Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Chapter 19

MONITORING OPTIONS FOR CO_2 STORAGE

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ABSTRACT

In this paper an overview of various monitoring techniques for CO_2 storage has been given, structured into three categories: instrumentation in a well (monitoring well); instrumentation at the (near) surface (surface geophysical methods); and sampling at the (near) surface measuring CO_2 concentrations (geochemical sampling techniques).

An overview of what these techniques can monitor has been provided in terms of features, events and processes (FEPs). The main categories of FEPs identified in this report are: cap rock integrity (leakage); ground movements (uplift, earthquakes); lateral spreading of the CO_2 plume; and verification of mass balance.

For the geophysical methods the physically measurable parameters have been provided and the effects of CO_2 on these parameters are discussed and partially quantified.

INTRODUCTION

The objectives of monitoring underground CO_2 storage are to ensure:

- the integrity of CO_2 storage;
- the safety requirements for subsurface activities during and after the operational phase; and
- the injection process takes place as planned in the intended formation.

The first objective is focused on providing information relevant to tariffs and legislation, i.e. whether the agreed quota as originally planned for CO_2 storage are met and maintained.

The second objective focuses on safety at the storage site. The main safety risks can be categorized as follows.

- Leakage to the atmosphere or other geological formations, including possible groundwater contamination. A number of more specific features, events and processes (FEPs) have been identified influencing the future integrity of the seal. A summary is given in Table 1.
- Uplift of the subsurface (overburden) due to injection of CO_2 or subsidence due to production or to a lesser extent migration of CO_2 may cause damage to structures in the vicinity of the storage project.

Monitoring efforts should be focused on these issues.

A secondary goal of monitoring is research and development regarding underground CO_2 storage. Gaining a greater understanding of the physical and chemical processes occurring in the reservoir is important for the optimization of storage sites in the future.

This study is directed to the improvement of long-term monitoring and verification for storage of CO_2 in various geological media [1]. The experience from other projects (SACS I&II, RECOPOL, Coal and gas

TABLE 1
FEPS IDENTIFIED INFLUENCING THE SEAL OF A RESERVOIR DESIGNED FOR CO_2 STORAGE

Fracturing or fault activation due to increased CO_2 pressure
Dissolution or dehydration of seal due to the presence of CO_2
Casing or cementation defects due to improper design or construction
Deterioration of cement plug after abandonment due to CO_2
Corrosion of casing due to CO_2
Formation damage due to drilling of well
Operational failure of well
Unrecognized features in seal like faults, joints or fractures

Thermie B, NASCENT, Dutch NOVEM study) has been used to set up guidelines for an optimum monitoring strategy for the different scenarios in different geological settings.

To monitor CO_2 storage it is important to have baseline measurements available prior to CO_2 injection, so that storage-induced changes can be measured. This implies that a monitoring technique actually has to be selected at the earliest stage of each storage project in order to have a "baseline". This study provides a "best practice" guideline for selecting monitoring techniques by defining the key geological parameters and an estimation of the accuracy of the available monitoring approaches.

CO_2 STORAGE MONITORING TECHNIQUES

A number of different monitoring techniques are available. Basically the systems are classified into three categories:

- instrumentation in a monitoring well;
- instrumentation at the (near) surface (surface geophysical methods); and
- sampling at the (near) surface measuring CO_2 concentrations (geochemical sampling techniques).

Monitoring in a well within the reservoir can be of great value for determining the CO_2 distribution within the reservoir, monitoring the solution of CO_2 in water and calibration of other monitoring techniques. However, penetrating the seal of the storage formation should be avoided as much as possible because these penetrations might affect the seal integrity. Monitoring of wells in aquifers above the reservoir can provide information regarding seal integrity and leakage. Pressure measurements, water analysis and saturation can all be monitored above the storage formation if wells are available.

From surface geophysical monitoring methods, time-lapse seismics have grown over the last decade to a mature technique with wide applications and with a number of recent successes. Depending on the type of reservoir, changes in fluid composition and reservoir pressure have been observed as any change over time. Within the European SACS project, seismic monitoring has been applied for the first time over CO_2 injected into a saline formation at depths of approximately 800–1000 m. The major success of the SACS project has been the demonstration that conventional, time-lapse, p-wave seismic data can be a successful monitoring tool. Even with the CO_2 in a supercritical, rather than a gaseous state, it has been shown that CO_2 accumulations with a thickness as low as about a meter can be detected at these depths, about seven times below the conventional seismic resolution. Even such thin accumulations cause significant, observable and measurable changes in the seismic signal, in both amplitude and traveltime. Of course the sensitivity of these seismic observables depends heavily on the type of reservoir and its overburden and a sensitivity study must be done for each situation.

Figure 1 shows an example of the time-lapse seismic data acquired at Sleipner.

In general it can be stated, that seismic monitoring potentially provides an image of the spatial distribution injected CO_2.

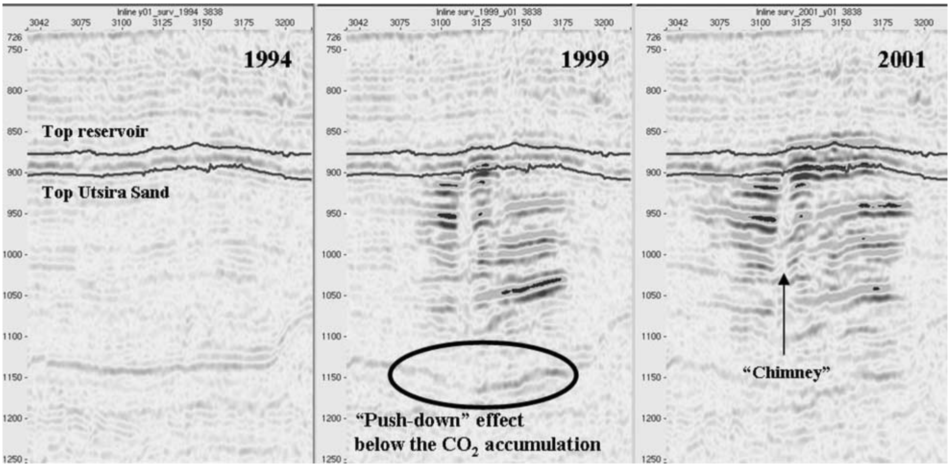

Figure 1: An inline through the injection area for the 1994, 1999 and the 2001 surveys (from Ref. [2]).

In Tables 2–4 an overview of the different monitoring techniques is given indicating what features, events or processes can be monitored. Of course, the sensitivity and accuracy of all these monitoring techniques depends on the geology of the storage site, the size of the storage project and a number of other factors. By combining monitoring methods, the sensitivity and accuracy can be improved (see Hoversten, this volume).

From Table 3b it may be obvious, that the FEPs causing leakage are very difficult to monitor from the surface at an early stage. From Table 3a it is clear that it is more likely that migration of the CO_2 plume can be detected. Fault activation or well bore failure (casing, cement plug) are difficult to detect with surface monitoring methods.

Physical Parameters

The geophysical methods mentioned in the previous section are based on changes in physical parameters. The main parameters responsible for detecting leaking CO_2 are enumerated hereafter. After each parameter the monitoring techniques that are sensitive to the parameter are mentioned.

Bulk density (seismic methods, gravity)

With the $P-T$ conditions known in the reservoir, the density of CO_2 can be determined quite accurately. Under supercritical conditions values for the density are typical in the range of 600–700 kg/m^3 [3]. This implies an important contrast with both densities of water and gas favorable to seismic and gravity methods. Seismic methods are sensitive to contrasts in bulk density. As an example, the change in bulk density of a 100% water saturated (purely quartz constituted) sandstone with a porosity of 20% would change from 2340 to 2260 kg/m^3 when 90% saturated with CO_2.

Compressibility (seismic methods)

The compressibility of CO_2 can be determined quite accurately based on the $P-T$ conditions in the reservoir. The compressibility of the CO_2 directly affects the seismic velocity in the reservoir. For the Utsira Formation, the compressibility of CO_2 is close to the compressibility of a gas ($K \sim 0.1$ GPa) causing very low seismic velocities in the reservoir. In saline formations and depleted oil fields these compressibilities give rise to large impedance contrasts. However, in a depleted gas reservoir with residual gas present, seismic methods might not be able to detect impedance contrasts due to compressibility effects. The small amount of residual gas has already lowered the overall compressibility.

TABLE 2
SUITABILITY OF MONITORING WELL TECHNOLOGY WITH RESPECT TO DIFFERENT FEPS

	Pressure–temperature sensors	**Resistivity**	**TDT**	**Micro-seismic**	**VSP**	**Crosswell**	**Fluid from reservoir**	**Fluid from aquifer above reservoir**
Cap rock integrity (leakage)	Good	Monitor above the reservoir	Monitor above the reservoir	Good	Good in area of investigation	Good in area of investigation	x	Lab tests
Ground movements	x	x	x	Detection of (small) earthquakes	x	x	x	x
Lateral spreading	Presence monitoring well	Presence monitoring well	Presence monitoring well	Possible	Limited area, calibration for seismics	Limited area, calibration for seismics	Presence monitoring well	Samples around reservoir
Verification or mass balance	x	x	x	x	Calibration for seismics	Calibration for seismics	x	x

TABLE 3A
SUITABILITY OF SURFACE GEOPHYSICAL MONITORING TECHNIQUES WITH RESPECT TO DIFFERENT FEPS

	Time-lapse seismic	**Subbottom profiling**	**Sonar**	**Gravity**	**EM**	**Geodetic**	**InSAR**	**Tilt meters**
Cap rock integrity (leakage)	Good	In case of leakage to the sea	In case of leakage to the sea	Low resolution	Low resolution	x	x	x
Ground movements	x	x	x	x	x	Good	Good	Good
Lateral spreading	Good	x	x	Low resolution	Low resolution	x	x	x
Verification or mass balance	Fair	x	x	Too low resolution	Too low resolution	x	x	x

TABLE 3B
SPECIFICATION OF THE SUITABILITY OF SURFACE GEOPHYSICAL MONITORING TECHNIQUES WITH RESPECT TO SPECIFIC FEPS RELATED TO CAP ROCK INTEGRITY

	Time-lapse seismic	**Subbottom profiling**	**Sonar**	**Gravity**	**EM**	**Geodetic**	**InSAR**	**Tilt meters**
Fault activation (high pressure)	Not likely	x	x	x	x	Not likely	Not likely	When downhole
Dissolution or dehydration of seal	Not likely	x	x	x	x	x	x	x
Casing/cementation failure	x	x	x	x	x	x	x	x
Deterioration cement plug	x	x	x	x	x	x	x	x
Corrosion of casing	x	x	x	x	x	x	x	x
Formation damage due to drilling	Not likely	x	x	x	x	x	x	x
Operational well failure	x	x	x	x	x	x	x	x
Fractures seal	Possible	x	x	x	x	x	x	x

TABLE 4
SUITABILITY OF “GEOCHEMICAL SAMPLING” MONITORING TECHNIQUES WITH RESPECT TO DIFFERENT FEPS

	Groundwater sampling	**(Isotopic) tracers**	**Atmospheric monitoring network**	**Geobotanical monitoring**
Cap rock integrity (leakage)	In case of leakage to the surface	Injected CO_2 discrimination	In case of leakage to the surface	In case of leakage to the surface
Ground movements	x	x	x	x
Lateral spreading	x	x	x	x
Verification or mass balance	x	x	x	x

For the RECOPOL project [4,5] monitoring of the ECBM process is carried out through crosswell seismics. The basic idea is that CO_2 molecules are adsorbed by the coals freeing CH_4 gas. The expectation is that not all the CO_2 can be adsorbed immediately by the coals, leaving free CO_2 in the system. The free CO_2 lowers the overall compressibility of the coal layer leading to a seismic contrast. Crosswell models have been run simulating the free CO_2 front mixed with freed CH_4. As an example some of the results are presented here. In a coal seam of 5 m thickness at a depth of about 1000 m, two vertical wells are drilled with a spacing of 400 m. CO_2 is injected in well 2, while well 1 produces CH_4.

Figure 2 shows a modeled shot gather (before injection, after injection and the difference) obtained with a crosswell geometry.

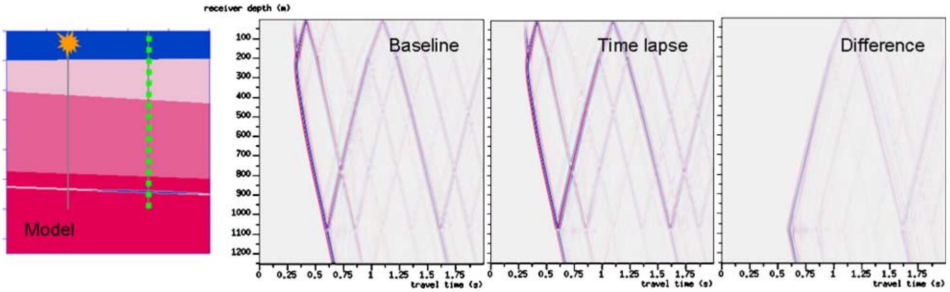

Figure 2: Shot gather of a time-lapse crosswell acquisition geometry with a source at $x = 300$ m and $z = 10$ m and receivers in well 2 at $x = 700$ m from 0 to 1250 m.

The first dipping event indicates the direct arrival or the first p-wave. Around a depth of 1100 m the first arrival reaches the coal bed layer. From that point a strong dipping event going in the opposite direction can be observed. This event is a result of energy reflected on the coal bed layer and then reaching the geophones as an upward traveling wavefield. This reflection is clearly visible on the difference plot since the CO_2/CH_4 has altered the reflection coefficient of the layer. The small part of the direct wave visible on the difference plot at depths larger than 1100 m is caused by the difference in traveltime of the energy going through the coal bed layer.

Effective pressure (seismic methods)
The velocity of sediments freshly deposited on the seafloor approximate the velocity of sound in water. Due to the growing overburden in time (sedimentation) an increasing pressure is applied on these sediments and they compact. The effect of this compaction is a reduction in porosity and an increase in the velocity related to the increasing stiffness of the material. The maximum velocity is determined by the velocities of the constituent grains with a porosity approaching zero. The velocity-effective stress relation for non-decreasing effective stress states is generally referred to as the virgin compaction curve (Figure 3). Note that this curve will flatten at a certain pressure [6].

Most of the porosity loss and velocity gain occurring during compaction is permanent. This means, that the velocity in the rock will actually not decrease along the virgin compaction curve when the effective pressure is released. Instead the so-called unloading curve will be followed (see Figure 3), showing higher velocities than on the virgin compaction curve.

If the effective stress is subsequently increased again, the velocity will go back up the unloading curve until the virgin compaction curve is reached. Beyond this point the velocity will once again follow the virgin compaction curve.

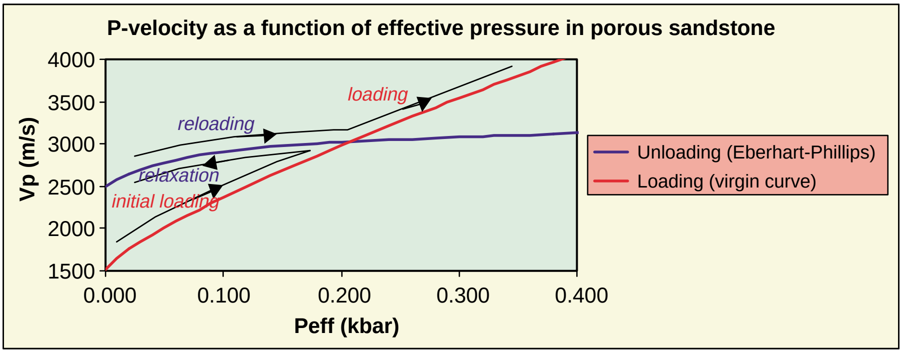

Figure 3: The p-wave velocity in porous sandstone as a function of effective pressure.

The above-indicated steps of initial loading, relaxation, reloading and loading again, are illustrated in Figure 3 with the arrows. In practice the virgin compaction curve can be determined from log measurements and burial history information. Note that the burial history is important to estimate the transition from the virgin compaction curve to the unloading curve. If, e.g. inversion has taken place in a region, pressure may have been higher than the current reservoir pressure.

The unloading curve is determined for various rocks by (numerous) laboratory experiments using ultrasonic measurements [7–9]. Different models (generally empirically determined) describing the unloading curves are available. The disadvantage of these models is that they are only valid for certain rock types under specific conditions, such as the Eberhart-Phillips relation [10] for porous sandstones as used in this study.

In this section only the effective pressure has been mentioned. Effective pressure is the pressure that balances the overburden pressure due to the weight of rock (which forms a matrix) and fluid (which fills the matrix) overlying this point, leading to the following equilibrium relation:

$$P_{\text{effective}} = P_{\text{overburden}} - nP_{\text{pore}}$$

where n is known as the Biot effective stress coefficient equal to 1 for soft sediments and <1 for cemented rocks. In the next example n has been chosen to be 1. A more elaborate study on the behavior of n can be found in a recent publication of Siggins and Dewhurst [11]. The process of injection causes an increase in the pore pressure. The overburden pressure can be considered constant. As a consequence, the effective pressure will decrease. Note that a decrease in the effective pressure will always follow the unloading (relaxation) curve (Figure 4).

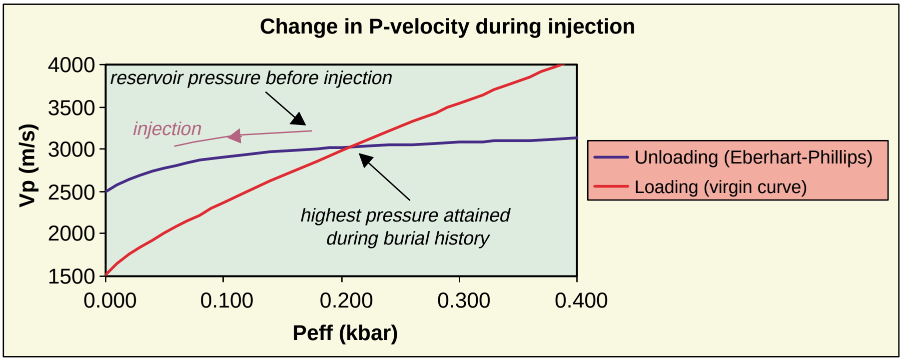

Figure 4: Example of the effect caused by the process of CO_2 injection on the effective pressure and the p-velocity.

The process of production decreases the pore pressure (Figure 5). The overburden pressure remains constant, since nothing changes in the overburden. (Note that this is not necessarily true, e.g. in the case of subsidence, but whether the effect is noticeable remains to be seen.)

As a consequence, the effective pressure will increase, leading to an increase in the velocity as well. In the case of production, it is not obvious which curve (the virgin compaction curve or the unloading curve) the velocity increase will follow. This depends much on the burial history of the reservoir determining the maximum effective pressure ever reached. Reconstruction of this history is recommended.

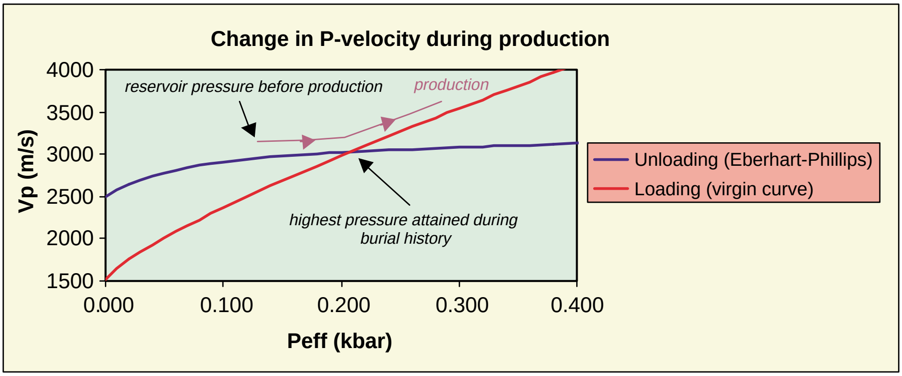

Figure 5: Example of the effect caused by the process of CO_2 production on the effective pressure and the p-velocity.

As an example a sensitivity analysis in terms of seismic measurable parameters such as amplitude and two-way traveltime (TWT) of p-waves has been carried out. Note that the analysis in this section is restricted to p-waves, though s-waves are probably more sensitive to pressure changes [12]. However, the use of shear waves for monitoring purposes is a less mature technology. The reservoir is assumed to be representative of a Rotliegend sandstone gas reservoir in the Dutch subsurface. The reservoir is at a depth of 2500 m and under normal hydrostatic pressure. The thickness of the reservoir is 100 m. The velocity in the overlying seal (anhydrites) is 5700 m/s. The bulk density is 2850 kg/m^3 in the seal and 2300 kg/m^3 in the reservoir. The velocity–pressure relation is determined by the unloading curve (see Figure 3) in the range of effective pressures from 0 to 300 bar. For pressures higher than 300 bar, the velocity–stress relation is governed by the virgin compaction curve (see Figure 3). The resulting composed curve is shown in Figure 6. Note once more that the virgin compaction curve will flatten at higher pressures as well, however, the effect is less drastic than on the relaxation curve.

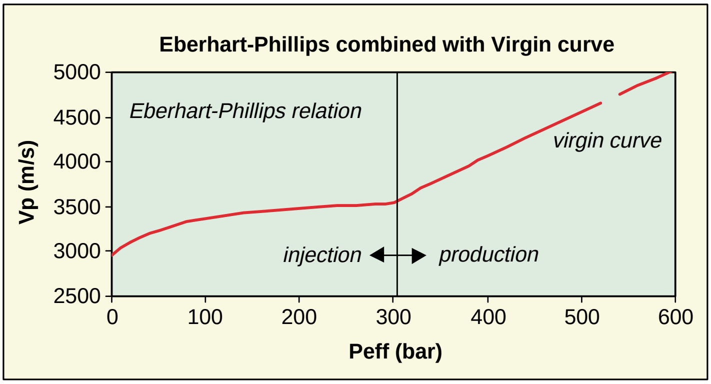

Figure 6: Estimated stress–velocity relation for a Rotliegend sandstone reservoir at an effective pressure of 300 bar.

Table 5 shows the results of the sensitivity analysis. The first row indicates the initial state of the reservoir, approximately at a depth of 2500 m. The next six rows correspond to a decreasing effective pressure. As indicated in a previous section, this represents the process of injection. The last six rows correspond to an increasing effective pressure, representative for the process of production.

The first row gives the initial situation with the effective pressure at 300 bar (column 2) at t_0. The next rows represent different time steps. The corresponding reservoir velocities at these time steps are given in column 3, the TWT in the reservoir in column 4. From column 5 and further, the actual sensitivity analysis starts. Column 5 gives the increase/decrease in effective pressure. Column 6 shows the effect on the velocity in the reservoir. In column 7 the change in TWT is indicated. Column 8 gives the reflection coefficient for p-waves at normal incidence at the top of the reservoir at t_0 and t_1. The relative change (in percentage) in the amplitude is given in the final column 9. Note that the key columns are column 7 (difference in TWT) and column 9 (relative change in seismic amplitude).

From Figure 6 it may be obvious already that pressure changes during production create a larger velocity change than during injection. The same observation follows from Table 5. If, e.g. the effective pressure drops 50 bar due to injection, the change in TWT amounts to only 0.47 ms and the relative change in amplitude 1%. On the other hand, an increase of 50 bar due to production results in a change of TWT of -3.93 ms and a relative change in amplitude of -10%.

TABLE 5
SENSITIVITY ANALYSIS OF THE EFFECT OF STRESS CHANGES ON THE SEISMIC MEASUREMENTS, TWT AND AMPLITUDE

$P_{\mathrm{eff}}(t_1) < P_{\mathrm{eff}}(t_0)$ means injection (unloading); $P_{\mathrm{eff}}(t_1) > P_{\mathrm{eff}}(t_0)$ means production (loading)

State	P_{eff} (bar)	V_p (m/s)	TWT (ms)	dP_{eff} (bar)	dV (m/s)	Increase TWT (ms)	Refl. coeff.	Relative change in amp (%)
Initial	300	3541	56.48				0.332	
Injection	240	3506	57.05	−60	−35	0.57	0.337	1
Injection	250	3512	56.96	−50	−29	0.47	0.336	1
Injection	260	3517	56.87	−40	−24	0.38	0.335	1
Injection	270	3522	56.78	−30	−19	0.30	0.334	1
Injection	280	3528	56.70	−20	−13	0.21	0.334	1
Injection	290	3533	56.61	−10	−8	0.13	0.333	0
Production	310	3595	55.64	10	54	−0.84	0.325	−2
Production	320	3648	54.83	20	107	−1.66	0.319	−4
Production	330	3701	54.04	30	160	−2.44	0.312	−6
Production	340	3753	53.28	40	212	−3.20	0.306	−8
Production	350	3806	52.55	50	265	−3.93	0.300	−10
Production	360	3858	51.84	60	317	−4.64	0.293	−12

Conductivity (EM)
The difference in electrical conductivity between CO_2 and brine is the basis for this monitoring technique. See Hoversten, this volume, for a discussion of electromagnetic methods for measuring electrical conductivity.

Fracturing (seismic methods, EM)
(Micro-)fractures can be a migration pathway for CO_2. In principle fractures can be detected by seismic or EM methods especially in the case of aligned systems of micro-cracks. In these cases anisotropy measurements (on seismic velocities or on EM) could provide insight in the preferential orientation of the system and hence the preferred migration pathway [8]. Most suitable are probably azimuthal VSP or crosswell measurements. The quantification of these systems in terms of an effective permeability, however, is highly speculative.

Porosity reduction/increase (seismic methods)
Chemical reactions might cause an increase or a decrease in porosity in the order of 3–4% (see Bryant et al., this volume). For the cap rock, an increase in porosity or permeability would be the most important parameter to monitor. In theory, seismic methods or even gravity methods should be able to detect these changes. However, in most cases such measurements are at the limit of resolution and are only useful when supported by other measurements.

RESULTS AND DISCUSSION

In this project monitoring of CO_2 storage has been approached in a systematic manner.

First a short inventory has been made of why CO_2 storage should be monitored. The answer to this question should determine what parameters should be monitored and the resolution needed. For example, is it sufficient to know that the CO_2 is not leaking to the surface (or overburden), or is it important to know where CO_2 migrates to within the reservoir. In this report, a broad approach has been chosen taking into account as many monitoring techniques as possible.

Globally three areas of investigation for monitoring have been identified:

- the reservoir containing the CO_2 (pressure, temperature, spreading and long-term behavior of the CO_2);
- the integrity of the seal (fractures, faults, wells, heterogeneous permeability); and
- the overburden and the atmosphere with possibly CO_2 leaking (migration pathways of CO_2).

The first and especially the second are probably the most important for monitoring. They provide an early warning system for possible leakage. In the ideal case, when leakage does not occur, no changes would be expected in the properties of the overburden.

CONCLUSIONS

In this paper a short description of various monitoring techniques has been given. To structure the discussion, monitoring techniques have been divided into three categories, namely:

- instrumentation in a well (monitoring well);
- instrumentation at the (near) surface (surface geophysical methods); and
- sampling at the (near) surface measuring CO_2 concentrations (geochemical sampling techniques).

An overview of what these techniques actually can monitor has been provided in terms of FEPs. The main categories of FEPs identified in this report are:

- cap rock integrity (leakage);
- ground movements (uplift, earthquakes);
- lateral spreading; and
- verification or mass balance.

For the seismic methods the physical measurable parameters have been provided and the effect of CO_2 on these parameters are discussed and partially quantified.

RECOMMENDATIONS

As a follow-up to this project the following recommendations are made.

1. The modeling should be extended to different migration pathway scenarios. Especially storage in a depleted gas-field requires more modeling. For most methods it is very difficult to separate effects of residual gas and stored CO_2. A more detailed analysis on a specific case (e.g. a Rotliegend gas-field) is recommended.
2. The FEP matrices showing which monitoring techniques can be applied should be updated. For example, the FEP analysis in the SAMCARDS Project will provide more insight in the most likely leakage scenarios and, more importantly, to the mechanisms causing the leakage. Monitoring techniques and strategies must be focused on these mechanisms at the earliest stage possible.

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