

Reservoir gas and water analysis are repeatedly applied and used to monitor changes in isotope signatures and changes in chemical components as a result of possible reactions of the CO_2 with the host rock or with the sealing cap rock. The CO_2 that is injected will have the isotope signature of the source gas from which it is produced. Comparing the isotope signatures of the injected and produced gas (including natural CO_2) might give an indication about the breakthrough (assuming that the isotope signatures are distinguishable). Composition of the produced gas and water is analysed to see if breakthrough occurs. Additionally pH can be measured. Formation water is expected to acidify when coming into contact with CO_2. Therefore, water and gas need to be analysed on a regular basis. However, the spatial information is depended on the availability of monitor wells, *e.g.* for the Weyburn CO_2 Monitoring Project many wells are available, while for the RECOPOL project only one well is available.

3.2 Reservoir and Background System

The reflection seismic method is based on the principle that acoustic signals generated at or near the surface are being reflected at interfaces in the sub-surface where physical (elastic) properties of rocks change. Also changes resulting from a change of gas- or fluid content of porous rocks may be detectable (depending on the circumstances). After processing of the reflected and recorded signals the seismic method provides a detailed 3D image of the sub-surface. Repeated 3D surveys are referred to as time-lapse or 4D seismic acquisition and provide an excellent monitoring tool.

In case of 4D seismic acquisition seismic sources and receivers can either be permanently installed or reinstalled and applied after a certain period of time (the time-lapse). Changes in the subsurface will result in changes in seismic response. However, the detectability of changes related to CO_2 presence or migration is site specific. The main physical parameters important for the seismic methods that may change as a result of CO_2 injection are: density, compressibility, and effective pressure. Due to chemical reactions also the porosity might change.

The result in the seismic response is a change in seismic amplitude (especially as function of source-receiver offset) and a change in travel time (because of changes in the propagation velocity of the elastic waves). In Figure 3 an example is shown from the SACS project where CO_2 is injected in a saline aquifer. Compared to the situation before injection the change in amplitude as a result of higher rock property contrasts is visible. Also the increase in travel time, as a result of lower velocities due to the injected CO_2, is obvious. At Sleipner we have estimated, that a change in the order of 5000 tonnes of CO_2 is probably detectable on the time-lapse seismic data. One must bear in mind, that such a threshold is highly dependent on the rock properties.

An advantage of the method is that a spatial coverage of the subsurface is obtained. Seismic acquisition can also be applied using one or more wells in which the receivers or source can be positioned. The other stations are positioned at the surface yielding a 3D coverage of the surface, or alternatively, in another well, in which case we speak of cross well seismic acquisition. In the latter case only an image between wells can be obtained.

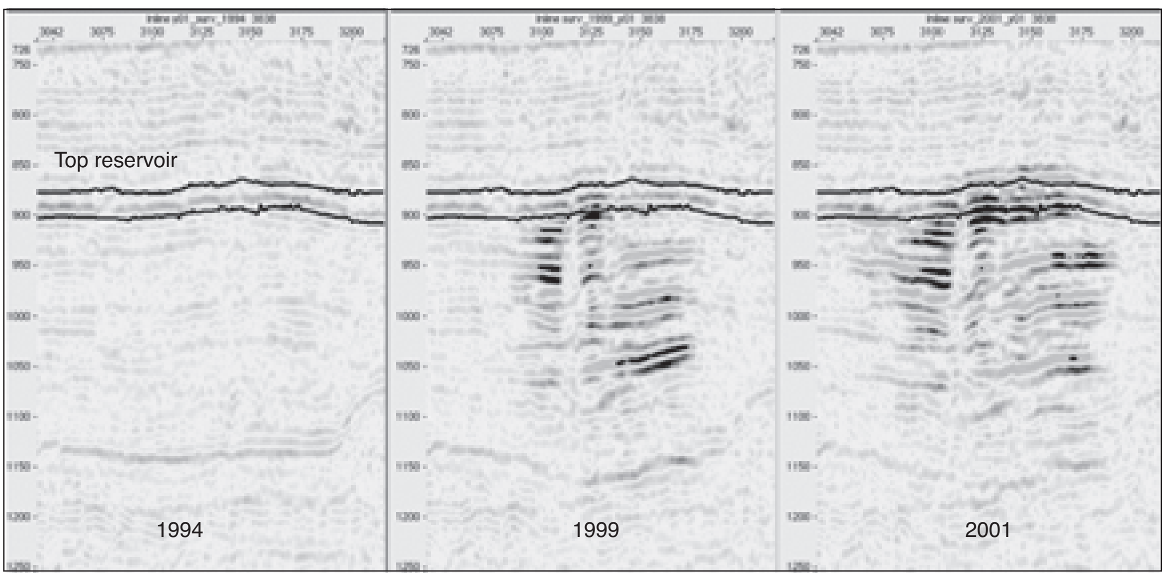

Figure 3

An example of the change in seismic response due to injection of CO_2 in a saline aquifer. Shown is the same seismic line before CO_2 injection in 1994 and during injection in 1999 and 2001 (from Arts *et al*., 2003). The injected CO_2 enhances the impedance contrast of internal layers in the aquifer.

Besides the conventionally used pressure waves in seismic acquisition also shear waves can be detected and processed. Shear waves are less sensitive to the pore fluids, but more sensitive to fractures. By using both pressure waves and shear waves the subsurface can be better characterised. Due to the nature of shear waves they occur in 3 directions. In case these waves are generated from a shear wave seismic source 9 components can be recorded. Acquiring these shear waves from a generated pressure wave (converted waves) 3 components (and the pressure) are recorded.

Microseismic monitoring is applied by positioning permanent seismic receivers in a well. It acoustically measures fracturing induced by increase in pressure as a result of injection. By recording all seismic events the spread of injected CO_2 can be mapped and faults might become visible. The size of the recorded events is used to estimate the seismic hazard (ground movement). The success of the method depends on the occurrence of recordable seismic events. Also it is assumed that the CO_2 front aligns with the seismic events.

Time-lapse gravity measurements can detect changes in mass in the subsurface. Therefore the method can be applied for injected CO_2 mass verification in case the in situ density of CO_2 is known. After the injection phase, changes in gravity might indicate migration or (large-scale) leakage to other, shallower geological formations. The estimated resolution at Sleipner for the time-lapse gravity monitoring is, that a change of 5 µGal can be detected.

Because gravity is a potential method the measurements are also influenced in case of heave as a result of the injection process. Gravimetry can also be applied in a well resulting in a higher resolution, but only measures around the well. With respect to seismic gravimetry is a low-cost monitor technique, but has (vertically) a lower resolution. A combination of both methods can improve the characterisation of changes in the subsurface.

Electric and electro-magnetic monitoring, repeated in time, measures the change in resistivity due to CO_2 injection. The resistivity is expected to increase when CO_2 replaces *e.g.* conductive brine. Also occurrence of fracturing can be detected. These methods can be applied from the surface, but, like seismic acquisition, also combinations with a well and between wells are possible. Alternatively, self-potential (or spontaneous potential) monitoring can be used to monitor CO_2 flow paths through the rock matrix and measures the change in electrokinetic parameter due to CO_2 migration (Moore *et al.*, 2004). In case the resolution is sufficient, these methods also provide a low-cost alternative to detect (large-scale) migration of CO_2.

3.3 Background System

Downhole logs can be used to measure well integrity and to monitor behind the casing. An example is the cement bound log. When repeated after a certain period of time changes in the response can be analysed and possible cement fall off or leakage can be detected. Logs only provide data from the near well region.

Overburden fluid analysis is applied to determine possible compositional changes and to determine isotope analysis. Chemical changes and shifts in isotopes might indicate leakage from the injected reservoir. Additionally, pH, pressure and temperature can be monitored.

Similar to the overburden fluid analysis, the well fluids after abandonment need to be monitored. Also here, chemical composition, isotopes, pH, pressure and temperature need to be monitored. Preferably the monitoring must be applied continuously.

3.4 Surface System

Satellite interferometry (InSAR) and geodetic measurements provide values for vertical displacement as a result of CO_2 injection. The InSAR (Synthetic Aperture Radar interferometry) technique is capable to map small changes (up to some millimetres) over wide areas, while the conventional geodetic surveying is more sensitive (less than 1 mm). The InSAR technique results in a continuous spatial coverage and uses phase differences between radar images recorded at different times over the same area. Conventional geodetic surveying results in a sparse network of very precisely measured points (Biegert *et al.*, 1997). Also tilt meters are used to determine the vertical displacement as a result of injection. In general, these techniques are applied in case of hydrocarbon production and map possible subsidence as a result of the production.

Airborne remote sensing uses hyperspectral imaging. Changes over time in spectral reflectance, that is related to changes in vegetation, might indicate possible CO_2 leakage. Additional monitoring is required to verify if the change is related to possible leakage. In general, there might be a relation between the (micro) biological occurrence, growth, and composition and the occurrence of CO_2. Changes might therefore reveal CO_2 leakage.

Soil gas and seabed gas can be used for direct detection of CO_2 using *e.g.* the infrared spectrum. Applying this technology most gases result in a unique spectrum. In case the gas can be collected it is possible to monitor chemical composition and to perform isotope analysis. Similar can be done using surface fluids. Changes might reveal possible leakage of CO_2. Because at the surface the overall part of CO_2 detected will be natural CO_2 isotope analysis, in combination with reference measurements before injection, is important to determine the origin of the detected CO_2.

3.5 Surface and Background System

Sub-bottom profiling is a marine geophysical method which provides a high-resolution image of the near-subsurface

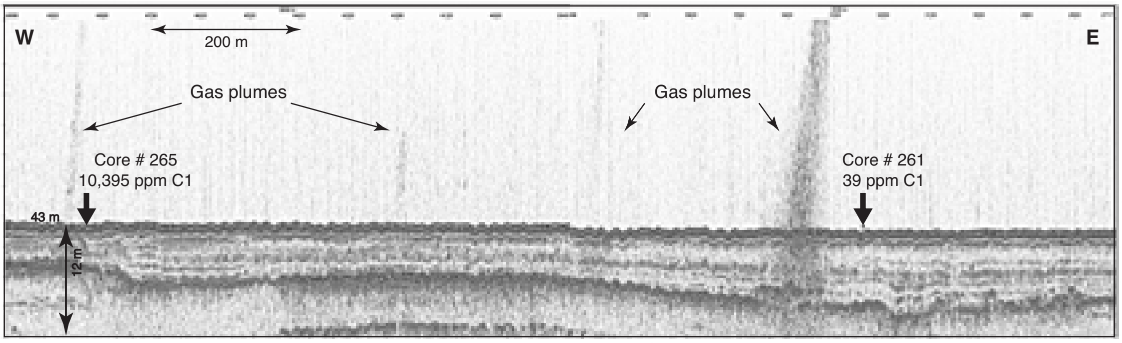

Figure 4

A high frequency acoustic profile (sub-bottom profiling) across North Sea methane seeps. The venting of gas into the water column is expressed as "gas plumes". The interpretation of these geophysical is confirmed by the presence of geochemical anomalies in the head space gas of seabed sediment samples (methane concentration shown at two sites).

(down to about 20 m below seabed). Anomalies in the shape of the sea floor, such as seabed pock marks, might reveal location of CO_2 leaks. In case of a considerable amount of leakage the presence of CO_2 can be detected in the water column. Gas vents then express themselves as gas plumes in the water. In Figure 4 an example is shown of a natural analogue, namely a methane seep in the southern North Sea (Schroot and Heggland, 2004). There is a strong lateral variation in gas concentration. Therefore spatial coverage or a dense grid of sensors is required to monitor such gas plumes.

Also marine side scan sonar and multi-beam echo surveying can be used to monitor the sea bed. Possible pock marks or changes in the sea bed as a result of CO_2 escape can be detected.

CONCLUSION

Depending on the CO_2 storage option, injection programme, the site situation and the part of the subsurface (including atmosphere) to be monitored, monitoring techniques can be applied to monitor: CO_2 movement in the reservoir, mass balance, to ensure that the injected CO_2 does not endanger safety and environment, and to improve the reservoir understanding. Also, more knowledge is gained regarding techniques and methodologies regarding subsurface storage of CO_2 and possible future gasses to be stored.

Based on expected features, events and processes with respect to CO_2 injection, the applied techniques can be subdivided in correspondence to their applicability and focus. This subdivision is:

- the atmosphere and the near- surface;
- the overburden (including faults and wells);
- the reservoir with its seals.

Another subdivision is made with respect to time, *i.e.* first monitoring during the injection and storage process and subsequently monitoring for the long term (after abandonment of the field).

Because there are many other CO_2 sources, it is important to characterise the injected CO_2, *e.g.* by isotope analysis. Also, important is characterisation and monitoring before injection in order to determine these other CO_2 sources and possible variations in CO_2 occurrence in time.

Furthermore, an overview is given of various currently applied monitoring techniques for CO_2 storage. The most common applied method is time-lapse seismic yielding spatial coverage of the subsurface with emphasis to the reservoir and its overburden. When applied after a certain period of time changes in seismic response can be related to CO_2 injection. Well logging can reveal possible leakage along the well. At the surface CO_2 can be directly monitored using soil gas or seabed gas. Satellite and airborne monitoring can be used to cover vast areas at the surface. A combination of monitor techniques is envisaged to use the advantages of each individual method. Data of different techniques are combined into a subsurface model. By adding new data the model is updated into a dynamic model that is able to predict future behaviour correctly. Based on the outcome of the dynamic model it can be decided how to continue the monitoring, *e.g.* applying reduced monitoring.

REFERENCES

Allis, R., Chidsey, T., Gwynn, W., Morgan, C. White, S. Adams, M. and Moore, J. (2004) Natural CO_2 Reservoirs on the Colorado Plateau and the Southern Rocky Mountains: Candidates for CO_2 sequestration.
http://geology.utah.gov/emp/co2sequest/pdf/reservoirs.pdf

Arts, R., Eiken, O., Chadwick, A., Zweigel, P., van der Meer, L. and Zinszner, B. (2003) Monitoring of CO_2 Injected at Sleipner Using Time Lapse Seismic Data. In: *Greenhouse Gas Control Technologies*, Gale, J., and Kaya, Y. (eds.), Elsevier Science Ltd., Oxford, 347-352.

Arts, R, Eiken, O., Chadwick, R.A., Zweigel, P., van der Meer, l.G.H., abd Kirby, G. (2004) Seismic Monitoring at the Sleipner Underground Storage Site (North Sea). In: *Geological storage of CO_2*, Baines, S.J. and Worden, R.H. (eds.), Geological Society, London, Special Publication, 233.

Arts, R. and Winthaegen, P. (2005) Monitoring Options for CO_2 Storage. In: *Carbon Dioxide Capture for Storage in Deep Geologic Formations - Results from the CO_2 Capture Project,* Thomas, D. and Benson, S. (eds.), Elsevier Science, **2**, 1001-1014.

Bachu, S. and Rothenburg, L. (2003) Carbon Dioxide Sequestration in Salt Caverns: Capacity and Long Term Fate. *Proceedings of the Second Annual Conference on Carbon Dioxide Sequestration*, May 5-8.

Biegert, E.K., Berry, J.L. and Oakley, S.D. (1997) Oil Field Subsidence Monitoring Using Spaceborne Interferometric SAR: A Belridge 4-D Case Study, Int. Centre for Remote Sensing and Potential Field Studies. http://www.atlantis-scientific.com/library/Oil_field_Subsidence_Monitoring_using_Spaceborne_Interferometric_SAR.html

Chadwick, R.A., Arts, R., Eiken, O, Kirby, G.A., Lindeberg, E. and Zweigel, P. (2004) 4D seismic imaging of a CO_2 Bubble at the Seipner Field, Central North Sea. In: *3-D Seismic Technology: Application to the Exploration of Sedimentary Basins*, Davies, R., Cartwright, J., Stewart, S., Underhill, J. and Lappin, M. (eds.), Geological Society, London, Memoirs, **29**, 311-320.

Espie, T. (2004) Understanding the Risk for the Long Term Storage of CO_2 in Geological Formations. *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*, Vancouver, Canada, 5-9 September.

Keeling, C.D. and Whorf, T.P. (2004) Atmospheric CO_2 Records from Sites in the SIO Air Sampling Network, In Trends: A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn. U.S.A.

Maul, P., Savage, D., Benbow, S., Walke, R. and Bruin, R. (2004) Development of a FEP Database for the Geological Storage of Carbon Dioxide. *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*, Vancouver, Canada, 5-9 September.

Moore, J.R., Glaser, S.D., Morrison, H.F. and Hoversten, G.F. (2004) The Streaming Potential of Liquid Carbon Dioxide in the Berea Sandstone. *Geophysical Research Letters*, 31 (17).

Pagnier, H., Van Bergen, F., Krzystolik, P., Skiba, J., Jura, B., Hadro, J., Wentink, P., De-Smedt, G., Kretzschmar, H.J., Fröbel, J., Müller-Syring, G., Krooss, B., Busch, A., Wolf, K.H., Mazumder, S., Bossie-Codreanu, D., Choi, X., Grabowski, D., Hurtevent, D., Gale, J., Winthaegen, P., van der Meer, B., Bruining, H., Reeves S. and Stevens, S. (2004) Field Experiment of ECBM-CO_2 in the Upper Silesian Basin of Poland (RECOPOL). *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*, Vancouver, Canada, 5-9 September.

Petroleum Technology Research Centre (2004) IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000-2004, ISBN 0-9736290-0-2.

Schroot, B.M. and Heggland, R. (2004) Natural Gas Migration to the Near-Surface Environment as an Analogue to Potential Leakage of CO_2 – Detection and Mechanisms. *Poster # 537 presented at the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*, Vancouver, Canada, 5-9 September.

Van Bergen, F., Pagnier, H.J.M., Van der Meer, L.G.H., Van den Belt, F.J.G., Winthaegen, P.L.A. and Westerhoff, R.S. (2002) Development of a Field Experiment of CO_2 Storage in Coals Seams in the Upper Silesian Basin of Poland (RECOPOL). *Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies (GHGT-6)*, Kyoto (Japan), 30 September-4 October.

Van Bergen, F., Winthaegen, P., Pagnier, H., Jura, B., Kobiela, Z. and Skiba, J. (2005) Monitoring Techniques Applied for CO_2 Injection in Coal. *Extended abstracts, 67th European Association of Geoscientists & Engineers Conference*, A018.

Wildenborg, T., Leijnse, T., Kreft, E., Nepveu, M. and Obdam, A. (2004) Long-Term Safety Assessment of CO_2 Storage: the Scenario Approach. *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*, Vancouver, Canada, 5-9 September.

Zhou, W., Stenhouse, Arthur, R., Whittaker, S., Law, D.H.S., Chalaturnyk, R. and Jzrawi, W. (2004) The IEA Weyburn CO_2 Monitoring and Storage Project – Modelling of the Long-Term Migration of CO_2 from Weyburn. *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7)*, Vancouver, Canada, 5-9 September, I4-6.

Zweigel, P., Arts, R, Lothe, A.E. and Lindeberg, E. (2004) Reservoir Geology of the Utsira Formation at the First Industrial-Scale Underground CO_2 Storage Site (Sleipner area, North Sea). In: *Geological storage of CO_2*, S.J. Baines & R.H. Worden (eds.), Geological Society, London, Special Publication, **233**, 165-180.

Final manuscript received in June 2005