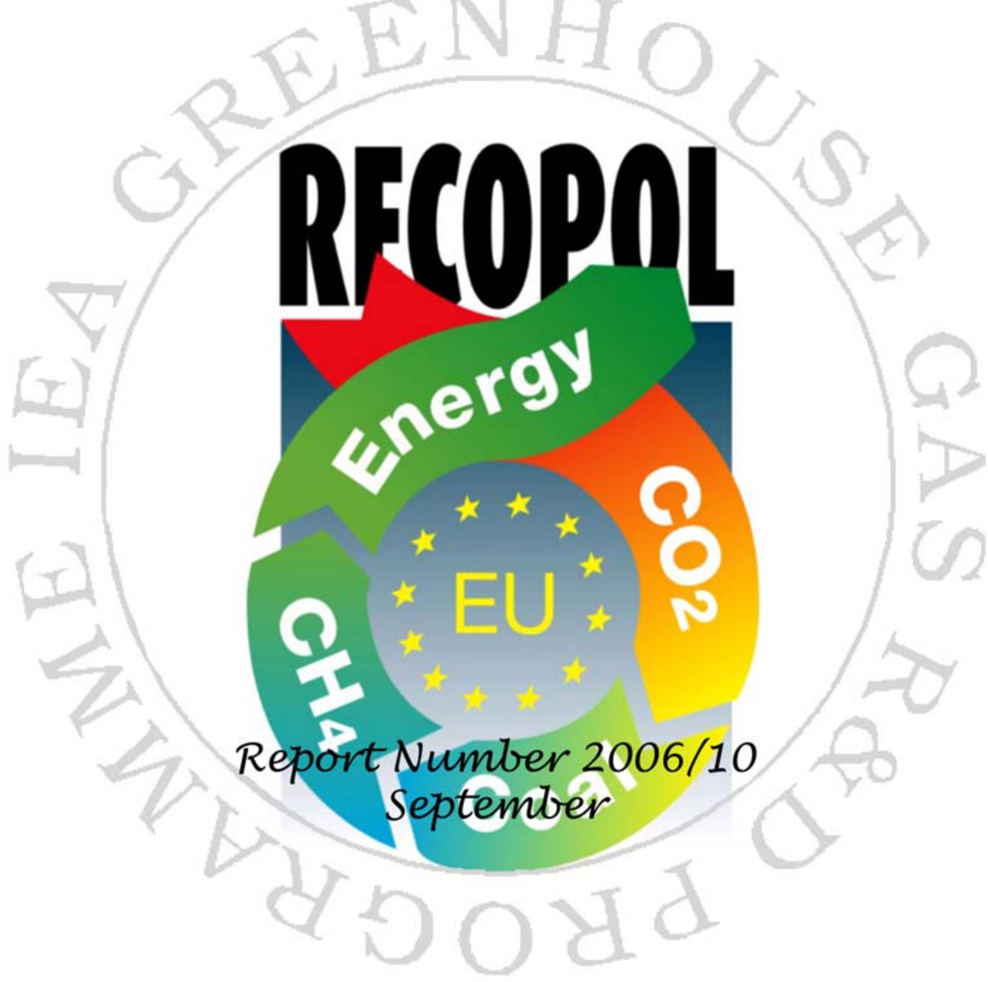

Report Number 2006/10
September

Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian coal basin of Poland (RECOPOL)

A project co-sponsored by the
European Commission
Fifth Framework Research Programme

Acknowledgements

This report has been produced by IEA Greenhouse Gas R&D Programme with the kind permission of the European Commission and TNO on behalf of the RECOPOL project.

The RECOPOL Project

Background

The capture and geological storage of CO_2 from large point sources is widely acknowledged as having the potential to play a vital role (in combination with other mitigation options) in achieving deep reductions in anthropogenic greenhouse gas emissions. The three main options available for the geological storage of CO_2 are deep saline aquifers, depleted oil and gas fields and unminable coal seams. Deep saline aquifers have the largest theoretical storage potential (capacity between 2,000 to 100,000 Gt), followed by oil and gas fields (approximately 930Gt) and finally unminable coal seams (150Gt). Although by far the smallest in terms of global capacity, coal seam storage can have the benefit of being an economically attractive niche option in some regions. The injection of CO_2 into the coal seam displaces methane that was bound within the coal and can enhance the production of methane from coal seams compared to conventional coal bed methane (CBM) production techniques. The process is known as CO_2 enhanced coal bed methane recovery (CO2-ECBM). Providing the CH_4 released is used in place of higher carbon intensity fuels then there is a potential for net greenhouse gas emission savings from this storage option.

The IEA Greenhouse Gas R&D Programme (IEA GHG) studied the potential prospects for CO_2 storage in coals seams and identified a number of potential regions of the world that would be suitable as demonstration sites for CO2-ECBM projects[1]. The potential regions included: Australia, China, India and Poland. The region in Poland that was selected was the Silesian Basin an area with an established bituminous coal production base and where coal bed methane production has also taken place. Subsequent to the IEA GHG study the European Commission has supported a CO2-ECBM pilot project in the Silesian Basin, this project was known as the RECOPOL[2] project. This report provides a summary of the RECOPOL project results, of which IEA GHG was a participant. IEA GHG was keen to participate in the project because it offered an opportunity to develop our knowledge of the technical status of this geological storage option

Project Outline

RECOPOL was a European Commission funded project, and was carried out by an international consortium (including the IEA Greenhouse Gas R & D Programme), which was led by TNO-NITG[3]. Although a number of pilot scale projects of this technology have now taken place in Canada, the USA, China and Japan on various scales, the

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[1] IEA Greenhouse Gas R&D Programme, Report No. Ph3/34, Enhanced Recovery of Coal Bed Methane with CO2 Sequestration – Selection of Possible Demonstration Sites, September 2000.

[2] Reduction of CO_2 emissions by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland

[3] Netherlands Organization for Applied Scientific Research – Netherlands Geological Survey

RECOPOL project is the first to be undertaken in Europe. The project was also the first to attempt injection and production through different wells[4].

The main aim of the project was to demonstrate the feasibility of CO_2 injection in coal under the conditions encountered in Europe[5], and that storage of CO_2 in this fashion is a safe and viable option for the long term.

The RECOPOL project aimed to couple the geological storage of CO_2 with enhanced production of coal bed methane (ECBM). The Silesian Basin area of Poland was chosen as the demonstration site due to the favourable physical properties of the coal seams, and because the site has actively produced coal bed methane (CBM) in the past, providing historical data with which to compare experimental results.

The full details of the project design are given in the main report.

Results Summary

During the initial practical site work, it became apparent that continuous injection into the bituminous coal seams was not immediately attainable, and it wasn't until the coal seam was fractured that continuous injection was achieved. Once achieved, injection rates reached a level of approximately 12 to 15 tonnes of CO_2 per day. This was sustained for over a month until the supplies of CO_2 were exhausted at the scheduled end of the project in June 2006. The well stimulation also had a positive effect on the production of methane – increasing production rates from circa $40m^3/d$ to over $700m^3/d$. This compares to a baseline peak production level of approximately $100m^3/d$ according to the historical data available from the CBM production at the site.

From an engineering perspective, much was learned throughout this project that should enable smoother start-up stages of further projects of a similar nature. Despite the success of establishing continuous injection into a bituminous coal seam, the project showed that there are however still gaps in understanding. For example, the project proved that methane production is enhanced following CO_2 injection, but the processes underlying this are not fully understood, in particular the effect of CO_2 absorption on coal swelling and reduction in permeability around the injection well. Also, coal permeability is still acknowledged as an important factor; however it is believed that lower permeability coals can achieve satisfactory results following stimulation activities. The average permeability of the coal seams in the study area in the Silesian Basin is typically between 1 - 3 mDarcy (although seam 405 is considerably lower). This compares to the low permeability coal seams studied in the Hokkaido project in Japan which have a permeability of <1mDarcy.

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[4] Early projects in Canada and more recently in China were "huff and puff" with small volumes of CO_2 injected and produced through the same well. The only project prior to this that had involved multiple wells was the Burlington pilot project in the San Juan basin in USA. The Japanese project has a similar dual well design to RECOPOL.

[5] Bituminous coals with permeability's ranging from 0.5 to 5 mDarcy

Conclusions

The results and knowledge gained from this project are encouraging, and will assist greatly in the planning and application of any future demonstration projects.

The project has demonstrated for the first time that continuous injection into bituminous coal seams can be achieved and that CH_4 recovery is enhanced as a result.

The levels of injection and production achieved in this project are considered to provide a sound basis on which to develop larger scale demonstration projects in the future. Locations with higher prospects in terms of physical characteristics and higher storage/production potentials are anticipated within the Silesian Basin region, and it is expected that the experience of this project will lead to optimisation of future demonstration sites and procedures.

It is still premature, based on the results of this project, to conclude that CO2-ECBM is a technically feasible geological storage option, although the results gained here are encouraging. Further injection tests are needed to demonstrate the range of coals that are suitable for CO_2 injection and further research is needed to develop an understanding of the key processes involved CO_2 adsorption and CH_4 desorption.

Next Steps

A new CO2-ECBM project is planned to build upon the late success achieved by the RECOPOL project. The project called MOVECBM (Monitoring and verification of CO_2 storage and ECBM in Poland) commenced in November 2006. The MOVECBM project aims to:

- Develop a better understanding of the adsorption/desorption and migration characteristics in coal seams;
- To determine optimised practices for both storage and production; establishment of a monitoring and verification methodology for the technology;
- To facilitate the transfer of the knowledge to further locations throughout the EU, China, Australia and the USA.

The project is again being undertaken by a consortium of European research organisations led by TNO-NITG and IEA GHG is again a partner.

In addition, there may be value in IEA GHG considering the establishment of a new international research network on CO2-ECBM to help bring together the various research groups in the field to exchange results and better co-ordinate their activities.

Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland

Final report

Executive Summary

Introduction

The RECOPOL project is an EC-funded research and demonstration project to investigate the technical and economic feasibility of storing CO_2 permanently in subsurface coal seams. This is considered to be an option for CO_2 sequestration, which will be required to meet the Kyoto protocol. The main aim is to demonstrate that CO_2 injection in coal under European conditions is feasible and that CO_2 storage is a safe and permanent solution before it can be applied on a larger scale in a socially acceptable way. This final report describes the activities that are undertaken in the period from the 1st of November 2001 to the 31st of July 2005 within the context of the RECOPOL project. The RECOPOL project is funded by the European Commission under contract number ENK-CT-2001-00539.

The specific goals of the RECOPOL project can be summarised as follows:

- Is subsurface storage of CO_2 in coal, while simultaneously producing CBM, a technically viable option under European conditions?
- Is subsurface storage of CO_2 in coal a safe and permanent solution?
- How much CBM is produced for each tonne of injected CO_2?
- Can subsurface storage of CO_2 in coal be applied on a larger scale in an economical and social acceptable way?
- What are the main criteria (geological/technical/economical/social) for any coal basin, in or outside Europe, to be suitable for this technique?

An international consortium of research institutes, universities and industrial partners is carrying out the project activities. This is the first field demonstration experiment of its kind in Europe.

Location

The Upper Silesian Basin in Poland was considered as the most suitable coal basin in Europe for the application of ECBM. This basin has (relatively) favorable coalbed properties (depth, permeability, gas content, etc.) and was subjected to CBM production before. The location of the pilot site in the village Kaniow, about 40 km south of Katowice, was selected at an early stage of the project. There are two wells which were formerly used for a short period to produce CBM. The selected site is located within the concession of the Silesia mine, which has been in operation for decades. The principal targets for CO_2 injection are coal seams between 1.3 and 3.3 m thick of Carboniferous age in the depth interval between 900-1250 m. The Carboniferous deposits are disconcordantly covered by circa 200 m thick Miocene shales.

Activities

Laboratory experiments

Along with the field activities laboratory work was carried out since the beginning of the project. This resulted in a better fundamental understanding of the exchange process. Several papers were published in international journals.

Site development

The development of the pilot site in the Upper Silesian Basin in Poland began in summer 2003. One of the existing coalbed methane wells was cleaned up, repaired and put back into production. A new injection well was drilled at 150 m from the production well. This distance was chosen to establish a breakthrough of the injected CO2 in the production well, in order to learn as much as possible from the operations. Activities in autumn 2003 included the finalizing of the injection facilities.

Injection
First injection with CO_2 took place in the first week of August 2004. Several actions were taken to establish continuous injection, which was eventually reached in April 2005, following a frac job of the coal seams. This stimulation was required because the permeability of the coal seams reduced in time, presumably due to swelling as the result of contact with the CO_2. After fraccing in the injection well circa 12-15 tonnes per day were injected in continuous operations from late April to early June 2005. In total circa 760 tonnes of CO_2 were injected between August 2004 and the end of June 2005.

Production
Gas was produced from the production well to evaluate possible enhancement of the gas rates. Production has started at the end of May 2004, to establish a baseline production. Unexpectedly, a slow rise in the CO_2 content in the production gas was observed since November 2004 which could be attributed to the injected CO_2. In addition, a decrease in total gas production was observed during longer fall off periods. This indicates a clear response of the production well on the injection activities. In April 2005 the gas production increased rapidly after the frac job in the reservoir. The CO_2 concentration in the production gas also rapidly increased, clearly indicating the breakthrough of the gas. However, the amount of daily produced CO_2 was much lower than the amount of daily injected CO_2, indicating a clear sink of CO_2 in the reservoir. This was confirmed by the rapid decrease of production rates after continuous injection stopped in June 2005.
Compared to baseline production, the production of methane increased significantly due to injection activities. Recovery of methane is, however, low which is probably related to low diffusion rates into and out of the coal. Probably, this can be improved by giving the system sufficient time to allow for diffusion of the gas into and out of the coal matrix.

Monitoring
Along with the field activities, an extensive monitoring programme has been set-up to detect and assess any potential, although unlikely, leakage of CO_2 to the surface. It was concluded that leakage of the injected CO_2 to the mine in the overburden and/or to the surface is very unlikely. Extensive datasets were collected that can be used to show, although relatively small scale, the potential of several of these techniques for monitoring purposes. Better assessment of can be made of the baseline conditions, also in similar environments in future projects.

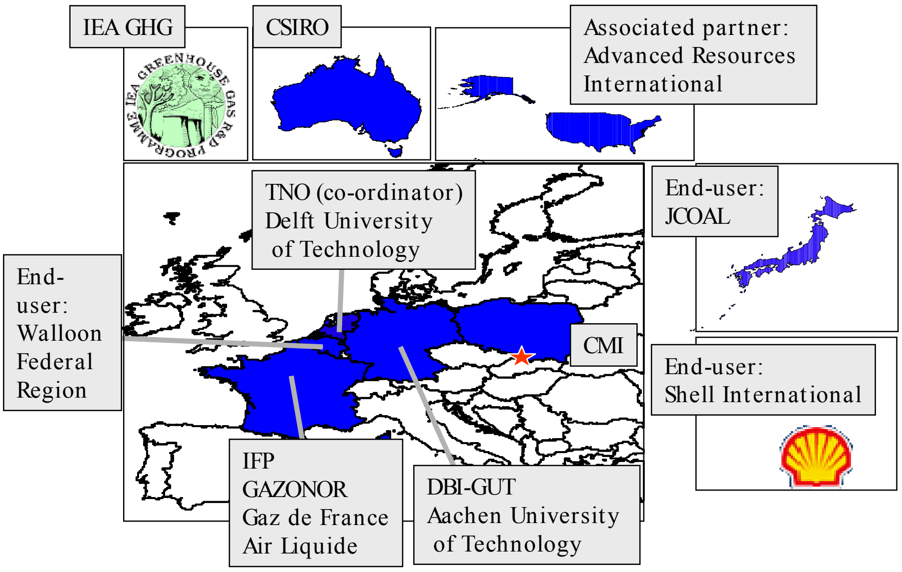
History matching
History matching of the injection and production results was done in the last phase of the project by numerical simulation of the process during and after injection of the CO_2. History matching of the results was possible and provided additional insight in the ongoing processes.

Socio-economics
Along with the technical work, an economical evaluation and a future-technological assessment was executed.

Conclusions
Several months of injection showed that injection without stimulation is difficult under the local field conditions. The injected amounts after stimulation of the injection well provide a good basis for a future upscaling of the operations. The consortium showed that with a limited budget it is possible to set up an on-shore pilot in Europe and to handle all “soft” issues (permits, contracts, opposition, etc.) related to this kind of innovative projects. The lessons learned in this operation can possibly help to overtake start-up barriers of future CO_2 sequestration initiatives in Europe.

This report represents the combined work of the RECOPOL consortium, consisting of the following institutes, universities and companies:

TNO-NITG
Central Mining Institute
Aachen University of Technology
Delft University of Technology
DBI-GUT
IFP
Gaz de France
GAZONOR
CSIRO
IEA Greenhouse Gas R&D Programme
Air Liquide
Advanced Resources International (associated partner)



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[1]Netherlands Institute of Applied Geoscience TNO, [2]Central Mining Institute (Poland), [3]Air Liquide (France), [4]DBI-GUT (Germany), [5]Aachen University of Technology (Germany), [6]Delft University of Technology (the Netherlands), [7]Institut Français du Pétrole (France), [8]CSIRO (Australia), [9]Gaz de France (France), [10]Gazonor (France), [11]International Energy Agency Greenhouse Gas R&D Programme, [12]Advanced Resources international (USA)

Editor: Frank van Bergen

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Annexes

1 Introduction

Stabilising atmospheric greenhouse emissions, a goal set by UNFCC, has become an international priority. It is generally accepted now that in order to achieve this deep reductions in global CO_2 emissions will be required. To achieve deep reductions in CO_2 emissions it will be necessary to employ all mitigation options available, such as fuel switching, energy efficiency & renewable energy. However, despite all past and ongoing efforts put into the development of sustainable energy supply, the world still depends heavily on fossil fuels and will continue to do so for years to come. For this reason, technology options are required that will allow for the continued use of fossil fuels without substantial emissions of CO_2. Capture and subsurface storage of CO_2 is considered as one promising perspective, which is currently being investigated world-wide. In the latter case, the CO_2 emitted from anthropogenic sources, such as power plants and other major energy using industries (cement, iron and steel, fertiliser plants, oil refineries and chemical plants) can be captured and then stored in a suitable geological formation. There are a number of formations that are suitable for storing CO_2 which include oil and gas fields, deep unminable coal seams and deep saline aquifers. Global assessments suggest that there is sufficient potential in these reservoirs to store all the worlds CO_2 for many years to come.

One of the options considered in this context is the storage of CO_2 in underground coal seams. This type of storage is anticipated to be combined with the production of coalbed methane (CBM). In conventional CBM-production, as applied successfully in the United States, gas is released from the coal by pumping water from the reservoir, thereby reducing hydrostatic pressure. Because gas production rates per CBM well are several orders of magnitude lower than natural gas wells, a relatively large number of wells is required. It is expected that the production rates of such CBM-wells and the recovery from the coal seams can be enhanced by simultaneous injection of CO_2 in the coal seams in nearby wells (therefore the term Enhanced CBM production, or ECBM). The injected CO_2 is expected to be retained by the reservoir and is therefore stored in the subsurface.

It must be emphasized that this technique is not yet a well-established and mature technology, and therefore, implies some inevitable uncertainties and risks. Although several theoretical studies illustrated the potential of the process, pilot projects are required in order to gain necessary practical experience with ECBM production schemes, in particular with respect to drilling techniques and reservoir conditions. In general, the research window for projects on subsurface CO_2 storage has therefore slowly but surely shifted from desk studies to demonstrations. A few experimental ECBM/CO_2 field sites have been realized worldwide to date. A micro-pilot field test was set-up in Alberta (Canada; Gunter et al., 1997 and 1998), a similar test was recently developed in China, a two-well test is ongoing in Japan, while the world's first large-scale ECBM pilot using CO_2 injection was operated in the San Juan Basin in New Mexico, U.S.A. (Gunter et al., 1998; Erickson & Jensen, 2000; Reeves and Schoeling, 2000; Schoeling & McGovern , 2000). This report gives an overview of the results obtained in the first European field demonstration in Poland. The main goal of this project is to demonstrate, in the Upper Silesian Coal Basin in Poland, that CO_2 injection in coal under European conditions is feasible.

2 Laboratory experiments

2.1 Introduction

Along with the development of the field site and the field operations, laboratory work was carried out since the beginning of the project. Samples were taken from the cores of the new MS-3 injection well and from the same seams of interest at shallower depths from nearby mines (Brzeszcze and Silesia). The main tasks of the laboratory work were:

- Characterisation of the coal samples
- Ad-/desorption experiments on crushed coal samples
- Sorption capacity (CO_2,CH_4 and mixtures)
- Preferential sorption (CO_2/CH_4 mixtures)
- Sorption kinetics (diffusion measurements)
- Flow-through (Flushing) experiments on cores
- Permeability & porosity determination in 3D

Several extensive reports were published with the results and the evaluation of the laboratory experiments. In this report, a condensed overview is given of the most important results (see appendix 1) and observations of the laboratory experiments.

2.2 Simulation approach

Following the laboratory results, some general recommendations were given by the institutes involved, which were thought to be of important concern for the simulation approach.

- IFP
  1. The layering : it concerns the overall number of layers in the simulation and the number of layers for each coal seam.
     - For each coal seam we recommend **5 layers**
     - Between coal seams we recommend another **5 layers**

     That implies the following layering: 3 layers above the 364 + 5 layers representing 364 & 401 coal seam + 5 layers between the 401 and 501 coal layer and finally 5 layers for the 501 and 3 layers below the 501 coal seam. That represents a total of **21 layers**. The X/Y discretisation remaining the same (34 cells by 37 cells) we have a total of **26418** cells.
  2. The heterogeneity should be introduced according to the method detailed above whereas only one permeability and one porosity should be introduced in the facies between coal (according to a VDP to be defined by the user).
  3. The initial vertical permeability within the coal should be $K_v/K_h=\mathbf{1}$, whereas for the facies between coal the value should be $K_v/K_h=\mathbf{0.01}$ (this is a typical value for shaly sands).
  4. As stated, we recommend including the simulation of the facies between the coal seams. The idea is to include the possibility - not to be neglected - for the CO_2 to escape the coal and to migrate upward within the non-coal reservoir. The simulation of the BT will indicate, if given the injection rates, this hypothesis is justified or not. During that match, the K_v/K_h can always be set to near zero if needed.

- <u>RWTH</u>
    1. We agree on the recommendations of IFP to include additional layers between the coal seams in the simulation runs. The introduction of clay layers (very low permeability, relatively high porosity and sorption capacity) shows a significant influence on the simulation run. The ratio of K_v/K_h for facies between the coal should even be lower than 0.01 (recommended: **0.001 to 0.005**)
    2. The relative Tau-values for CO_2 and CH_4 should be chosen according the table in "diffusion and characteristic times". Here, the controlling parameter for the equilibrium state is the slow sorption process.

- <u>Delft</u>
    1. Incorporation of dynamic capillary pressure curves into the model.
    2. Incorporation of a pressure depending wetting change around 90 bar from water to CO_2 wet. Adaptation of PVT-tables for specific surface tension.

2.3 Conclusions

The laboratory experiments resulted in a better fundamental understanding of the exchange process. Several papers were published in international journals. The results from the laboratory experiments will be introduced in these reservoir models, where possible. Upscaling of these results, core to inner-well and field scale is required.

3 Specifications of the RECOPOL site

3.1 Location

The Upper Silesian Coal Basin (USCB) is located in the south of Poland, north of the Carpathian mountains and west of the city of Krakow. This basin was selected as the most suitable coal basin in Europe for the application of ECBM (Stevens et al., 1999; Wong et al., 2000). It is the largest coal basin in Poland and one of the largest in Europe, and has (relatively) favourable coalbed properties (i.e. depth, relative thick seams, higher permeability, fair gas content, etc.) compared to other European coal basins. Exploration and production of coalbed methane was undertaken in the 1990's. The main aim of this conventional CBM production was the recovery of gas, which proved, at that time, to be uneconomical. In ECBM operations there is a focus on both methane recovery and CO_2 storage, which has the potential to make these kinds of operations economically feasible in the future.

The location of the pilot site in the village Kaniow, about 40 km south of Katowice, was selected at an early stage of the project (Figure 1). Two wells were in place, 375 m apart, which were used for a short period to produce CBM in the second half of the 1990s. The selected site is located within the concession of the Silesia mine, which has been in operation for decades. The characteristics of the site have been documented from these activities and from the activities in the nineties by Metanel, the owner of the existing wells MS-1 and MS-4 and concession holder for the gas production. As many data as possible were collected and evaluated, in order to get a good background for the development plan of the site.

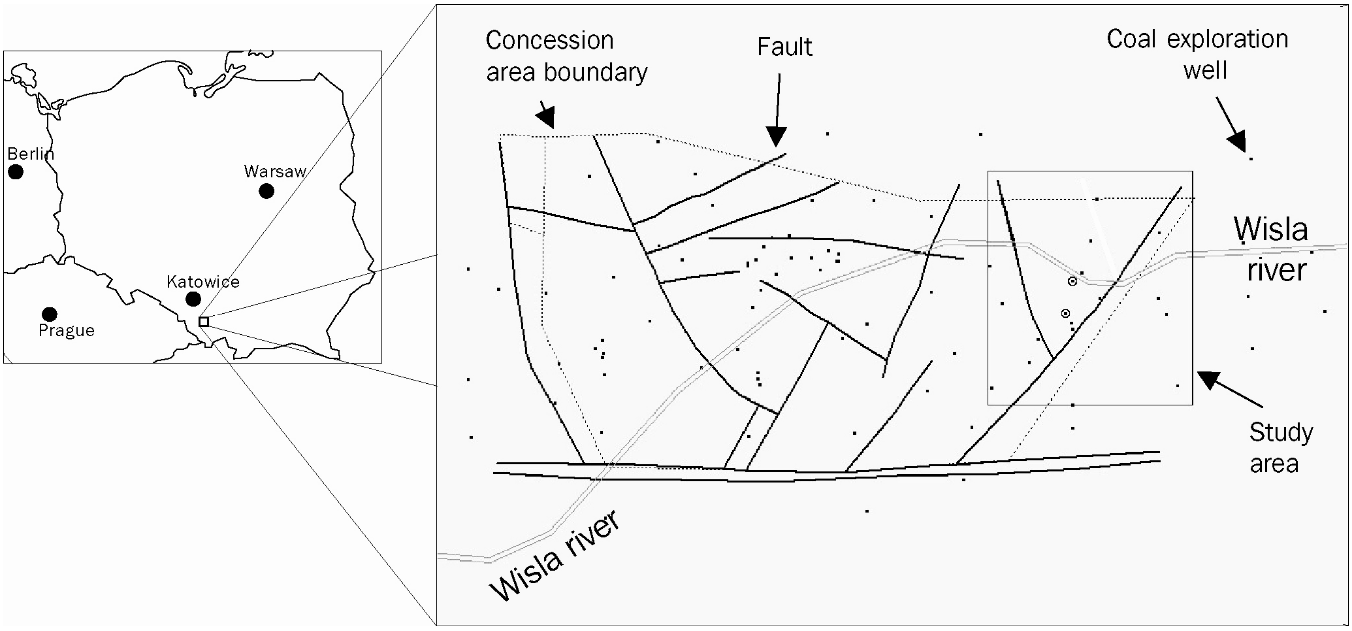


Figure 1: Location of the site in the Upper Silesian Coal basin (blue outline). The existing CBM-wells are indicated with the small circles, the new injection well is not shown.

3.2 Geological setting

The coal-bearing deposits in the USCB were deposited in an intermontane basin during the Carboniferous and have a total thickness of at least 1000 m (3280 ft) in the area. The deposits within the interval of interest (between 950-1250 m or 3117 - 4101 ft) are of Late Namurian to Early Westphalian age (Figure 2). Coal seams occur throughout the entire depth interval. The Late Namurian succession, approximately 75 to 125 m (246 to 410 ft) thick, consists of sandstone-dominated to claystone-dominated fluvio-deltaics. The overlying 125 to 200 m (410 to 656 ft) thick succession of Early Westphalian age is dominated by claystones.

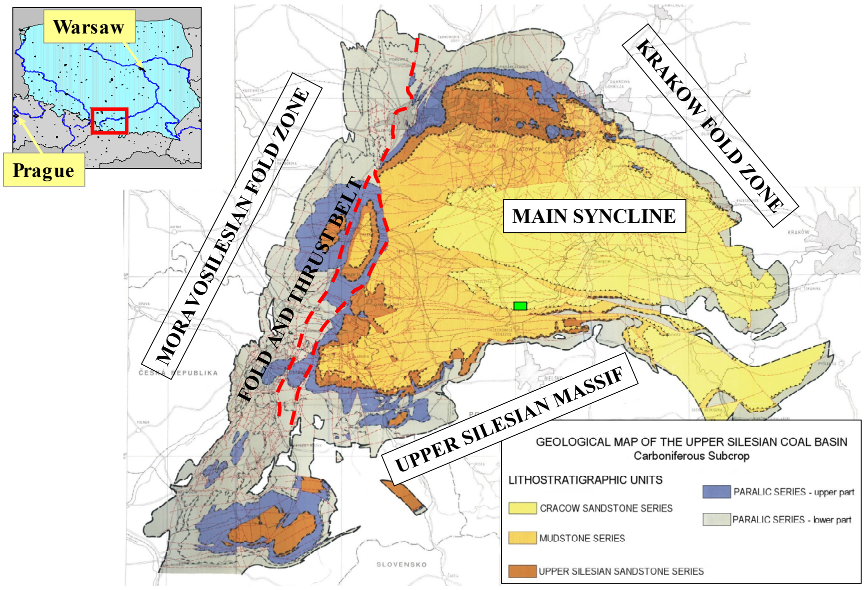
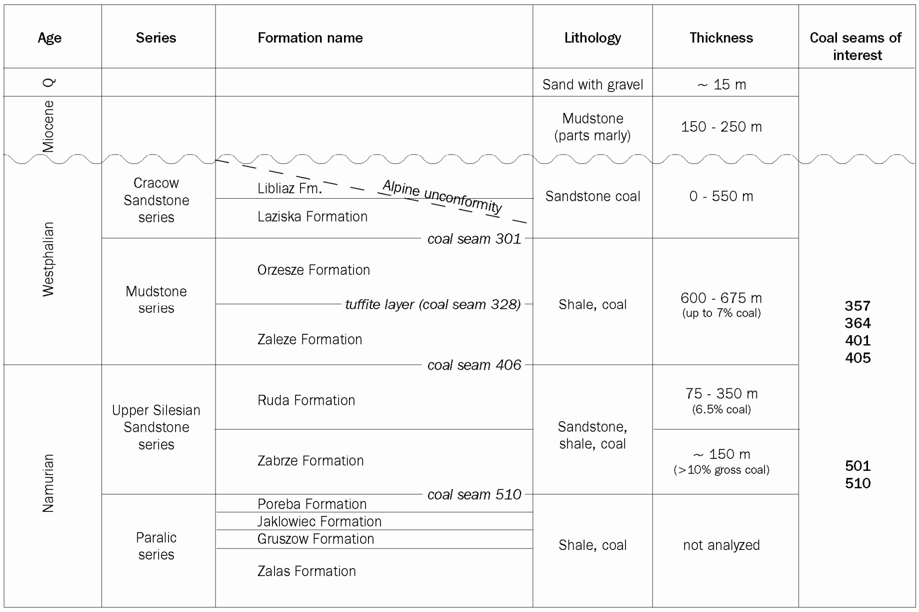


Figure 2: Geological map of the top of the Carboniferous in the Upper Silesian Coal Basin. The location of the site is indicated in green.



Age	Series	Formation name	Lithology	Thickness	Coal seams of interest
Q			Sand with gravel	~ 15 m	
Miocene			Mudstone (parts marly)	150 - 250 m	
Westphalian	Cracow Sandstone series	Libliaz Fm. — Alpine unconformity	Sandstone coal	0 - 550 m	
		Laziska Formation			
		coal seam 301			
	Mudstone series	Orzesze Formation	Shale, coal	600 - 675 m (up to 7% coal)	357 364 401 405
		tuffite layer (coal seam 328)			
		Zaleze Formation			
		coal seam 406			
Namurian	Upper Silesian Sandstone series	Ruda Formation	Sandstone, shale, coal	75 - 350 m (6.5% coal)	
		Zabrze Formation		~ 150 m (>10% gross coal)	501 510
		coal seam 510			
	Paralic series	Poreba Formation	Shale, coal	not analyzed	
		Jaklowiec Formation			
		Gruszow Formation			
		Zalas Formation			

Figure 3: Overview of the stratigraphic succession in the area of the pilot site and surrounding area, based on well evaluations and after McCants et al. (2001). In well MS-3 the Libliaz Fm. was not encountered during drilling.

The majority of the sandstone bodies are between 5 and 8 m (16.4 and 26.2 ft) thick, and their distribution suggests that they were deposited along syn-sedimentary faults (Figure 3). Some of these bodies cut into underlying coal seams, thereby destroying the lateral continuity of the coal. This indicates that there was tectonic activity during deposition of these sediments. In general, the faults with a north-south orientation in the area are related to Carboniferous tectonic events. The tectonic history of the area, and of the entire USCB, is complex, especially compared to commercial coalbed methane basins in the U.S.A (McCants et al., 2001). Periods of active tectonic periods have alternated with periods of relative inactivity, as is for example indicated by the upward decrease in the abundance of sandstone bodies. This likely indicates a period of relative low tectonic activity. The area of interest within the USCB is mainly characterized by fault block tectonics. The pilot site is located on a large block that was upthrusted during the Alpine orogeny. In general, faults with an east-west orientation can be attributed to this event. The fault block is triangular and wedged between a hangingwall block in the west and a footwall block in the east. The bounding faults have a NE-SW and a NW-SE orientation (Figure 1 and Figure 3). These faults are pre-Miocene and were already active in the Carboniferous. Experience from the coal mines suggests a sealing character of these intra-Carboniferous faults (Wător, pers. comm.). The major E-W fault zone to the south, bordering the upthrusted block, is still active. There are no faults detected inside the block; coal seams are therefore expected to be continuous within the bounding faults. However, the possibility of the occurrence of smaller (sub-seismic) faults can not be excluded. The thickness of the overburden in the area is about 250 m, mainly consisting of shale deposits of Miocene age that uncomformably and disconcordantly overly the Carboniferous deposits (Figure 2). Local mining experience showed that the Miocene shales are sealing and are not in hydrological contact with the Carboniferous (Wător, pers. comm.; Adamaszek, pers. comm.). The sealing capacity of the Miocene shale is proven by the occurrence of natural gas pockets in the sandstones of the top Carboniferous. It is therefore expected that the Miocene sediments form a cap rock on top of the Carboniferous. The Carboniferous faults do not continue in the overburden and are therefore considered to have ceased activity before the Miocene.

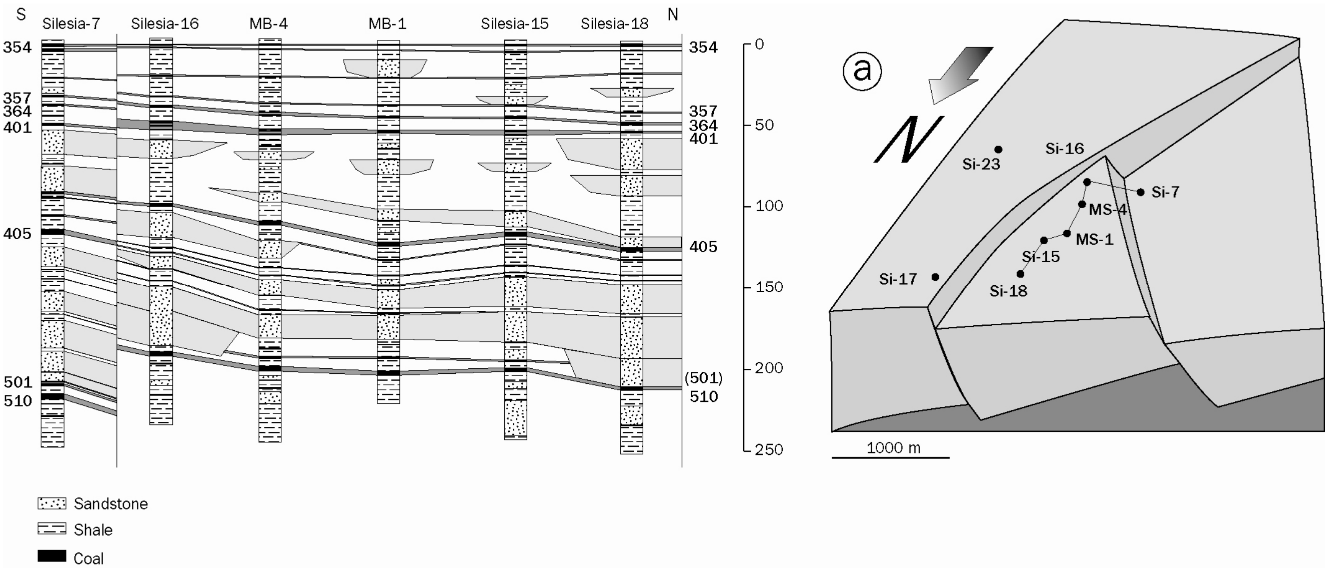


Figure 4: Stratigraphic cross section (N-S) of the site through 6 wells using coal seam 354 as datum. Identification and correlation of the coal seams is based on experience from the Silesia mine. Thickness variations across fault between Silesia 7 and Silesia 16 well indicate synsedimentary tectonic movement.

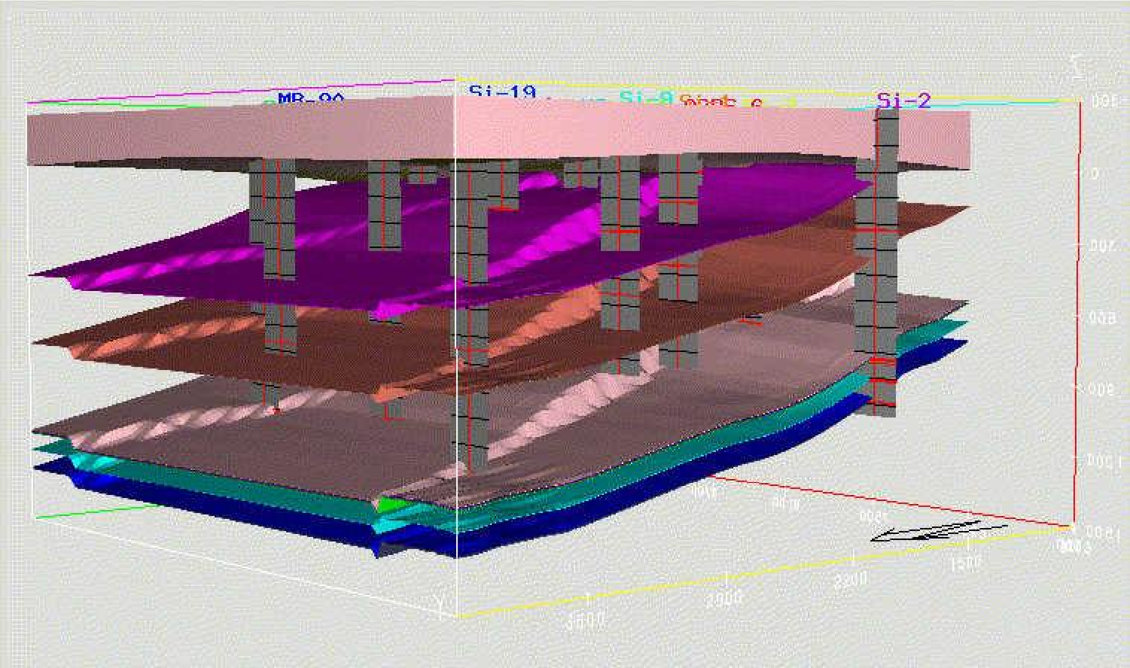


Figure 5: 3D model as constructed in PETREL

3.3 Implications of the geological conditions

Evaluation of well information showed that the coal seams in the top of the investigated interval (seams 357, 364, 401 & 405) are positioned within a 20 m thick package of alternating shale and coal layers. Injection in these seams reduces the chance of leakage. From a sedimentological point of view, the top three coal layers are more likely to be continuous than the lower seams in absence of large sand bodies (Figure 6).

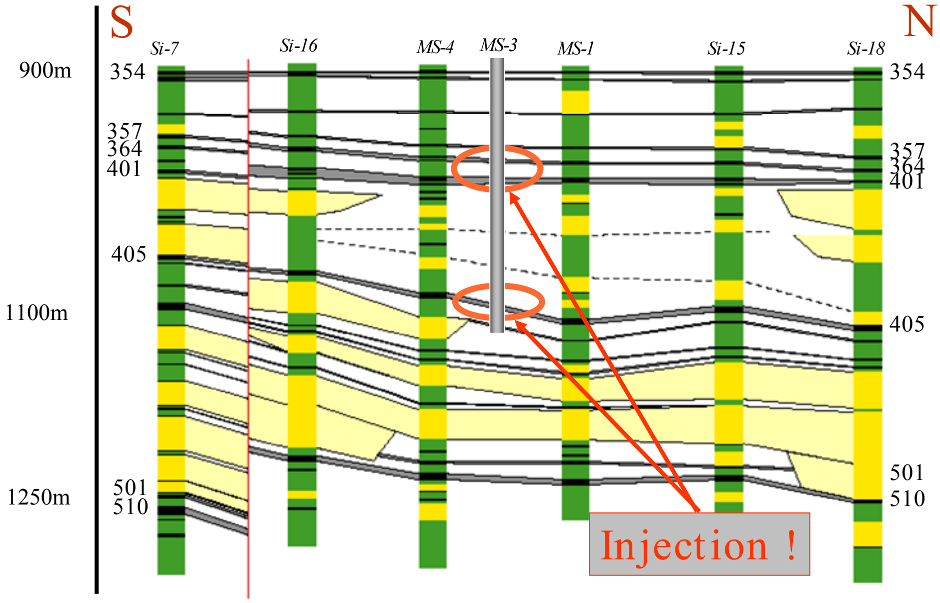


Figure 6: Cross section based on the wells in the area, indicating the lateral continuity of the coal seams.

3.4 Coal characteristics and gas content

Within the area 6 main coal seams are present in the depth interval of interest (950-1250 m; 3117 – 4101 ft), varying in thickness between 1 and 3.5 m (3.3 and 11.5 ft). Multiple thinner seams are occur in-between these main seams. From a sedimentological point of view, the top three coal seams (seams 357, 364, and 401) are more likely to be continuous than the lower seams because of the absence of large sand bodies. These seams are positioned within a 20 m (65.6 ft) thick package of alternating shale and coal layers, and the risks of leakage of the injected CO_2 to other strata is considered to be low. Seam 405 is also positioned between shale layers, but the chance of connectivity to an adjacent sandstone body is higher.

Generally, the main component of the coal seams is vitrinite (48-72%), with lesser amounts of inertinite (15-32%) and exinite (6-14%). Mineral matter ranges between 5 and 19%. The coal is high-volatile bituminous with a rank of about 0.8-0.85 %Rr. Ash content, i.e., the inorganic part of the coal, ranges between 5 and 19%. However, analysis of the samples taken from the new injection well showed that the composition of the coal seams can vary significantly over short distances. For example, seam 405 showed a very high content of inertinite and relatively low content of vitrinite (Figure 4), whereas it is vitrinite dominated in wells nearby. The coal is high-volatile bituminous with a rank of about 0.8-0.85 %Rr.

During the course of the geological history of the area, the coal seams were buried deeper in the past than they are at present times (McCants et al., 2001). This resulted in relatively low to moderate permeability (1 – 2 mD), declining gradually with depth (McCants et al., 2001). The in-situ permeability of the coal seams was assessed in September 2003 by a well test directly after the perforation of the casing. The permeability of the coal seams 364 and 401 was in the lower range (~ 0.4 – 1.5 mD)of the regional variation (1 – 2 mD). The permeability of seam 405 was very low (~ 0.01 – 0.05 mD), which is possibly related to the composition of this seam (Figure 4). The permeability of the coal is, given the cleat system, likely to be anisotropic. The cleat system of the coal, as measured in the Silesia mine, has two main directions (15° and 105°). The orientation of 105° is assumed to be the open direction, based on observations in the nearby Silesia mine. However, extrapolation of this orientation is not straightforward, since orientations of open cleats can vary significantly on a local scale. No preferred orientation of the joints or cleats could be established by evaluation of the caliper log data.

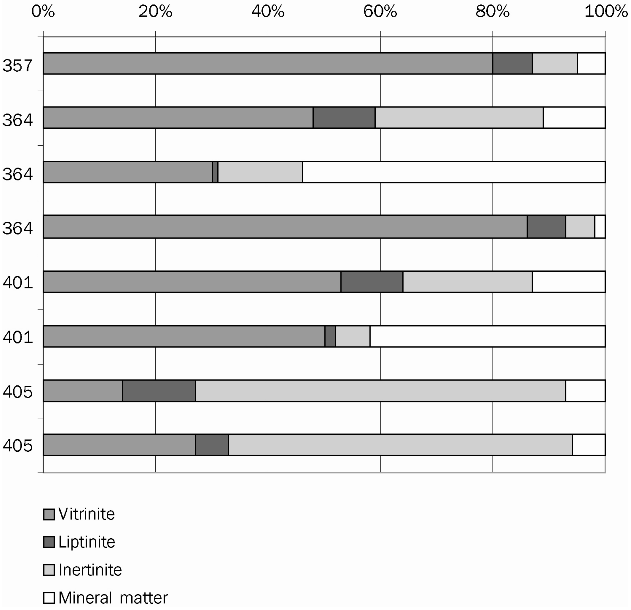


Figure 7: Composition of coal samples from cores of the main coal seams drilled by the MS-3 well.

Exploration activities for CBM showed that the gas content in the USCB is relatively low, mainly as a result of degassing through faults during uplift phases (Kotas, 1994; McCants, 2001; Kędzior, 2002). This resulted in under-saturated coals because there was no new generation of gas after the last uplift phase. In the study area a relation seems to exist between faults and the gas content of coal, which is lower in the vicinity of the faults (Kędzior, 2002). Due to the undersaturation of the coal, the free gas in the cleat system of the coal will be very limited. Also, the gas content of the sandstone intervals will be relatively low because the majority of these intervals are connected to the coal seams.

During the drilling of the MS-3 well a total of 9 core and 29 cutting samples were collected for desorption tests, that were performed on site and in the laboratory after collecting the last core samples. For the coring a conventional core retrieval system was used, implying relatively long trip time between coring and canister storage. Correction for lost gas was applied, although the amounts of lost gas were limited because desorption rates are very low. Desorption tests took several months, probably due to low diffusion rates, and the amount of residual gas was high, especially for the cores (Figure 5). Still, the total gas content of the cores was up to 10 m^3/ton (dry ash free, i.e., corrected for moisture and mineral content of the coal), indicating that the total amount of gas in place is fairly good. The gas from canister tests from the wells MS-1, MS-4, and MS-3 showed CH_4 concentrations of usually 95 % or higher, with some percentages of N2 (0.5-3 %) and CO_2 (1-3 %) and traces of other gases.

Thus, the coal seams are undersaturated because of an uplift in the geological past. However, the coal seams are able to become saturated because the capacity of gas sorption is still existing. The undersaturated coal could therefore still be interesting for CO_2 sequestration, once the coal seams are saturated with CO_2.

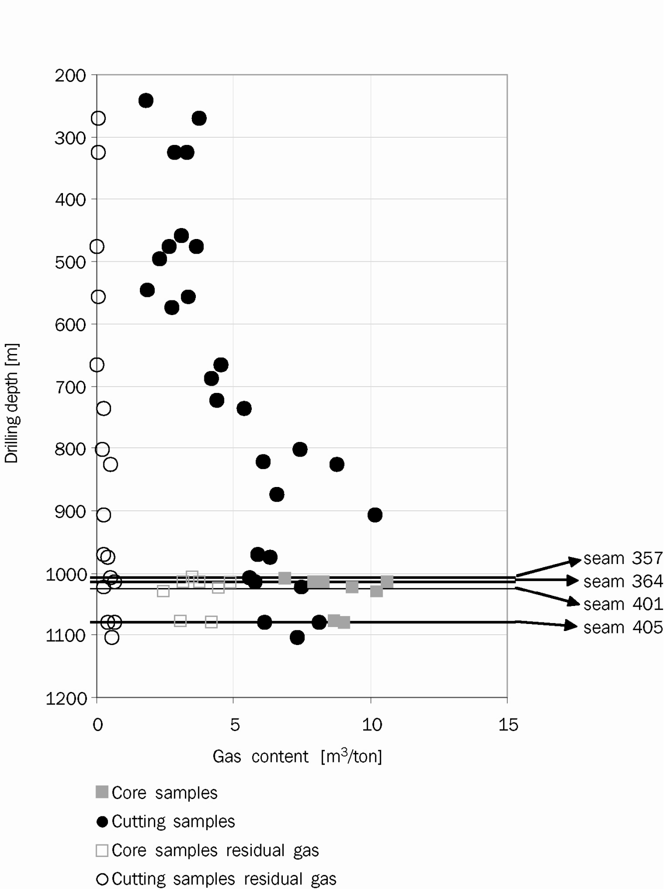


Figure 8: Gas content from desorption tests of cuttings and cores from the MS-3 well.

4 Pre-operational numerical simulation of the operations

4.1 Introduction

One of the main aims of the RECOPOL project is the gaining of more quantitative knowledge of the reservoir flowing- and adsorption processes active in a CO_2 driven ECBM process. Numerical simulation studies were initiated in order to investigate all phases of the planned Enhanced CoalBed Methane (ECBM) pilot test. Initial studies were conducted to assist in the design of the development plan for the intended test. From the outset of this project it was established that a breakthrough of injected CO_2 at the production well would render the maximum amount of information concerning the ECBM potential of the Silesian coal. The feasibility of the breakthrough, within the project lifetime, was investigated by reservoir modelling of the operation at the starting phase.

4.2 Numerical simulation

Two software packages were used: SIMED and COMET. Two scenarios were taken into consideration for the development plan.

- Drilling of a new well for CO_2-injection and putting the two old wells back into CH_4-production. The exact location of the well will be mainly defined by spatial constraints at the surface.
- Usage of one of the existing wells as an injection well From the start, this option was not preferred, and was only taken into consideration to investigate cost reduction options.

A uniform data was compiled and used by CSIRO, ARI and TNO (Figure 9Figure 10, and Figure ***11***) in order to make a direct comparison possible between all simulation attempts. With the set of simulation cases the sensitivity of several parameters (porosity, permeability, anisotropy, injection/production scheme) was investigated (see separate reports).

In the first scenario, breakthrough was found unlikely within 1.5 years when the CO2 is injected in all six coal seams, as a result of the limited amount of CO_2. It was therefore suggested that only three coal seams should be used for injection, preferably positioned within a thick package of alternating shale and coal layers. Modelling results show that, when injecting in three seams, breakthrough is unlikely within 1.5 years when the distance between injection and production wells is more than 200 meters.
In the second scenario, with a distance of 375 meters between the wells, no breakthrough is predicted to occur. Therefore, this last option was abandoned.

The overruling conclusion of all initial simulation work was that the final distance between the CO_2 injection well and the closest CH_4 production well was the key to the success of the pilot test. Consensus was found in fact that the initially adopted distance of 175 meter between the two wells would be too large to guarantee breakthrough. To increase the chances on a breakthrough, it was recommended that the new well should be drilled in line with the two production wells, within about 150 m from the updip well. However, spatial constraints at the surface could require a deviation from this line. A well design distance was adopted of a minimum of 100 meters and a maximum of 150 meters between the new injection well and well MS-4.

The success of the test was predicted to be largely dependent on the CO_2 adsorption mechanism of the coal. Furthermore, simulation showed that the doublet type of test would exhibit a very slowly increase of CO_2 in the production well at breakthrough above the natural CO_2 content of the produced gas.

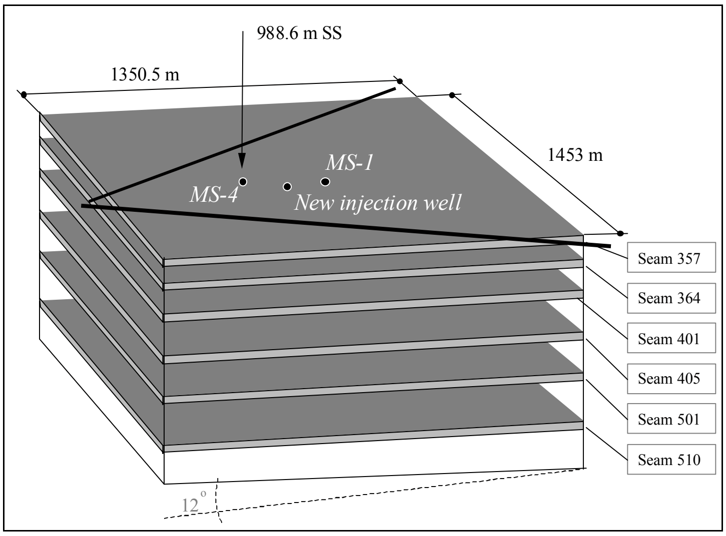


Figure 9: Layer model in SIMED, used by TNO, for reservoir modelling of the injection/production

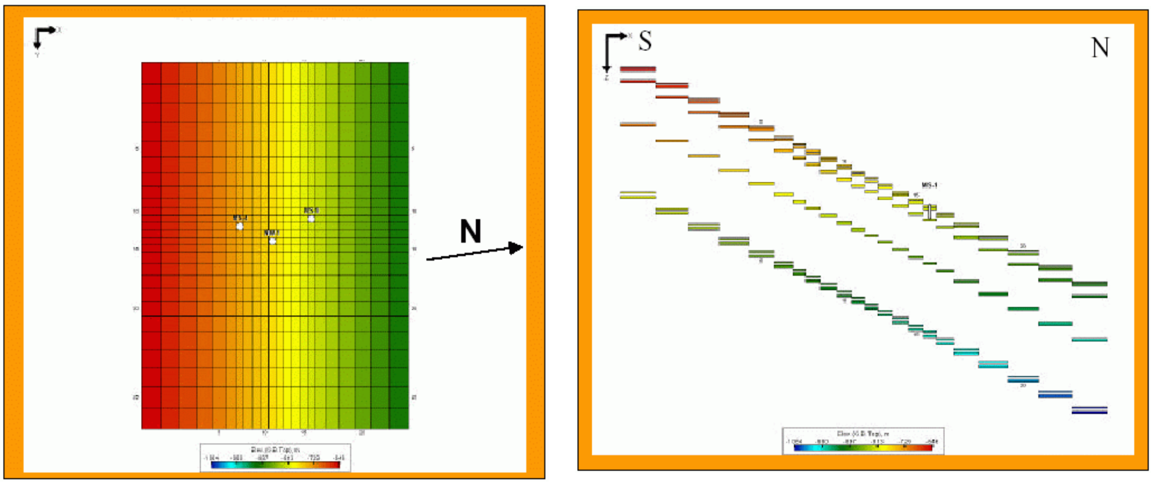


Figure 10: modelling approach in COMET II, used by ARI, for reservoir modelling of the injection/production

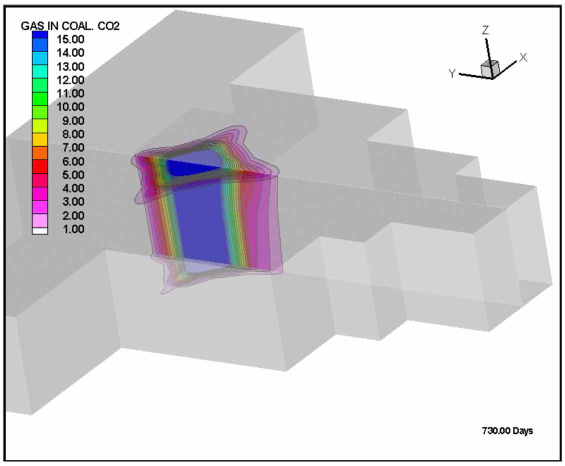


Figure 11: Results of SIMED Modelling by CSIRO, of the injection/production

5 Site development

5.1 Introduction

The design and development of the pilot site was one of the major tasks in the RECOPOL project. The selected site is located within the concession of the Silesia mine, which has been in operation for decades. The characteristics of the site have been documented from these activities and from the activities in the nineties by Metanel, the owner of the existing wells MS-1 and MS-4 and concession holder for the gas production. As many data as possible were collected and evaluated, in order to get a good background for the development plan of the site.

It was decided, within the strict budgetary conditions, to drill a new well for CO_2-injection and to put the MS-4 back into production. The location of the new injection well (MS-3) was set north (downdip) of the existing MS-4 production well (Figure 12) to a depth of 1120 m. This location, thus the distance to the production well, was defined by numerical modeling in the development phase of the project (see chapter 4). It was limited to 150 m because it was intended to establish a breakthrough of the CO_2 in the production well, within the project lifetime and with the available CO_2.
It was decided to maintain the standard conventional facilities for the CBM production (Figure 13). Also, surface CO_2 injection facilities were designed and developed (Figure 14).

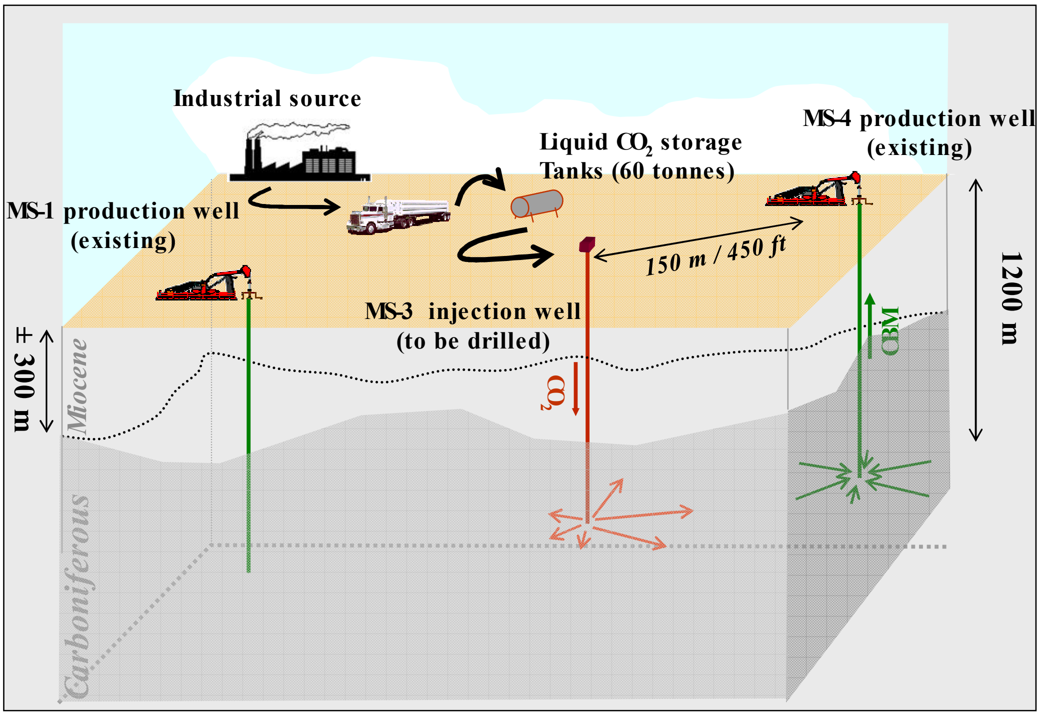


Figure 12:Design of field experiment

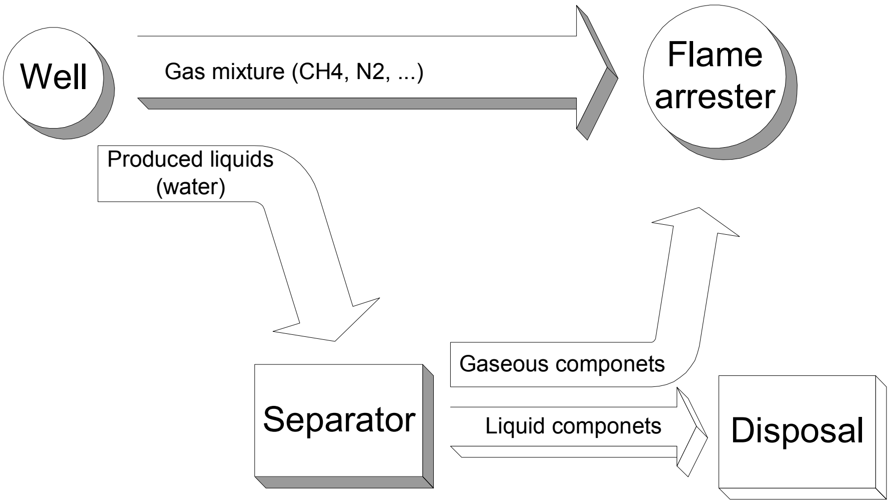


Figure 13: Basic flow chart production CBM

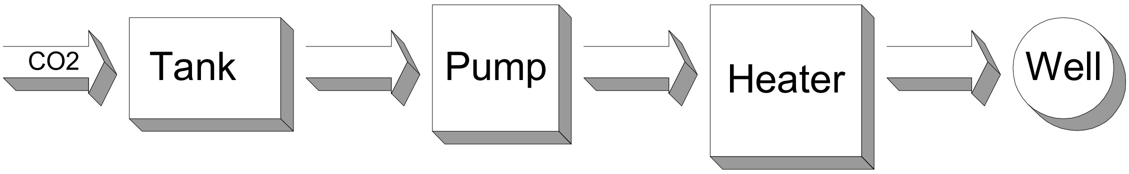


Figure 14: Basic flowchart of CO_2 injection facilities

5.2 Permits

Drilling the new injection well in between MS-1 and MS-4 caused an unforeseen problem, because the selected location was located in an area that was planned for gravel exploitation in the near future. For this reason a lease contract of the site was concluded with the owner of the land. A tender procedure was started in order to select a company that would be awarded with the subcontract for the drilling of the new injection well. All required permits were arranged for both the drilling and the further operations.

5.3 Repair, workover and testing of MS-4 production well

To put well MS-4 back into production, a workover job on this well was executed in the summer of 2003. the work consisted of the following activities:

1. Downhole pumping equipment was checked
2. New pump and tubing was acquired
3. Well was cleaned by lowering of a mill bit
4. The gauge was verified and the 5 ½” casing was cleaned.
5. The two bottom perforations were isolated with a bridge plug
6. The integrity of the 5 ½” casing and the casing head was checked.
7. DST test was run on 405 seam

It was established that the perforations were open and an initial reservoir pressure of 9.0 MPa was determined from the DST test (Table 1). In order to eliminate the contribution of the 501 and 510 seams, that were not drilled by the MS-3 well, a bridge plug was placed in the MS-4 well between seams 405 and 501.

Table 1: DST results on 405 seam

		Remarks
Program	packer was set at a depth of 1041m	It was noted that air bubbles were continuously coming out to surface during both flow periods.
	25 minutes of an initial flow period	
	60 minutes of an initial shut-in period	
	240 minutes of a final flow period	
	120 minutes of a final shut-in period	
Interpretation	Reservoir pressure = 9.045 Mpa	1.7 m^3 of formation fluid recovered after testing (s.g=1.06; Cl-=51.5g/l)
	Pressure gradient = 0.0088 MPa/m	

Further activities on the MS-4 well included seismic tomography (see below). In addition, a deviation log was run in MS-4 before the installation of the pump. A gas pipeline was installed to transport the gas to the flare. A separator was installed where the produced water will be led through before being stored for disposal. The gas from the separator will be added to the gas pipeline that leads to the flare. A storage container for the produced water was installed, with a brine-resistant pump to transfer the water into a truck. The water was disposed via the water treatment facilities of the Silesia mine. From a budgetary perspective, analogue meters were installed to measure the produced gas and water. Taps were installed to be able to take samples from the gas stream for compositional analysis. In a later stage of the project (March 2005) a Siemens Ultramat analyser was installed with a digital output to measure the CH_4 and CO_2 concentration in the gas.

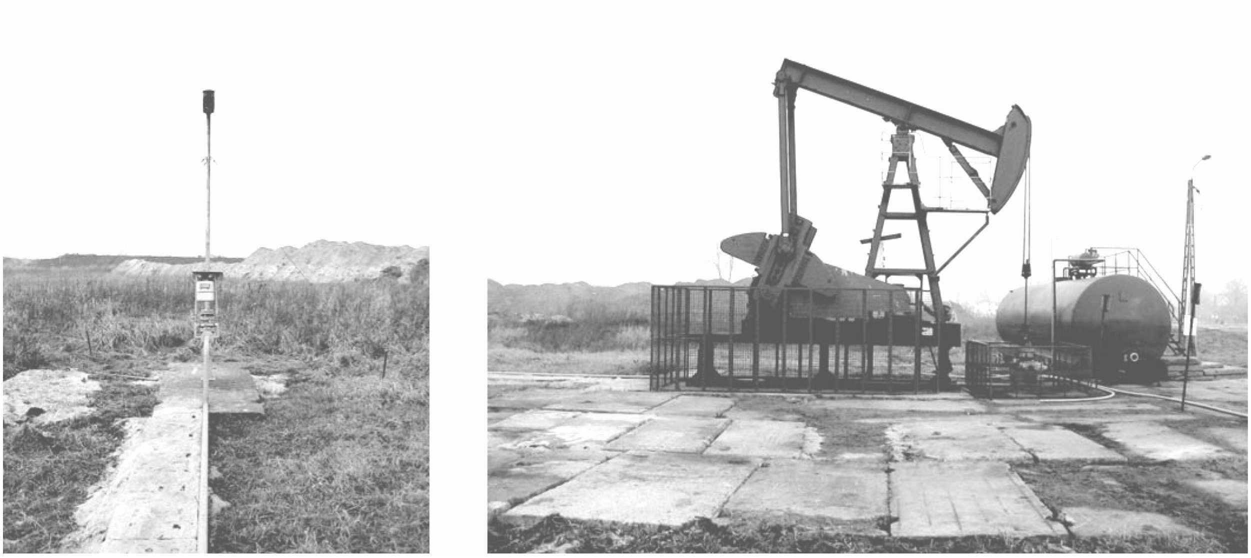


Figure 15: Picture of the MS-4 production well and pump. The gas is flared (left), while the water is transported by truck to a disposal site.

5.4 Driling, testing and installation of MS-3 injecction well and injection facilities

5.4.1 Drilling of MS-3

Site construction, mobilisation and rig up took place between mid July and the 1st of August 2003. The drilling diameters were variable:

- from 0 to 20 m – Ø 438 mm (in Quarternary formations),

- from 20 m to 200 m – Ø 311 mm (in Tertiary formations and water-bearing thick sandstones of Laziska Beds),
- from 200 m to 1120 m – Ø 216 mm (in Carboniferous formation)

A depth of 1120 m was sufficient to drill the target coal seams (seams 357, 364, 401, and 405) and ca. 50 m additionally (***Figure 16***).

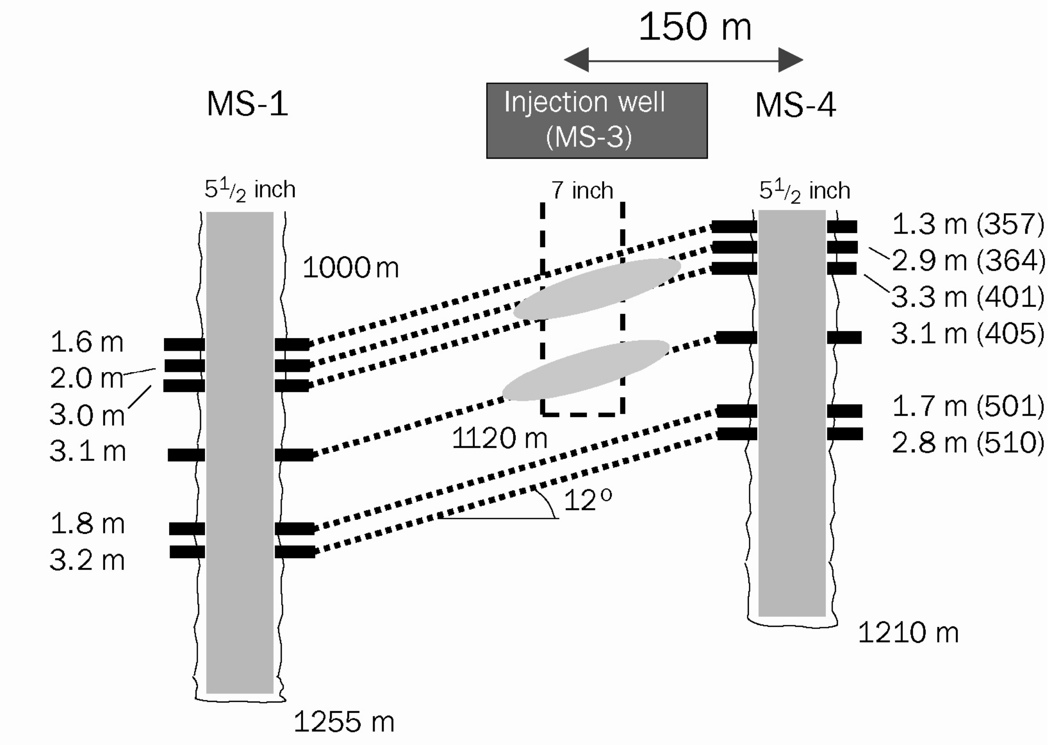


Figure 16: Correlation and thickness of target coal seams for CO_2 sequestration at the RECOPOL pilot site.

During the drilling, a mud-logging service was provided to continuously monitor the drilling parameters, gas detection in mud and the analyses of drill cuttings. Also, the geological section of the operational documentation included a lithologic description of rocks based on the analysis of cuttings and core. During the drilling of MS-3 well cutting samples were collected every 5m or every 10m depending on depth intervals. Core samples were collected from the following depth intervals:

1. from 1004.5 to 1031.5m, including coal seams: 357, 364, 401 & 402
2. from 1077.5 to 1081.0m, including coal seam: 405

For the coring a conventional core retrieval system was used. It was observed that there was a very low rate of penetration (0.5m – 3m per hour, ave: 0.7m/h). Total core recovery (including sand and clay layers) was 93% (30.5m cored / 28.3m recovered). Difficulties were encountered in obtaining intact coal core (). Core run number 3 showed a poor recovery: the whole coal seam (0.6m thick) was not recovered. Also, the core diameter shrank at 1m interval, probably due to a piece of hard rock that attached to the drill bit. To solve the coring problems, the core bit was replaced before running core number 4 (with the 405 coal seam). This core was recovered after cutting the inner barrel (Figure 17). In total 9 core and 29 cutting samples were collected.

Figure 17: Pictures of coring activities. Top pictures are from the first core, which was relatively unsuccessful. Bottom pictures show the successful recovery of the 405 core by cutting the core barrel in half.

5.4.2 Logging

Wireline logging in MS-3 well was done before running the 7” casing. The aim of the wireline logging is to determine petrophysical properties of rocks including: resistivity, radioactivity, permeability and cleat system. The following logs were acquired:
0 – 200 m (measurement through 9⅝” casing): Gamma Ray (GR)
200 – 1117 m (measurement in open hole): Gamma Ray (GR), Compensated Density Log (CDL), Dual Spaced Neutron (CNT), Dual Lateral log (DLL), Sonic (BCS), Long Spaced Sonic (LSS), X-Y Caliper (XYC), Six-Arm Dipmeter (SED), Spectral Gamma Ray (SGR).

The log analysis was performed in conjunction with the logging and included lithology, porosity and saturation, dipmeter calculation, LSS analysis, composite log, well deviation from SED, and SGR log presentation.

5.4.3 Completion before well testing

The well was completed with casing of the following diameters: from 0 to 20 m - 13⅜” J55, from 20 m to 200 m - 9⅝” K55, and from 200 m to 1120 m – 7” K55. The casing was cemented and the cement job was checked by running a Cement Bond log (CBL). The CBL showed that the cement job was fairly good to good. Also, a collar locator log (CLL) was run.
Perforation of the casing and cement was performed after the cement job (13/14 September 2003). The following zones of interest were perforated: the seam 364 (over a total of 1.8 m), the seam 401 (over a total of 2.6 m), and the seam 405 (over a total of 2.0 m). The perforation density was 5 shots/ft under an angle of 60° with a penetration depth of 30.18 inch (767 mm)[1].

5.4.4 Well testing

Two individual intervals were tested directly after perforation:

- the perforated zones of coal seams 364 and 401 together, and
- the perforated zone of coal seam 405 separately.

The in situ permeability of the coal seams was assessed in September 2003 by a well test directly after the perforation of the casing. The perforated zones containing coal seams 364 and 401 were tested together, and the perforated zone with coal seam 405 was tested separately.
The well tests showed that the permeabilities were lower than could be expected on the basis of regional experience from earlier CBM wells. The permeability of the coal seams 364 and 401 was estimated at 0.4 and that of seam 405 at 0.04 mD, while permeabilities in the range of 0.5-1.5 were anticipated. Possible explanation is the composition of the coal seams. Analyses of the core samples from the MS-3 well indicated that composition of the coal seams is variable (vitrinite up to 80%, inertinite up to 50 %, liptinite up to 10%), with locally high ash contents (up to 50 %). However, seam 405 is characterized by a very high content of inertinite and a relatively low content of vitrinite. This could be related to the low permeability of this seam.

5.4.5 Seismic monitoring: tomography

As a part of the RECOPOL project crosswell seismic tomography was carried out in order to image the target subsurface structures in which it is envisaged to inject CO_2. The first survey was performed in the second half of September 2003, prior to CO_2 injection. A summary of the activities and results of the crossborehole seismic monitoring are reported in a separate report (Winthaegen, 2005).

5.4.6 Completion of the well

The x-mas tree and downhole equipment were installed in October 2003, consisting of injection tubing (2 7/8”TDS) and packer (7”). The well lay-out is a 7” cased hole with a 2 7/8” tubing (1010 m) and a packer (ca 975 m, 250 Bar delta P). There are three perforation intervals at circa 1012, 1022, and 1076 m, cumulative thickness circa 6 m.

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[1] 4 ½ ” O.D. gun 5 SPF loaded with 36 gram RDX DP charges Penetration depth 30.18 inch (767 mm).

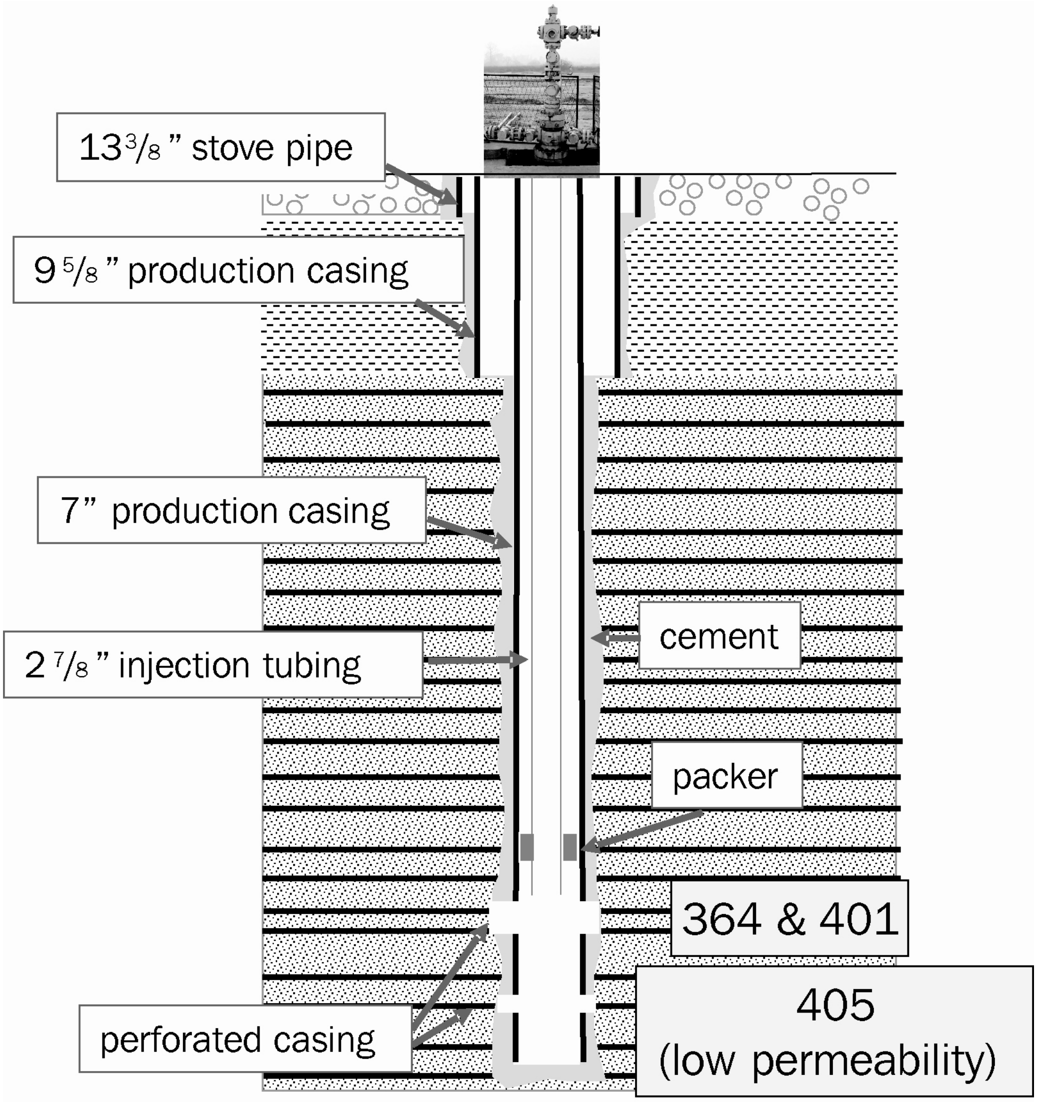

Figure 18: Well lay-out of the 1120 m (3,675 ft) deep injection well (MS-3). The well was completed with a 0.18 m (7 inch) casing. The casing was cemented and the cement job was checked by running a cement bond log. There are three perforation intervals at circa 1012, 1022, and 1076 m (3320, 3353, and 3530 ft). These intervals correspond with the seam 364 (over a total of 1.8 m or 5.9 ft), the seam 401 (over a total of 2.6 m or 8.5 ft), and the seam 405 (over a total of 2.0 m or 6.6 ft). The perforation density was 16.4 shots/m (5 shots/ft) under an angle of 60° with a penetration depth of 0.767 m (30.18 inch). In October 2003 the x-mas tree and downhole equipment were installed, consisting of a 0.073 m (2 7/8 inch) injection tubing of 1010 m (3314 ft) length and a 0.18 m (7 inch) packer at 975 m (3199 ft).

5.4.7 CO_2 injection infrastructure

A road capable for 20 ton trucks was constructed and power supply to the site was realized. Surface facilities (including foundations) for CO_2 storage, handling and injection were constructed at the site in the autumn of 2003. The CO_2 is stored at the site in liquid form at a temperature of circa -20 °C and medium pressure of circa 2 MPa in containers isolated with polyurethane. In order to have sufficient CO_2 in reserve to assure continuous operation, two containers (over 60 tonnes in total) were placed. A high-pressure CO_2 pump-unit was installed with a capacity of 800 kg/h, i.e. daily injection rates are maximal about 20 tonnes in a 24h operation. Heaters was installed on the pump unit to heat up the

CO_2 at the initial injection, to prevent frost in the injection line, wellhead and tubing. The CO_2 surface equipment was connected to the wellhead.

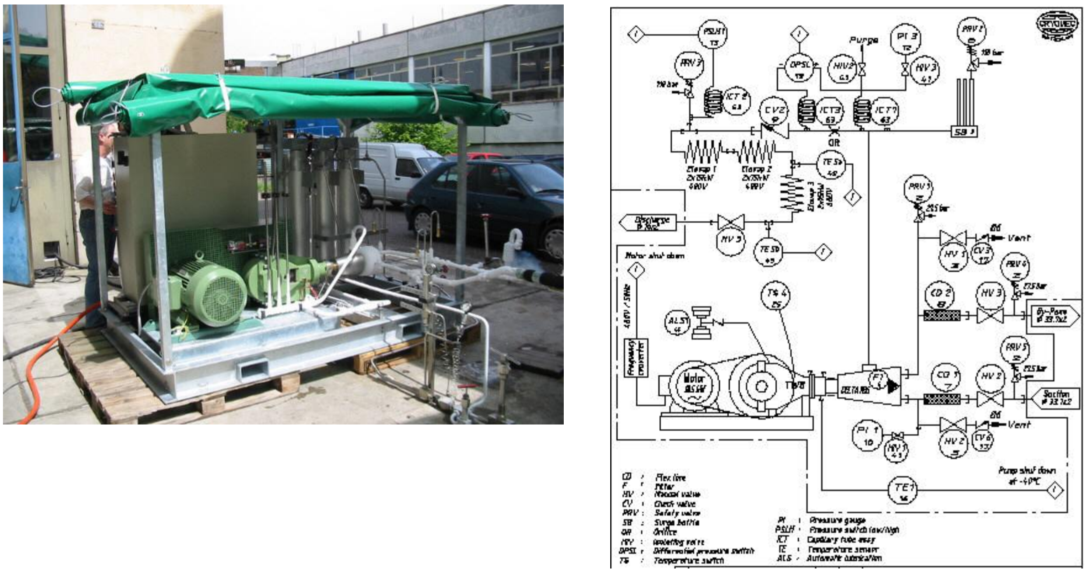

Figure 19: High pressure pump unit for the operations.

5.4.8 Miscellaneous site infrastructure and activities

A cabin was installed on the site with a computer for data registration, electricity and water, furniture, heating, mobile telephone connection, etc. This allowed having personnel at the site continuously. The site is protected via fences.

The pressure and temperature conditions in the water filled injection well were determined before injection, as well as the initial equilibrium water level in the tubing (146 m below surface). The CO_2 flow during injection, casing pressure, tubing pressure and tubing temperature are registered digitally at a variable time interval (15 s during injection).

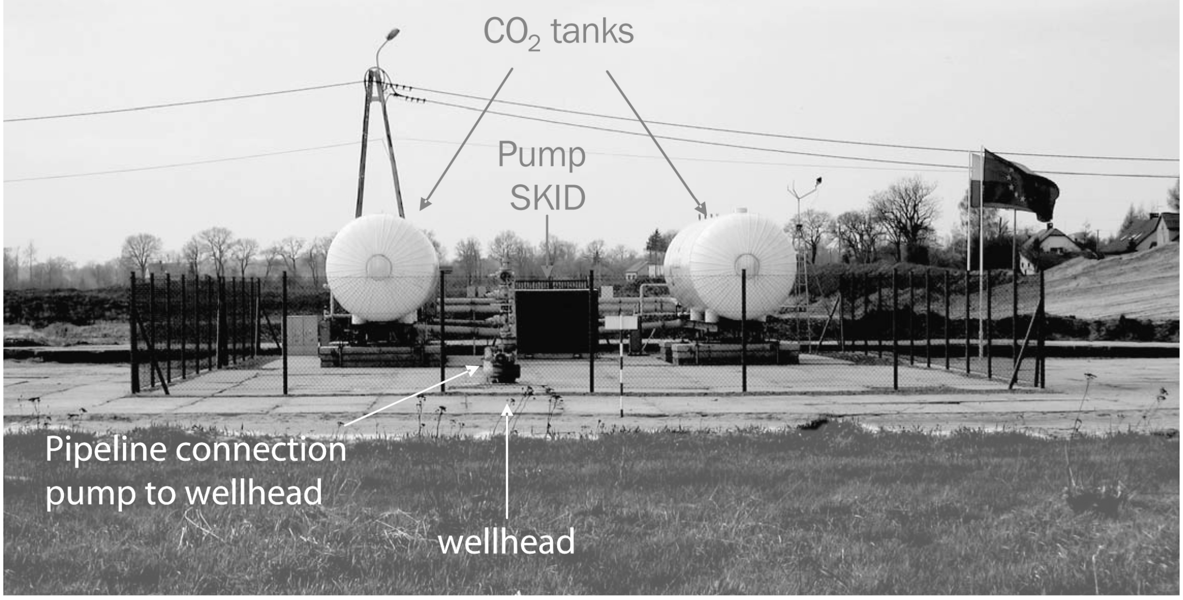

Figure 20: Picture of the well site of the injection operations

Site preparation

The new injection well (MS-3) was drilled 150 m (492 ft) north (downdip) of the existing MS-4 production well (Figure 9) to a depth of 1120 m (3,675 ft). The location of the well was defined by numerical modeling in the development phase of the project in order to establish a breakthrough of the CO_2 in the production well, within the project lifetime (maximum of 18 months of experimental operations) and with the available CO_2 (1,000 to 1,500 tonnes). The cemented casing was perforated in three zones, which included the coal seams 364, 401 and 405, over a cumulative thickness of circa 6 m (19.7 ft; figures 10 and 11). The CO_2 is stored at the site in liquid form in containers (Figure 12). A high-pressure CO_2 pump unit with heaters was installed to be able to prevent frost in the injection line, wellhead and tubing. The pressure and temperature conditions in the water-filled injection well were determined at 1,000 m (3,281ft) before injection at 8.6 MPa (1,247 psi) and 39.5 ºC (103.1 ºF), respectively. Also, the initial equilibrium water level in the tubing was established at 146 m (479 ft) below surface. The CO_2 flow during injection, casing pressure, tubing pressure and tubing temperature are registered digitally at 15 seconds time intervals. The time intervals were changed during specific injection periods or during longer periods of operational standstill.

6 Operational results and interpretation

Chapter 5 described the activities and tests that were performed before the start of the actual operations. The operational activities on the pilot site took place during a period of 13 months from May 2004 to June 2005. Four periods could be distinguished in this time: 1) baseline production before injection, 2) injection and production before stimulation of the reservoir by a minifrac job, 3) the period between the mini-frac and the frac job, and 4) injection and production after stimulation of the reservoir by the frac job. These different periods will be described separately.

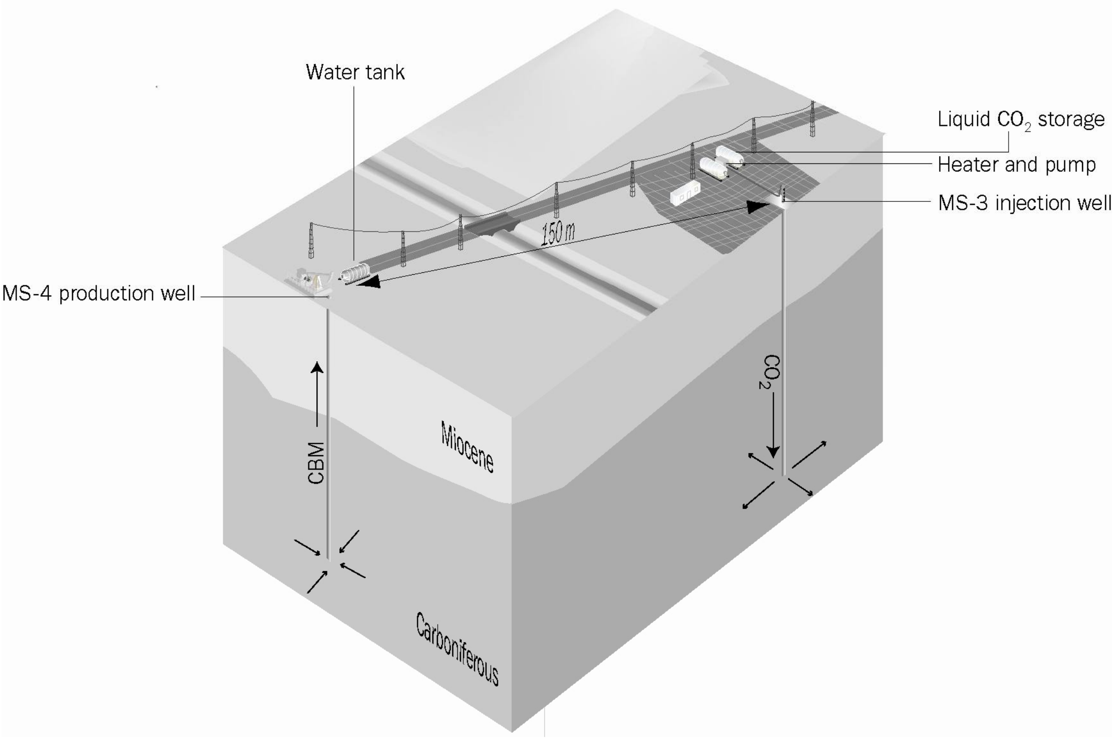

Figure 21: Schematic overview of the field experiment. The boundary between the Carboniferous and the Miocene cover is schematically indicated.

6.1 Period 1: Baseline CBM production (May 2004 to August 2004)

In order to evaluate possible effects of CO_2 injection, it is mandatory to establish the initial, or baseline, conditions that existed before the start of the injection operations. Evaluation of historical data from 1996 shows a peak production of ca.100 m^3/d (3,531 cf/d) after circa 20 days of production declining to 60 m^3/d (2,119 cf/d) after 60 days. These figures represent the cumulative production figures of the 357, 364, 401, 405, 501 and 510 seams. Of these seams, only the seams 364, 405 and 510 were stimulated by fracturing.

The existing coalbed methane production well (MS-4) was cleaned and repaired (see previous chapter). An initial reservoir pressure of 9.0 MPa (1,305 psi) was determined and the water level in the MS-4 was measured at ca. 170 m (558 ft) below surface, comparable to the level in the MS-3 well. Given the period of inactivity of several years, this level can be considered to be the equilibrium level. This indicates that the reservoir pressure in the well is hydrostatic towards the top of the Carboniferous, confirming that the Miocene is not in hydrological communication with the underlying Carboniferous. In order to eliminate the contribution of the 501 and 510 seams, that were not drilled by the MS-3 well, a bridge plug was placed in the MS-4 well between seams 405 and 501. The well was put back into production at the end of May 2004 with varying pump intervals. During the first month gas production rates varied, because the pump frequency optimum still had to be established. After this first month, production rates were circa 40 m^3/d (1,413 cf/d) in the beginning and declining towards circa 30 m^3/d (1,059 cf/d), where they appeared to stabilize. This trend appears to be a continuation of the historical trend described above, given that the amounts are slightly less because seams 501 and 510 are isolated by the bridge plug. Analysis of the produced gas showed that it was composed of circa 97 % CH_4, 1.5 – 2 % CO_2, and small amounts of other gases. This composition was comparable to the composition of the gas from the canisters. Both carbon dioxide and methane have a specific isotopic signature, which depends on the type and source of generation. The stable carbon isotope signature of the produced gas, for both CO_2 and CH_4, was analysed before the start of the injection to establish the baseline conditions.

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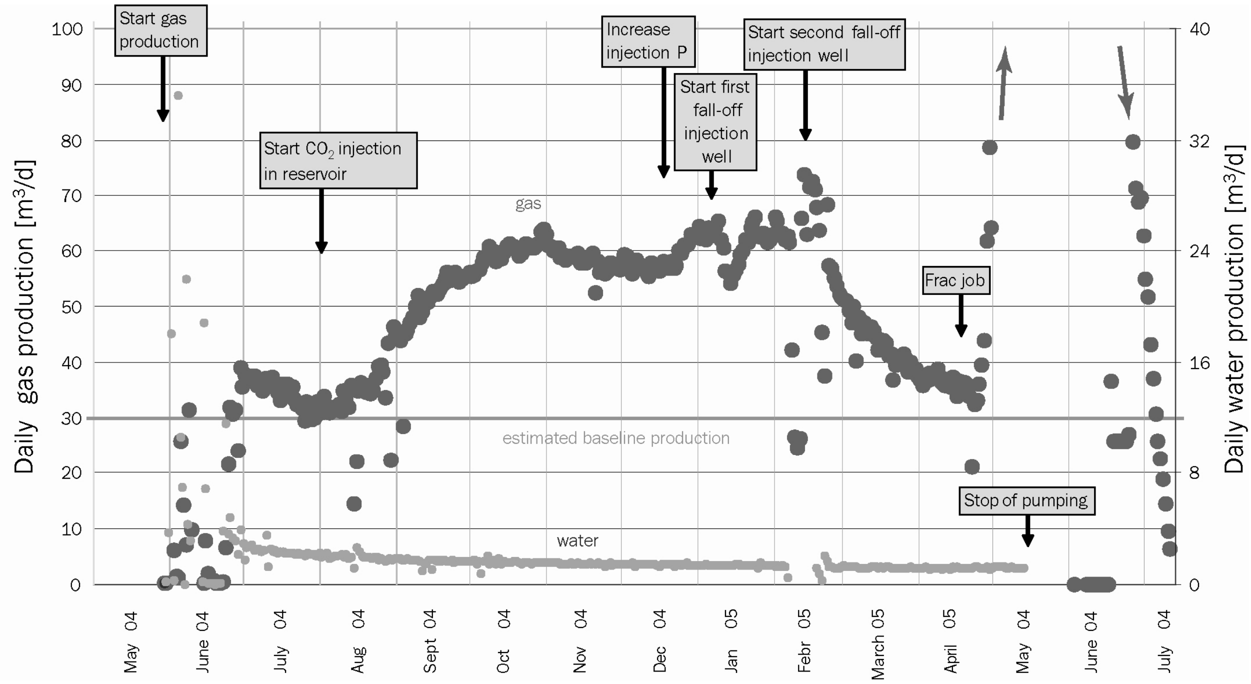


Figure 22: Gas production from MS-4 well between May 2004 and April 2005.

Water production has, after varying production in the start-up phase, declined since the start to circa 1-2 m^3/d (35.3 – 70.6 cf/d; Figure 22). The composition of the produced water was analyzed on a regular basis before the start of the injection to establish baseline conditions and its natural variation. The data before the start of the pumping were taken at irregular intervals with very low amounts of water produced. Therefore, the analyzed fluid sampled before and directly after June 2004 was highly influenced by the operations for testing and repair of the MS-4 well (Figure 23). These data show significantly higher amounts of iron and manganese ions, indicating the influence of the steel casing of the well on the composition of the reservoir water. Also, the lower concentration of bicarbonate (HCO3-) suggests that the water experienced some degassing of (natural) CO_2 as a result of the lower pressures during the earlier production.

The relation between bicarbonate in the water and gaseous CO_2 is established by the well known carbonate equilibrium reactions and Henry’s Law:

$$CO_2(g) + H2O \rightarrow H2CO3(aq)$$
$$H2CO3(aq) \rightarrow H+ + HCO3-$$

It took until July 2004 to produce reservoir water that was not influenced by the earlier activities, providing the actual baseline conditions of the formation water. The baseline data, after the start of the pump, show that the water is highly saline (circa 140 kg/m^3 or 3.96 kg/cf, Na+ 40 g/l, Cl- 80 g/l, Ca2+ 6 g/l, Mg2+ 2.5 g/l).

6.2 Period 2: CO_2 injection and CBM production (August 2004 to March 2005)

6.2.1 CO_2 injection (August 2004 to March 2005)

First injection tests with water took place at the beginning of July 2004. Liquid CO_2 from an industrial source was injected for the first time at the beginning of August 2004. From the start, it was not possible to maintain continuous injection. Required injection pressures with the applied injection rates (ca. 10 l/min or 0.01 m^3/min or 0.35 cf/min) appeared higher than initially anticipated. The injection of CO_2 was therefore realized by intermittent pumping up to 9 MPa (1,305 psi) at the well head, followed by a fall off period until the pressure reached 5.5-6 MPa at the well head. From October onwards, the pressure fall off after injection was limited to about 7 MPa at the well head. In the second half of December, adaptation of the injection equipment allowed higher injection pressures up to 14 MPa (2,031 psi) at the wellhead. Still, no continuous injection could be established. From late December to mid-February, injection was taken place in pulses from 11 to 14 MPa at the wellhead. The injection was estimated at circa 1-1.3 ton per day in the build-up/fall-off cycles. Between mid-February to March 2005 injection stopped in order to have a long fall-off period to be able to determine the permeability.

Evaluation of wellhead pressure and temperature data during the pressure build-up and fall-off of the intermittent injection periods, taking into account phase behavior and density changes of the CO_2, showed that the build-up time is decreasing and the fall-off time is increasing in time (Figure 24 and Figure 25). Additionally, the steep fall-off in the beginning of the curve during start-up (with water downhole) has disappeared in November and December. Both observations indicate a reduced permeability in time. Downhole pressure gauges were installed during the start-up in the beginning of July and August 2004 (28th of June to 5th of July 2004 and 2nd to 10th of August 2004), after the increase of injection pressures (16th of December 2004 to 11th of January 2005), and during the fall-off period in February (8th of February 2005 to 1st of March 2005). The downhole data can be correlated very well to the wellhead data, by taking into consideration the density variation with depth due to phase behavior. The daily and seasonal temperature changes at the surface have only shallow effects and therefore minor effects on the bottom hole pressure. The data showed that the CO_2 is in supercritical phase at in situ bottom hole temperature (relatively constant at circa 40 ºC) and the pressure conditions (varying between 8,6 and 24,5 MPa (1,247 and 3,553 psi) during operations), but its density and the viscosity are variable during the pressure fall-off period. This phase behavior of the CO_2 in the well complicated the interpretation with the available software, which is currently not designed to handle this. The fall-off tests that have been conducted in January and February 2005.showed that there is a rapid fall-off directly after shut-in of the well that lasts for several minutes. This seems to be independent of the injection pressure as it also occurred before the increase in injection pressure in mid-December. After the period of rapid fall-off, the pressure behavior can be explained by “well-bore storage” (CO_2 expansion causing injection).

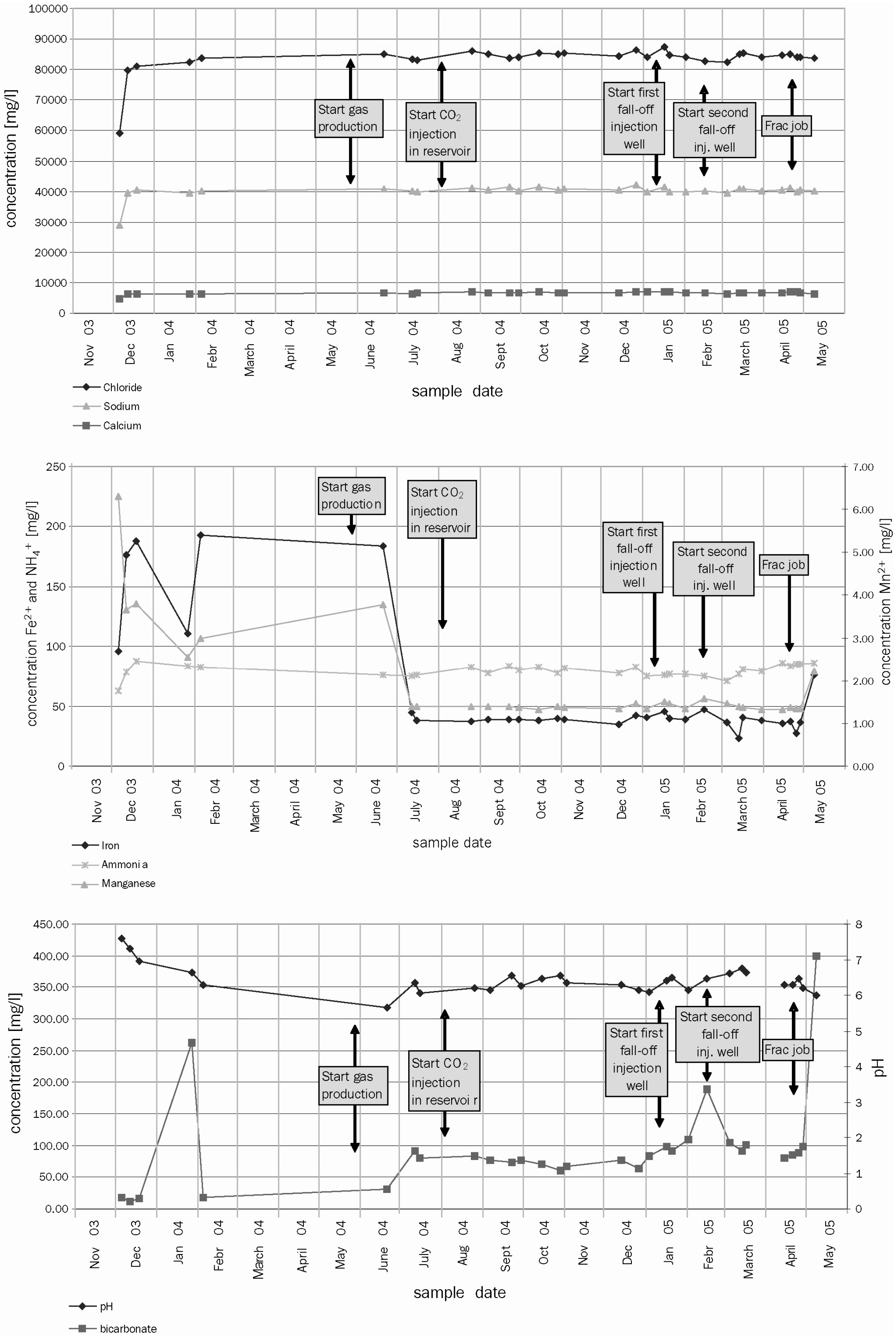


Figure 23: Composition of the produced water of the MS-4 well.

Despite the difficulties in the interpretation, the data clearly showed that the permeability of the coal seams decreased in time. Since well damage (e.g., blocked perforations) is unlikely as shown by a negative skin factor , the reduced injectivity is presumably the result of swelling of the coal after contact with the CO_2. Additionally, it was observed that there were no indications of fracturing. This is remarkable, because bottom hole pressures that were reached during injection (with a maximum of 24.5 MPa) were higher than the originally estimated fracture pressure of the coal. This indicates a change in reservoir properties.

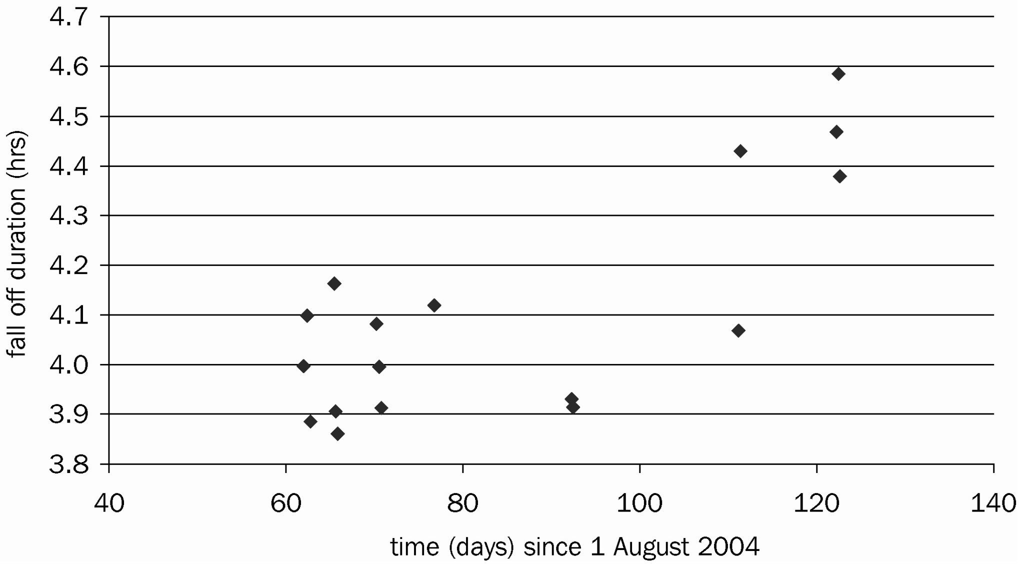


Figure 24: Variation of the duration of pressure fall-offs (between 9.0 and 7.1 MPa) from the start of the injection. These data are derived from well head data.

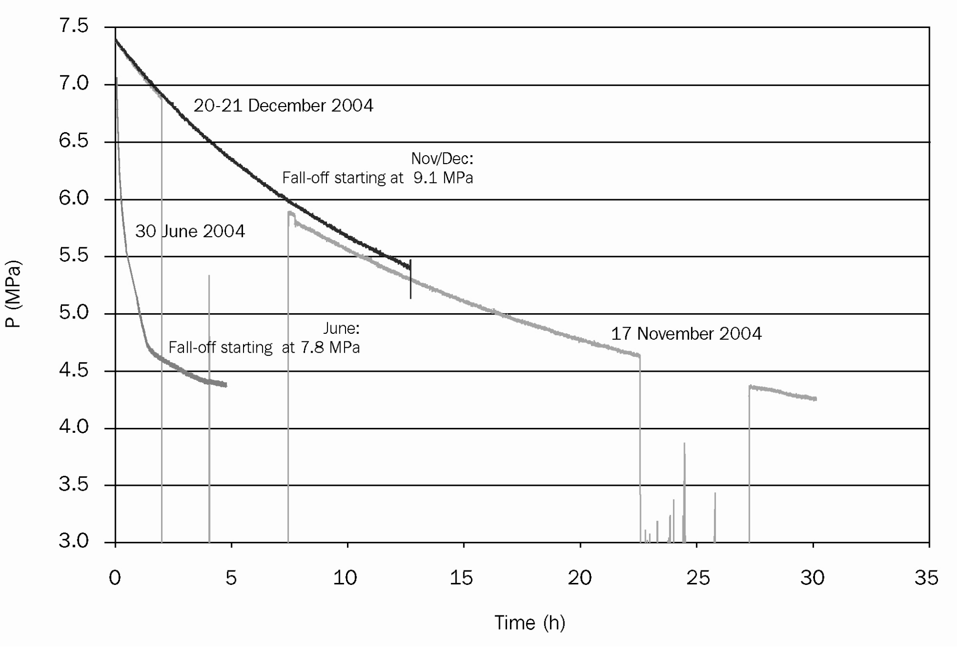


Figure 25: Comparison of pressure fall-offs in time at different stages of the project. Time is considered o at the stop of injection and subsequent closure of the wellhead valves. These data are derived from well head data.

6.2.2 Gas production (August 2004 to March 2005)

The gas production from the MS-4 well was rising (Figure 7) in the course of August 2004, several days after the start of the injection of CO_2 in the MS-3 well. This increase in production rate directly after the start of the injection is surprising, given the distance between the wells. The maximum gas production reached circa 65 m^3/d at the end of October. The increase can be an effect of the conventional production, but its appearance directly after the start of the injection seems too coincidental. Since there were no indications of breakthrough of the CO_2 at this time (see below), the most likely explanation is an effect of pressure. Because of a pressure reduction around the production well due to production of water, gas has desorbed from the coal surface into the cleats. On the other hand, reservoir pressure was increased around the injection well due to the injection. Therefore, a pressure gradient is created between the wells, with a varying downhole pressure of circa 13 – 18 MPa in the injection and of circa 0.1 – 1 MPa in the production well, that pushes the gas in the cleats towards the MS-4 production well. The total amount of desorbed gas was limited due to the undersaturation of the coal, and production decreases in November and December. During November and December, the gas production is declining towards a value of circa 55 m^3/d. Nevertheless, the production rates are significantly higher than the baseline rates, indicating that more gas is released than can be explained by conventional production. Therefore, it seems likely that exchange reactions between the CH_4 and the CO_2 are taking place, delivering coalbed gas to the production well. The expected dependency of exchange reactions on pressure is yet unclear. Therefore, given the pressure gradient between the wells, it is not clear where these exchange reactions take place: all along the pathway or only at those positions with optimal pressure conditions. A clear connectivity between the wells is shown by the response of the production rates on the changes in the injection rates, with increasing rates after increase of injection pressures and decrease in production when there was no injection. However, it is still unclear how this can be related to the adsorption behavior at the coal surface: the inverse relation was expected (adsorption capacity increases at higher pressure, thus higher pressure, more adsorption, lower production). Probably, diffusion time is more important than pressure, as shown by the increase of the production rate (to 75 m^3/d) after a period of standstill of the pump. By giving the system time to exchange and desorb, more gas is released from the coal surface. This is an indication that the exchange of CO_2 for CH_4 might be dependent on transport into (and out of) the matrix.

The production responses from December 2004 to January 2005 confirmed the observations above. At the end of December, a few days after the increase of the injection pressure, production is rising again until a maximum of circa 65 m^3/d on the 7th of January 2005, just before the first fall-off period. There is a rapid decrease in gas production during the 4 day fall-off period of the MS-3, and an increase to circa 65 m^3/d within a few days after the start of the injections on the 11th of January 2005. The production in the period between the 11th of January and the first week of February 2005 was variable, mainly due to operational problems due to frost. The second week of February showed an increase in production to circa 75 m^3/d. From the 14th February 2005 onwards, there was a decrease of production until a production of circa 50 m^3/d at the end of February 2005. Water production has declined since August 2004 to circa 1.2 m^3/day at the end of February 2005. Water production stopped or was very low during the frost period in the second half of January.

In order to establish the breakthrough of the injected CO_2 in the production well the composition of the produced gas was monitored (Figure 26). From November 2004 onwards, a slow rise in the CO_2 content in the production gas above the baseline was observed (maximum 10%) which could be attributed to the injected CO_2. During the fall-off period in the second half of February, the CO_2 content in the gas decreased to circa 3 %, still higher than the baseline content. The observations above indicate, in addition to the observations in the production rates, a clear response of the production well on the injection activities.

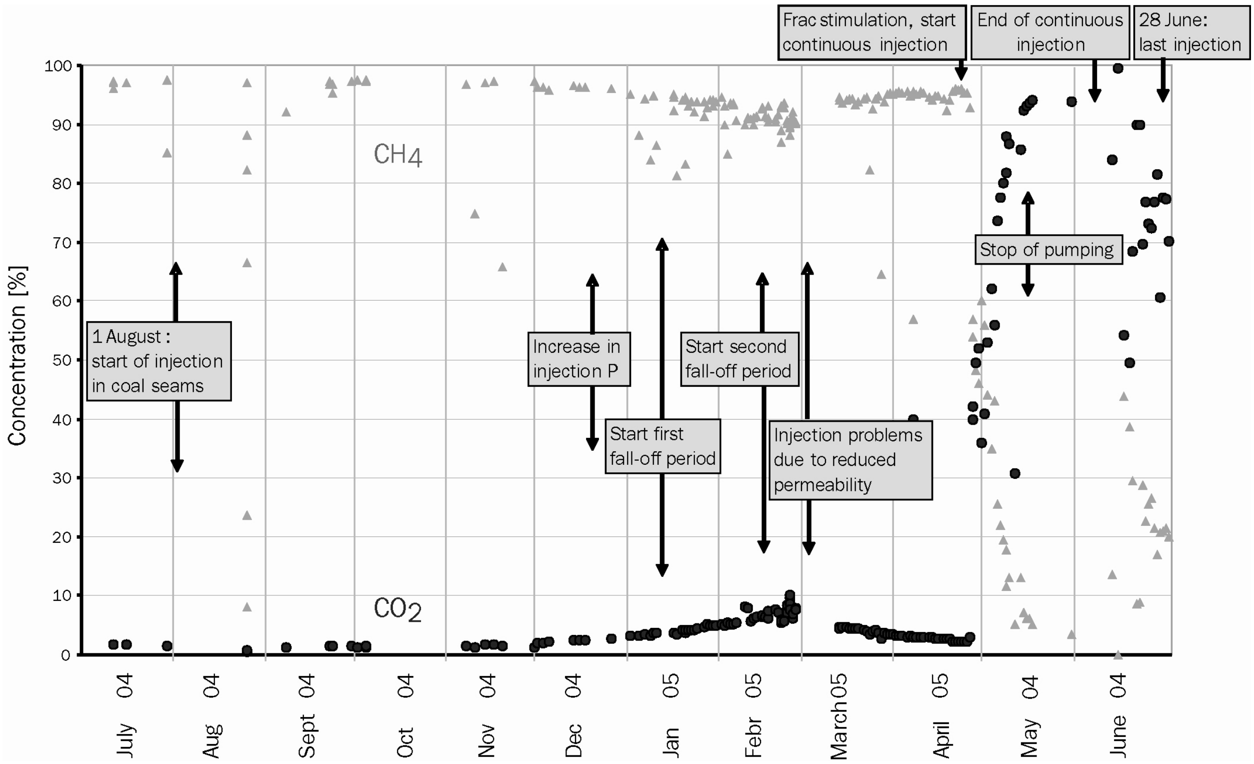


Figure 26: Composition of the production gas of the MS-4 well.

Samples from the produced gas were taken at several occasions after the start of injection for isotope analyses. Also, samples were taken from the CO_2 in the tanks that was used for injection. Investigation of the isotope signature of the gas shows that the δ13C of the carbon dioxide in the gas of the baseline production was slightly negative to positive (-0.3 to 7.6 ‰). This represents the naturally occurring CO_2 in the coal seams, most likely resulting from thermogenic generation. The δ13C of the injected CO_2 was distinctly different (-48.0 to -45.3 ‰). The values of the baseline production and of the carbon dioxide in the tank can be considered as the end members of a mixing blend: the closer the measured value gets to the value of the tank, the more it will consist of injected CO_2. The isotope signature of the production gas is relatively stable until at least mid-October 2004 (Figure 27), indicating that a breakthrough of the injected CO_2 before this time is not probable. Based on the decreasing δ13C of the CO_2, first breakthrough of the CO_2 likely occurred between mid-October 2004 and December 2004. This corresponds to the results of the composition of the produced gas. The value of δ13C(CO_2) decreased further until mid-February 2005, indicating that the part of injected CO_2 of the total was increasing. The stop of the injection during the fall-off period resulted almost instantly in a decrease in δ13C(CO_2) of the production gas. This could be explained by fractionation of δ13C in the adsorption process.

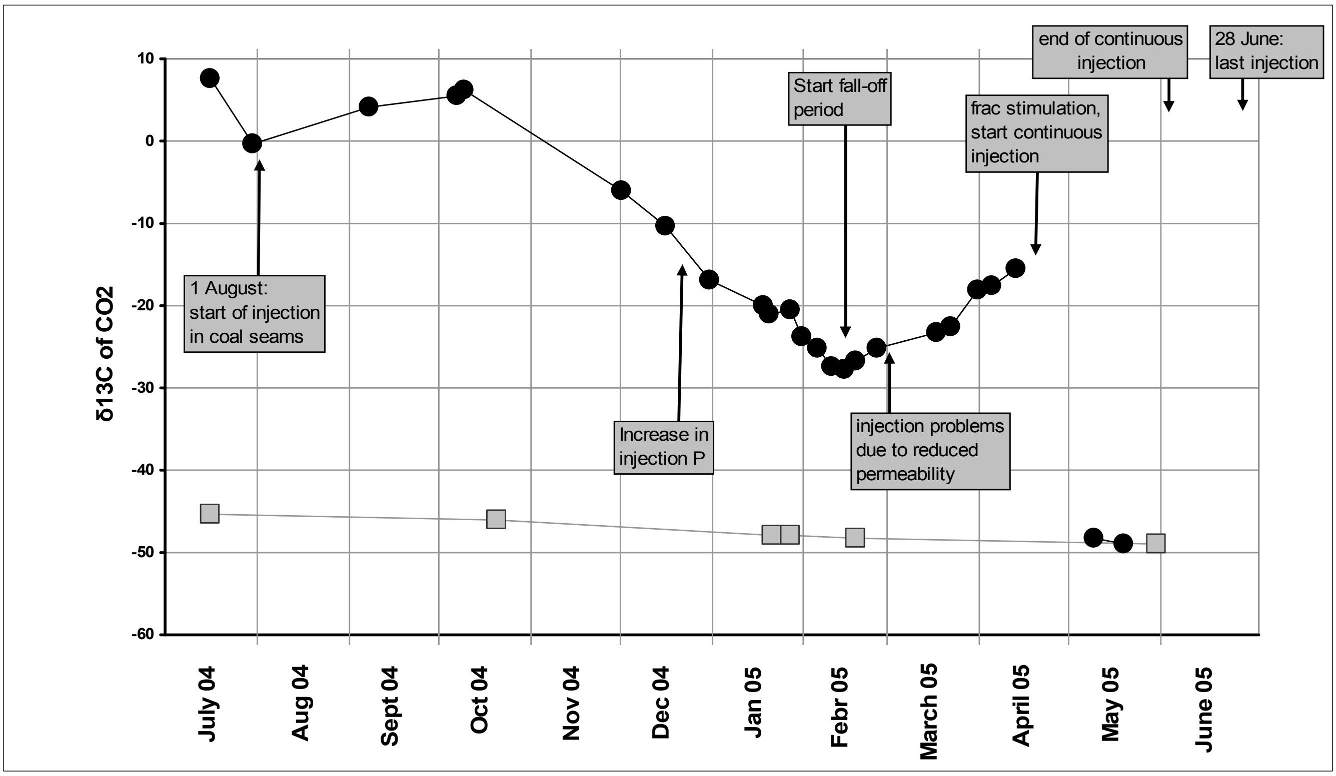


Figure 27: Values of $\delta^{13}C$ CO_2 (‰) determined in a period before and after CO_2 injection.

Although there are no samples taken in November, it appears that the composition of the water remained relatively stable until December 2004 (Figure 23). From December onwards, the bicarbonate content of the water was steadily rising. This is likely to be related to the contact between the formation water and the injected CO_2. There is no indication that the formation water is becoming more acidic (lower pH) from December onwards, as could be expected on the basis of the carbonate equilibrium reactions. This is probably due to the high salinity of the water, giving it a high buffering potential. Carbonate is present as secondary deposit in part of the cleats. There however are no indications for mineral dissolution, i.e. there is no increase in the concentration of calcium and magnesium ions. Based on the increase of bicarbonate, there is an apparent breakthrough from the beginning of December onwards, somewhat later than indicated by the gas composition and by the gas isotope signature. This can be explained by the higher mobility of the CO_2 as a gas compared to CO_2 in solution.

6.3 Period 3: CO_2 injection and CBM production after reservoir stimulation by minifrac job (March 2005 to mid-April 2005)

6.3.1 CO_2 injection (March 2005 to mid-April 2005)

Because the permeability of the coal seams decreased over time and injection rates were lower than expected, it was decided to stimulate the reservoir by performing a mini-frac job without proppant. The highly saline, thus high density, formation water produced from the MS-4 well was used as frac fluid. This mini-frac job was was intended to open the cleat system by applying high flow rates of fluid (water) into the reservoir. It was anticipated that if the cleat system was opened once, it would, even without proppant, remain sufficiently open to allow continuous injection at a wellhead injection pressure of circa 14 MPa (2,031 psi).

The mini-frac showed that at a wellhead pressure of circa 21 MPa a continuous injection of water of circa 50 l/min could be established for a prolonged time. The injection rates of water of 50 l/min at 21 MPa are, given the low permeability, quite high. If these rates could be established with liquid CO_2 it would be equivalent to circa 70 tonnes per day. However, the injectivity of CO_2 at lower pressures was very low after the mini-frac: it was reduced from circa 1 t/d to circa 0.1 t/d in discontinuous injection. This was due to the presence of water in the well that was difficult to displace by CO_2 with a lower density. The injectivity remained low even after the displacement of the water in the well, indicating that the cleat system closed after the operations.

Downhole pressure-temperature gauges were installed from the 2nd of March to 22nd of March 2005).

6.3.2 Gas production (March 2005 to mid-April 2005)

The production rates of the MS-4 well were declining since mid-February, probably because the injection in the MS-3 well stopped (Figure 22). In March 2005, production rates decreased further until a production rate of circa 36 m^3/d. Despite a small increase of the gas production in the beginning of April 2005, production rates are stabilizing around 35 m^3/d in the course of April, just over the baseline value. Water production is decreasing further until a production rate of circa 1.2 m^3/d. Possible enhancement of water production as a result of the water injection in the mini-frac was not observed, probably because the injected amount was too small to make a difference.
The CO_2 concentration in the production gas since mid-February decreased further to 2.2% in mid-April 2005, nearly to the baseline level. The observed shift in δ13C of the carbon dioxide in the production gas from mid-February onwards was continuing in March and April 2005, again coinciding with decreasing production rates (Figure 27). In the produced water, trend of decreasing bicarbonate concentration continued until it was back to the baseline level (Figure 23).

These observations indicate that the coal acts as a sink for the CO_2 during a period of relative inactivity, probably due to adsorption of the injected CO_2 on the coal surface.
If there was no sink, the CO_2 would continue to flow towards the MS-4 well due to the existing pressure gradient and buoyancy forces. This would have increased in gas production rates, and an increase in CO_2 content of the gas, instead of the observed decrease in rates and CO_2 content.

6.3 Period 4: CO_2 injection and CBM production after reservoir stimulation by frac job (mid-April 2005 to June 2005)

6.4.1 CO_2 injection (mid-April 2005 to June 2005)

Because of the low injectivity rates after the mini-frac, the reservoir was fracced with a sand proppant on the 20th of April 2005. The formation water was used as frac fluid and a cross-link gel was used. The fracture pressure was significantly higher than could be anticipated on the basis of earlier tests. After opening of the cleat system, circa 3 m^3 (106 cf) of proppant could be injected into the reservoir. After flushing with water, the well was further cleaned with nitrogen (flushing for 2 h) with a coiled tubing unit. This unit was also used to inject nitrogen until a wellhead pressure of circa 19 MPa (2,756 psi) was reached after 1 hour. After shut-in of the well an initial fall-off was observed of the nitrogen-filled well before the nitrogen was released until a wellhead pressure of circa 10 MPa (1450 psi) was reached.

Restarting of the CO_2 injection, initially at a continuous flow rate of 16 l/min followed by an injection at a continuous flow rate of 10 l/min, showed a slow increase of the wellhead pressure until stabilization at circa 14.3 MPa (2074 psi) during continuous injection (Figure 17). In the following days, there were several periods of standstill of the injection, due to operational activities and the arrangements for CO_2 supply.

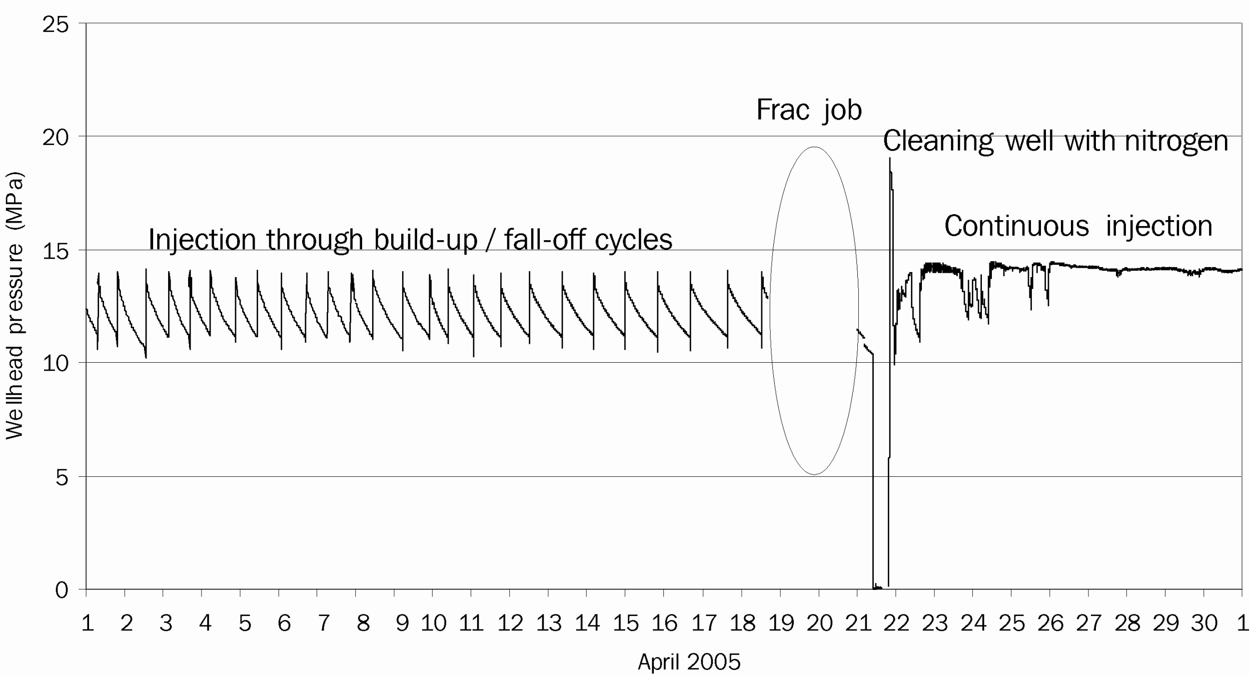


Figure 28: Pressure at the injection wellhead, showing the intermittent injection before the frac job and the continuous injection after the frac job.

Continuous injection could be established between the 4th of May and the 3rd of June 2005 (Figure 18). During the periods of continuous injection from April to early June, circa 12-15 tonnes of CO_2 were injected per day. The continuous injection could not be maintained during June 2005, in lack of sufficient amounts of CO_2. Until the end of June, injection took place in intervals of variable duration. In the second half of June, continuous injection could only be reached by reducing the flow rate. Downhole pressure-temperature gauges were installed from 21st of June to the 30th of June. The injectivity was eventually reduced to such an extent that the applied injection pressure of circa 14-14.5 MPa was insufficient to maintain the injection rate of 10 l/min. However, due to technical constraints this reduced flow could only be maintained for a limited period.

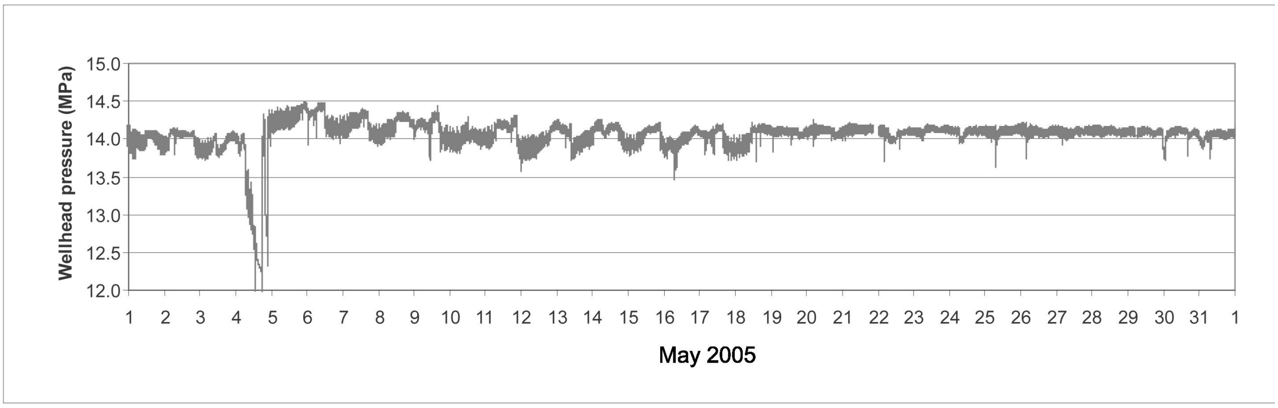


Figure 29: Pressure at the injection wellhead, showing the continuous injection after the 4th of May 2005.

The establishment of continuous injection showed that the frac job was successful, and that even a small amount of proppant is sufficient to open the cleat system around the wellbore. However, this is not a fixed situation. The stabilization pressure at the wellhead, where continuous injection was reached, increased after each period of standstill in the last week of April. This indicates that the reservoir becomes tighter, probably related to swelling of the coal. During the period of continuous injection, the stabilization pressure slightly decreased. This shows that the dynamics of the reservoir, i.e., the swelling, becomes less pronounced. At this stage, it seemed that the conditions in the reservoir were stabilized. However, in June 2005 the stabilization pressure at the wellhead increased again after each period of standstill. This shows that the coal has not ceased to be reactive, probably because pristine coal comes into contact with the CO_2 during periods of standstill. Again, this indicates that the performance of the operations depends on the time that is given to the system to equilibrate, thus the diffusive transport of the gases in the coal.

6.4.2 Gas production (mid-April 2005 to June 2005)

The gas production increased rapidly one week after stimulation of the injection well. Between the 28th of April and the 14th of May the daily production rates increased from circa 40 m^3/d (1413 cf/d) up to more than 700 m^3/d (24,720 cf /d). Because of the high production rates in the second week of May 2005, coal fines were released from the seams and damaged the downhole pump. For this reason, pump activity and water production ceased after 14 May 2005. Analysis of the coal fines showed that, based on their coalification rank and composition, they are most likely resulting from the upper seams rather than the lower 405 seam (Figure 30). Gas will thus be mainly produced from the upper seams, which is in agreement with the low permeability of the 405 seam.

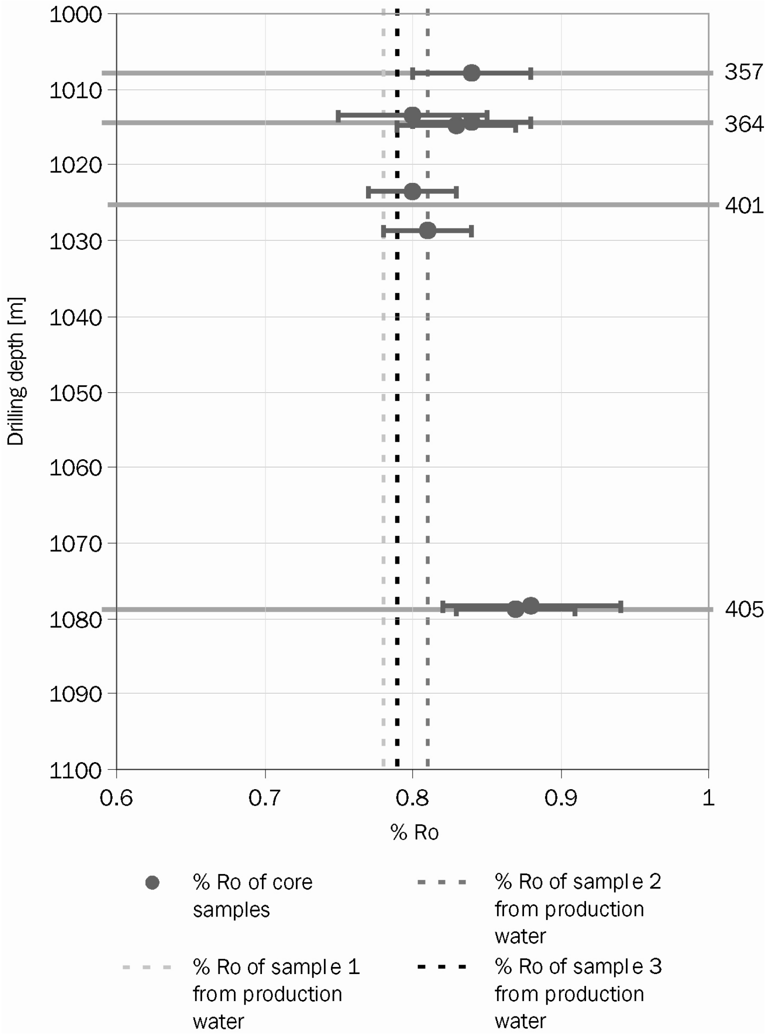


Figure 30: Vitrinite reflectance of seams 364, 401 and 405, and vitrinite reflectance of the coal fines that were produced by the MS-4 production well. The latter are corresponding to the values of the upper seams (364 and 401).

Gas production was continued, even without pumping, after the 14th of May 2005 because of the overpressure in the reservoir. Registration of production rates was difficult in the second half of May due to the sudden increase in rates, because adjustments were required in the equipment. However, the rates could be estimated with confidence within acceptable uncertainty. Maximum gas production reached circa 1350 m^3/d (47,675 cf/d) just at the end of May 2005. After pumping stopped the water level in the well was steadily rising to a depth of 240 m (787 ft) on the 1st of June 2005 (Figure 31). On this date the well was shut-in and the pressure rise was observed, showing stabilization at 5 MPa at the wellhead after circa 1.5 days. A second shut-in test, between the 6th and 16th of June 2005, showed a lower stabilization pressure of circa 2.2 MPa (319 psi) after one week. The water level in the well on the 17th of June was measured at a depth of 480 m (1575 ft), indicating a downhole pressure at 1050 m (3445 ft) of circa 8.5 MPa (1233 psi). This is close to the original reservoir pressure. In the second half of June 2005, there was a rapid decrease of production rates. Production rates increased occasionally in response to the interval injections. In combination with decreased production rates, this pressure response indicates the uptake of CO_2 in the reservoir since the end of continuous injection, most likely due to adsorption on the coal.

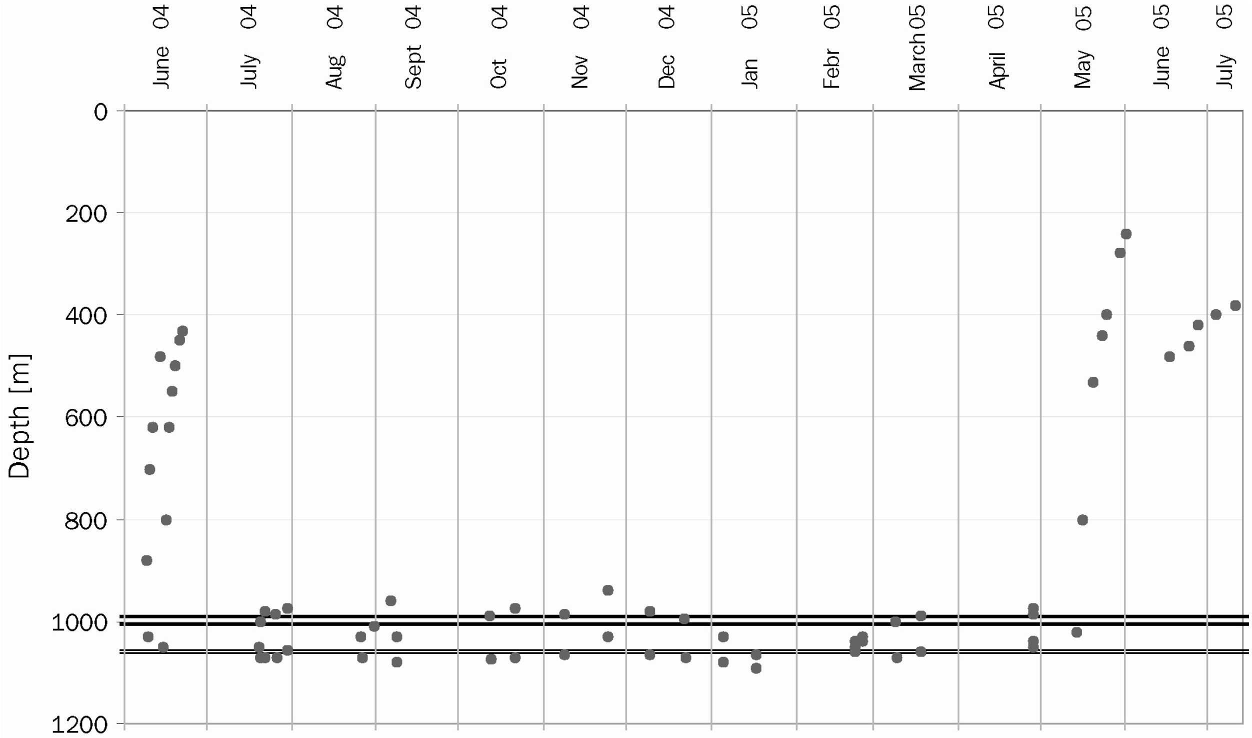


Figure 31: Water level in the MS-4 production well.

From March 2005 onwards, there was continuous measurement of the produced gas composition after the installation of a digital IR analyzer, with a data registry every 15 seconds. This analyzer was able to measure CH_4 between 0 and 100%, and CO_2 between 0 and 25 %. The results of the analyzer are in good agreement with the laboratory analyses of the samples (Figure 32, Figure 33, and Figure 34).The concentration of methane in the production gas dropped significantly one week after the frac job (Figure 32). This coincided with an increase in CO_2 concentration. The gas composition data do not show signs of nitrogen. In May 2005 there was, except for a small increase around the 5th of May, a general decrease of CH_4 concentration until it stabilized around 3-4 % in mid-May 2005 (Figure 33). After the shut-in tests in June 2005, the content of methane in the gas increased up to nearly 50 %. At the end of June, this decreased to a stable level of circa 20 % (Figure 34). Again, this shows that in order for exchange reactions to take place, sufficient time is required. Diffusion rates into and out of the coal appear to be the critical factors.

Analysis of the composition of the water shows a rapid increase in bicarbonate content, especially in the first weeks of May 2005 (Figure 23). Again, this shows the clear interference between the injection and production well and a breakthrough of the CO_2. Similar to the earlier observations, the breakthrough of the CO_2 in solution is later than that of the gas. Iron and manganese ion concentrations also show a slight increase in May 2005. This could indicate corrosion of the casing or well equipment as a result of the contact with CO_2. However, the pH of the water is relatively stable at a value of circa 6.

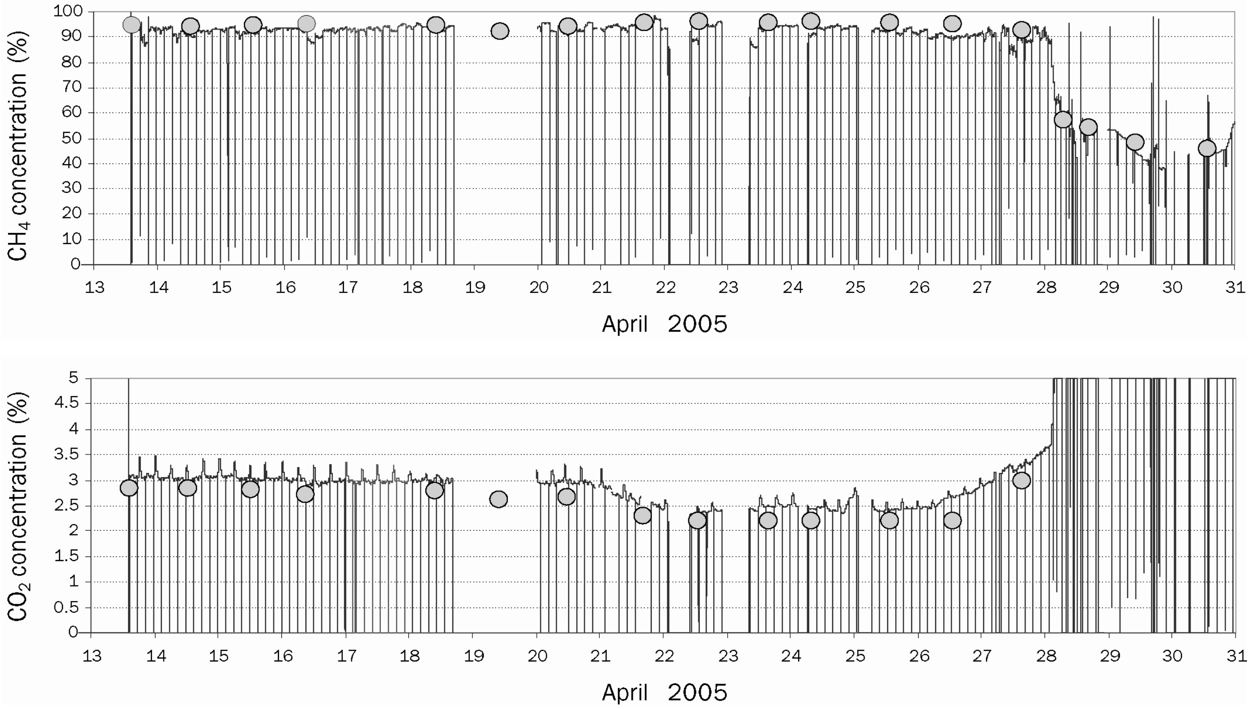


Figure 32: Composition of the production gas (CH$_4$ top graph, CO$_2$ bottom graph) of the MS-4 well at the end of April 2005, as measured with the IR analyzer (lines) and via gas samples (dots). The analyzer was able to measure CH$_4$ between 0 and 100%, and CO$_2$ between 0 and 25 %. The results of the analyzer are in good agreement with the laboratory analyses of the samples.

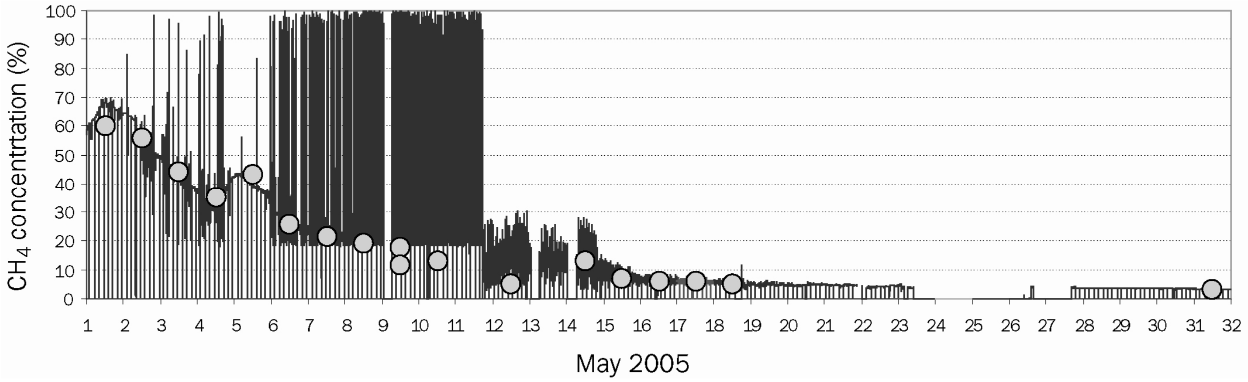


Figure 33: CH$_4$ content of the production gas of the MS-4 well in May 2005, as measured with the IR analyzer.

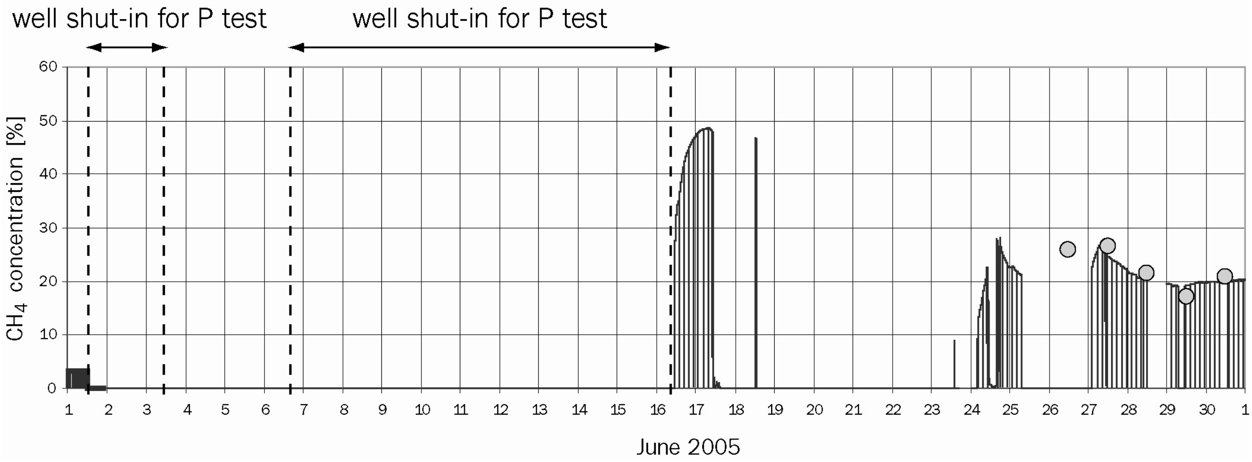


Figure 34: CH_4 content of the production gas of the MS-4 well in June 2005, as measured with the IR analyzer.

7 History matching of the operations

7.1 Introduction

The activities of the history matching are reported in more detail in a separate report. The injection test has been dominated by two effects. The relative low permeability has affected the CO_2 injectivity, while the technical limitations of the injection equipment were not able to overcome this problem. Due to the available pressure range it was only possible to inject CO_2 on the basis of a number of short injection pulses per day until April 2005. The effective injection behaviour could be deducted and reconstructed from the given fixed injection rate, a known pulse duration period and the number of pulses a day.

We have monitored both the injection behaviour of the new MS-3 injection well as well as the MS-4 production well for the total test period of almost a year. It was assumed that by water pumping in the production well the bottom hole pressure was stable at 1 bar for the whole test period. Later investigations have shown that the real BHP has fluctuated between 1 and 5 bar as a result of intermitted water pump activities. A total of five downhole measurements sequences in the injection well were available.

7.2 Final simulation model

The newly drilled MS-3 injection well confirmed the constructed reservoir model. Both wells, MS-3 and MS-4, are perforated in the coal layers 364, 401 and 405. Initial layer value for permeability and porosity were set constant for the each layer. Both grid size and orientation were unchanged from the initial planning and sensitivity study model (see Chapter 4).

Table 2: Simulation model layering

Model layer	Layer	Layer type	Thickness [m]	Permeability [mD]	Porosity [%]
9		Coal	0.70	0.3	0.006
8	364	Clay	0.50	0.0	0.0
7		Coal	0.72	0.3	0.006
6		Sandstone/clay	7.79	0.0	0.0
5		Coal	1.32	0.3	0.006
4	401	Clay	0.60	0.0	0.0
3		Coal	0.81	0.3	0.006
2		Sandstone/clay	51.09	0.0	0.0
1	405	Coal	2.3	0.3	0.006

7.3 History Matching

The total test sequence was split up into two distinct periods with the hydraulic fracture job in the MS-3 well as a switch-over point. The first part is dominated by the pulsing type of injection behaviour. The second part is characterized by the continuous injection of CO_2 into MS-3 and the only short CO_2 breakthrough production period of MS-4.

7.3.1 Pre-frac period

The behaviour of both wells is clearly demonstrated in Figure 35 and Figure 36. In general an excellent match was achieved with the exception of the water production between 70 and 170 days after start up of production. If we put this mismatch into proportion, its less than 1 Nm^3 water a day. But in relation to the total water production it is more significant.

This water mismatch is driven by the assumption that there is a relation between water and gas production. Gas and water coexists in the cleat system. If we need an increasing gas production automatically we notice an increase in water production as a result of the active water/gas distribution in the cleat system at a near constant BHP production pressure.

Considering the relation between the observed water and gas production period (70 and 150 days) we notice a sharp increase in gas production at a constant water production rate. So, there must be some process that activated the gas content in the cleat system. It is clear here that this sharp gas production increase coincided with the start up of the CO_2 injection activity. Initially the original permeability is not affected by the CO_2 injection activity resulting in a maximum displacement effect of methane gas to the direction of the production well. Later on, the permeability may be affected by the coal swelling effects of CO_2 injection and stress effects in the area near the production well.

The present history match was achieved by analysing change in injectivity operations in relation to possible permeability changes. The overall injection over time of CO_2 will induce coal swelling and result in a permeability reduction. Large CO_2 injection rate changes will result in increased permeabilities around the injection area. The final permeabilities used are displayed in Figure 40.

We made use of injection rate control mode calculating a flowing bottom hole injection pressure in case of the injection well MS-3 (Figure 36). As can be seen the calculated injection pressures are a good match with measured ones. The calculated shut in pressure are not very well matched (Figure 37).

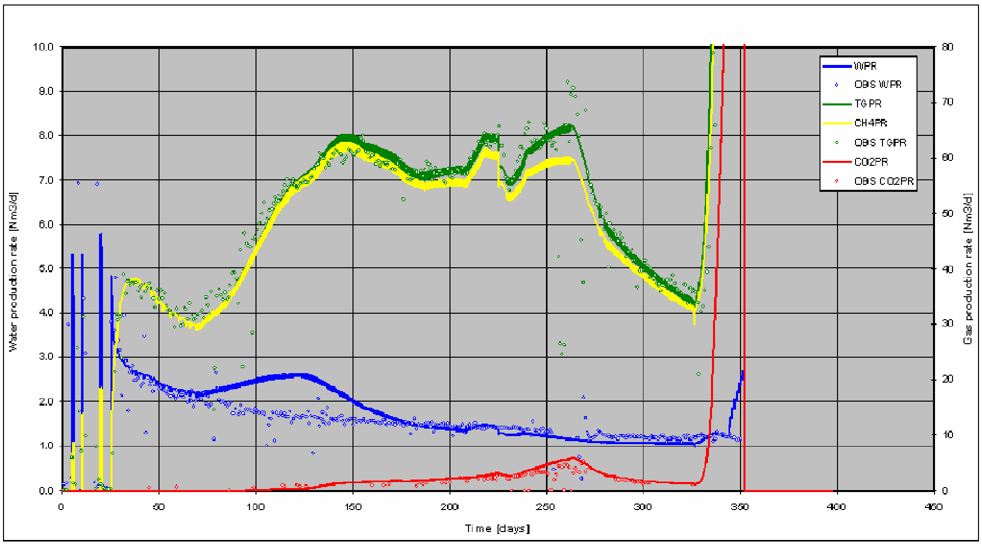


Figure 35: MS-4 Production behaviour. The observed daily production rate of both water (blue), total gas (green) and CO_2 (red) is clearly displayed with the help of dots. The results from the history matching activity with the simulation model are displayed with solid lines. An extra yellow line in this plot represents the daily simulated CH_4 production rate.

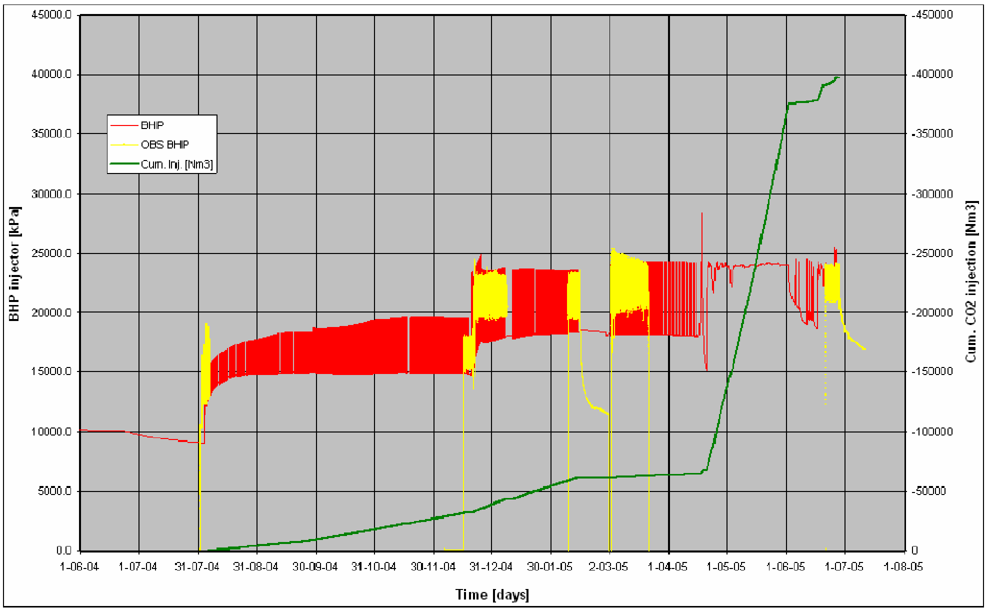


Figure 36: CO_2 injection well MS-3 – Injection performance. The red line represent the calculated bottom hole pressure and the yellow marked data are the measured data from the five down hole pressure measurements. As can be seen the calculated injection pressures are a good match with measured ones. The calculated shut in pressure are not very well match.

From the observed pressure shut in behaviour is very clear that the effective permeability around the wellbore more or less collapses after the injection is stopped. This observation is also made by other ECBM test sites. All observations made indicate that there must be a large contrast between the injection and shut in permeability. The present reservoir model lacks detail to study these phenomena.

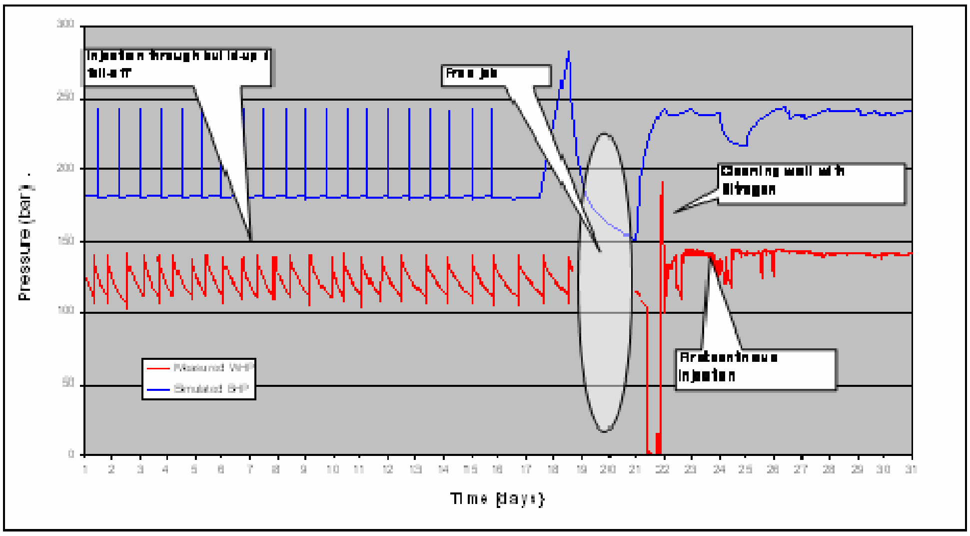


Figure 37: History Match MS-3 CO_2 injection pressures April 2005

7.3.2 Post-frac period

In the numerical simulation the trend of the daily average well head pressure data were used as a guideline to simulate the post frac period. Furthermore, we have made the assumption that the general pressure level would be in the neighbourhood of the maximum pre-frac injection pressure. These wellhead data are in good accordance with the measured downhole data. Plotting this data on the simulated data confirmed the correctness of the previous made assumptions (Figure 38 and Figure 39).

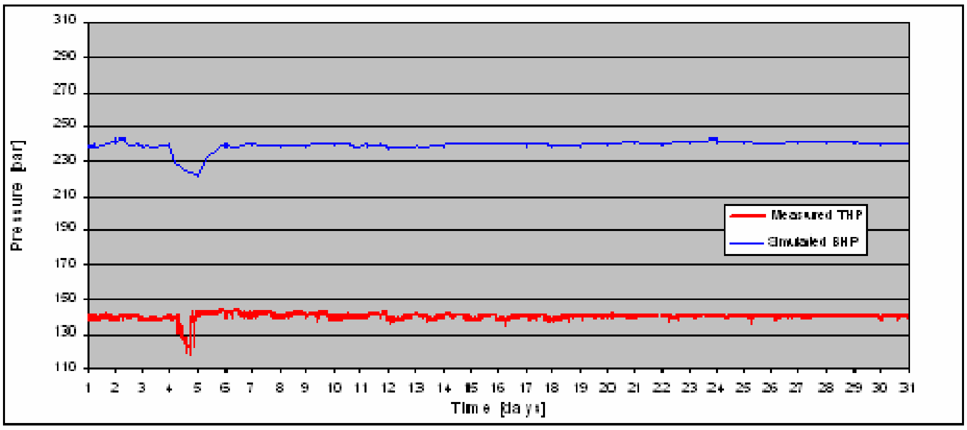


Figure 38: History Match MS-3 CO_2 injection pressures May 2005

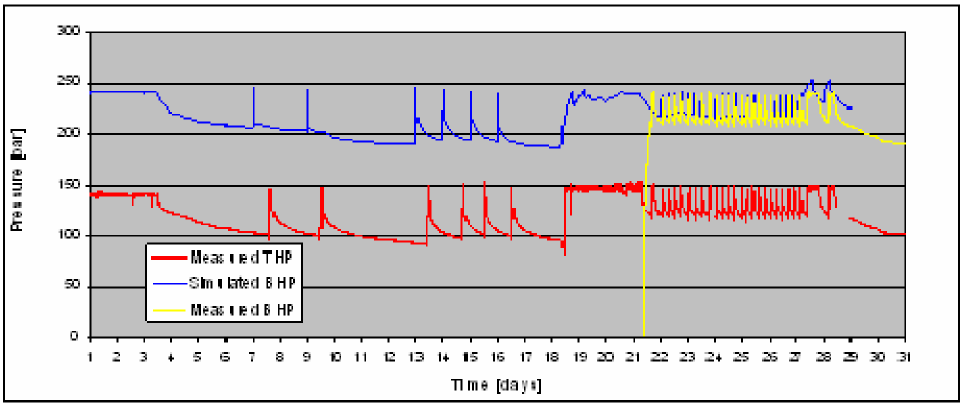


Figure 39: History Match MS-3 CO_2 injection pressures June 2005

The dramatic decrease in injectivity, as a result of temporary interrupted injectivity during the first part of June, is one of the remarkable factors of the post frac injection period. The combined effects of large increase in normal stress on the cleat system and large swelling effects due to CO_2 absorption must be the basis of the reduction in injectivity.

Figure 40 displays an interpretation of the changes in permeability made in order to achieve the shown pressure and rate history match. The initial increasing and later decreasing permeability level is responsible for the water production behaviour in the same time frame. The initial permeability is increasing to nearly 10 times the original value as a result of the so-called ballooning effects. Through time this effect is diminishing as a result of coal swelling. From the observed pressure fall-off data (Figure 40) we can clearly conclude that as the well is shut-in the permeability of the area around the well very rapidly decreases substantially.

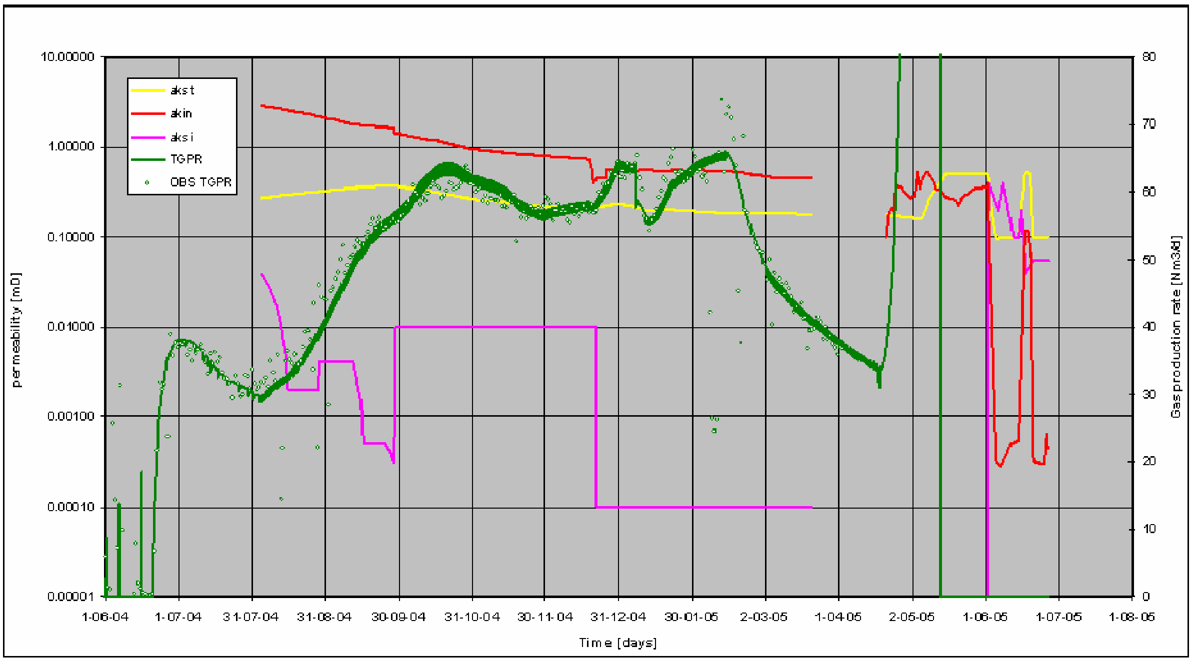


Figure 40: History match permeabilities. Three curves are visible: a red, yellow and pink line. The yellow one represents the permeability development for the general effected area including the area around the MS-4 production well. The data shown here refer to real absolute permeability. The red curve shows the permeability for the CO_2 drainage area of the MS-3 injection well if active injection is taken place. The pink line shows the permeability at times that the injection well is shut-in.

7.4 Conclusions

The history match of the ECBM field test shows some interesting results. In the first place a very stable water production rate was observed over the total test period despite large changes in gas production rate, mechanical and fluid flow properties of the coal around the wellbore. This observation shows that not only the coal seams are contributing water. Extensive numerical simulation work has shown that almost all production effects are the result of permeability changes resulting from either swelling-shrinkages processes or changes in the normal stress field. But, we have also found events which not could be directly explained. Possible explanation of these could be changes in adsorption characteristics or changes in effective adsorption/absorption surfaces. One of these effects is the large gas production increase at the start of the CO_2 injection.

8 Discussion of operational results and interpretations

Several months of injection showed that injection was more difficult than expected. It was expected that a small additional pressure above the reservoir pressure would be sufficient to establish continuous injection, but this was clearly not the case. The injection pressures required were nearly twice the reservoir pressure. The injection in the first period (August 2004 to March 2005) was estimated at circa 1-1.3 ton per day in build-up/fall-off cycles, while 20 ton per day in continuous operations was expected. Apparently, this was the result of a permeability decrease of the reservoir, as was clearly indicated by the evaluation of the well-head and downhole data. This observed permeability reduction is most likely due to swelling of the coal. These observations are in line with the observations in Canada and the United States (Van der Meer and Fokker, 2003; Reeves et al., 2003; Reeves, 2003). Experiments on cores have shown that coal swelling can indeed cause a significant decrease in permeability (Mazumder et al., 2005a, 2005b, 2005c).

In November 2004 an unexpected early breakthrough of the injected CO_2 occurred in the production well. This breakthrough was determined on the basis of observations of the gas composition, isotope signature of the production gas, and the composition of the water. This breakthrough was unexpected for the following reasons: 1) the high permeability cleats are oriented perpendicular to the flow line between the wells; 2) numerical modeling indicated that the injected volume until November 2004 was insufficient to result in breakthrough; 3) CO_2 was expected to be adsorbed by the coal; 4) CO_2 injection was expected to result in a reduction in permeability. Conclusively, the observations show that it is very difficult to get the CO_2 into the reservoir, but that once it is injected, it is able to flow relatively fast towards the production well. Transport through high permeability streaks (small sand channels, fractures) is unlikely, because by far the most of the CO_2 remains in the reservoir (see below). The most plausible explanation is the existence of a very low permeability zone around the injection well, while the permeability is higher outside this zone. The frac job was able to connect the wellbore compartment with the zone of higher permeability, explaining the increase of injection rates after the frac job. However, once the system is given time to diffuse and re-equilibrate, the zone of low permeability is extending, as is shown by the increase in stabilization pressure in April and June 2005.

Another observation is the apparent change of the frac pressure of the coal seams. The frac pressure was determined during the well testing in advance of the operations, i.e., before the coal had been in contact with the CO_2. During the mini-frac job and the frac job, i.e., after the coal had been in contact with the CO_2, it appeared that the fracture pressure was significantly increased. This is an indication that the coal changed under the influence of the CO_2. One of the changes, and an explanation of the increased fracture pressure, could be that the coal has become more plastic or “rubbery”, as was suggested by Larsen (2004).

8.1 Enhancement effect

The total maximum amount of gas that could have been produced by conventional production between 1st of August 2004 and 28th of April 2005 (270 days) is, estimated at ca. 8,100 m^3 (286,049 cf), assuming a baseline production of 30 m^3/d (1059 cf/d). The actual production of methane amounted up to 13,900 m^3 (490,874 cf), thus an increase of ca. 70 %. The baseline production after the frac job, between 28 April 2005 and 5 June 2005 (38 days), is estimated to have been circa 1,100 m^3 (38,846 cf). The high concentration of CO_2 in the production gas during this period requires an evaluation of the total methane and carbon dioxide productions, using the gas composition data. Total methane production between 20 April 2005 and 5 June 2005 amounted up to 1,700 m^3 (60,035 cf). This is an increase of ca. 55 %. The absolute amounts of CH_4 that were produced are significantly higher than the baseline production with conventional production (***Figure 41***). Estimates after June 5 are difficult, since the production well was shut-in during several days.

The absolute amounts of CH_4 that were produced are significantly higher than the baseline production with conventional production. It can therefore be concluded that the injection activities had a positive effect on the gas recovery within the project lifetime, probably due to exchange reactions. However, the role of pressure in relation to the adsorption behavior and the exchange reaction is still unclear. The enhancement factor is decreasing as a result of the higher injection rates after the frac job, i.e., while the frac job helps in getting the CO_2 into the reservoir and is good from the storage point of view, it actually decreases the amount of methane produced. A probable explanation is that at higher injection rates the time for exchange and adsorption reactions is decreased. The contact time between the coal and the CO_2 was higher before the frac job, allowing diffusion of the gas into and out of the coal matrix.
Despite the enhancement the produced amounts and the recovery factor are very low, probably due to the low diffusion in the coal as shown by the desorption tests. However, it must be emphasized that high production rates were not the primary goal of the RECOPOL project. Only a limited number (3) of coal seams were completed because of the research character of the project.

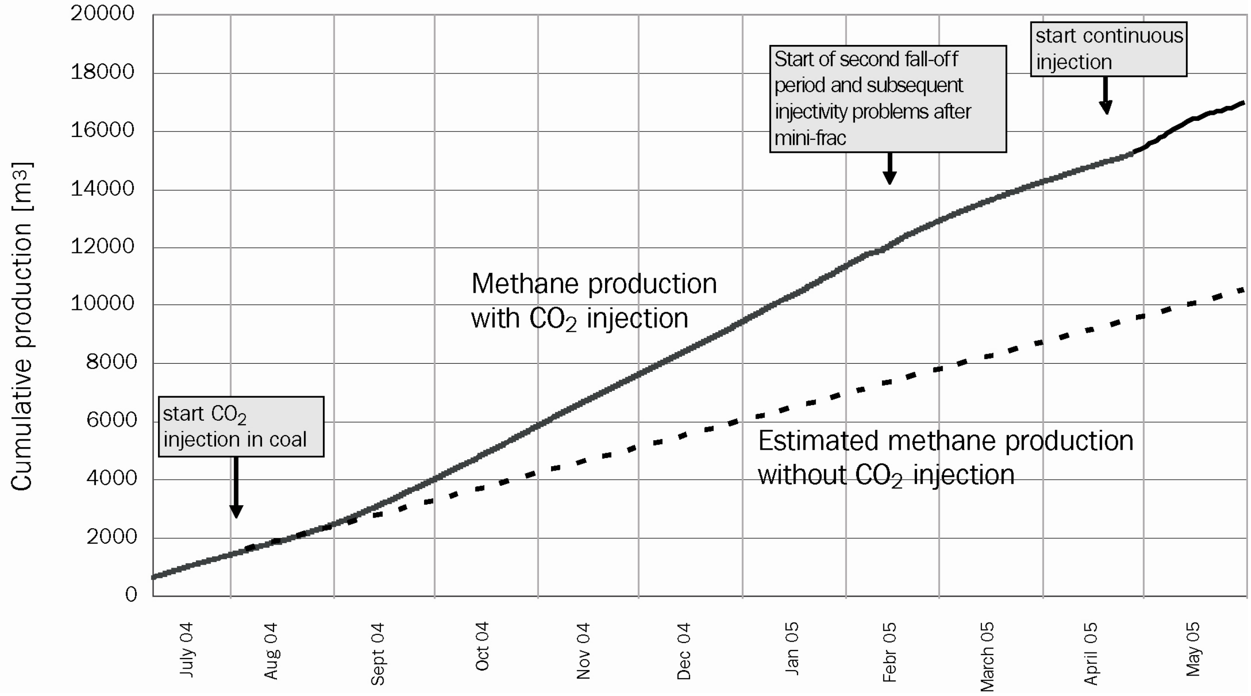


Figure 41: Cumulative amount of produced methane in time in the RECOPOL project. The positive effect of the injection activities on the gas production is clearly visible once compared to the projected baseline production.

8.2 CO_2 storage

In total circa 760 tonnes of CO_2 were injected between August 2004 and the end of June 2005 (Figure 42). The amount of the injected CO_2 that was produced back in this period by the MS-4 production well varied per period. The production of injected CO_2, thus baseline corrected, is estimated to be 0.25 [t] from November to mid-February and 0.09 ton from mid-February until the breakthrough on the 28th of April. Between the breakthrough and the stop of the continuous injection on 5 June 2005, total CO_2 that was produced back amounted up to 54 tonnes, while an additional 13 tonnes were produced between 5 June and 28 June 2005. Peak CO_2 production was 2.6 tonnes of CO_2 per day, circa 15-20 %

of the daily injection at that time. The total amount of produced CO_2, 68 tonnes, was much lower (ca. 9%) than the amount of injected CO_2, indicating a clear sink of circa 692 tonnes of CO_2 in the reservoir. This sink was confirmed by the rapid decrease of production rates after continuous injection stopped in June 2005. Shut-in tests of the production well in June 2005 and measurements of the water level in June 2005 showed that the reservoir pressure around the production well was slightly increased compared to the initial pressure but was returning to its equilibrium level. This also seems to confirm that around the production well adsorption of CO_2 is taking place. However, pressure fall-off of the injection well after the stop of the injections appears to be very slow. Possibly, this is an indication of compartmentalization of the reservoir.

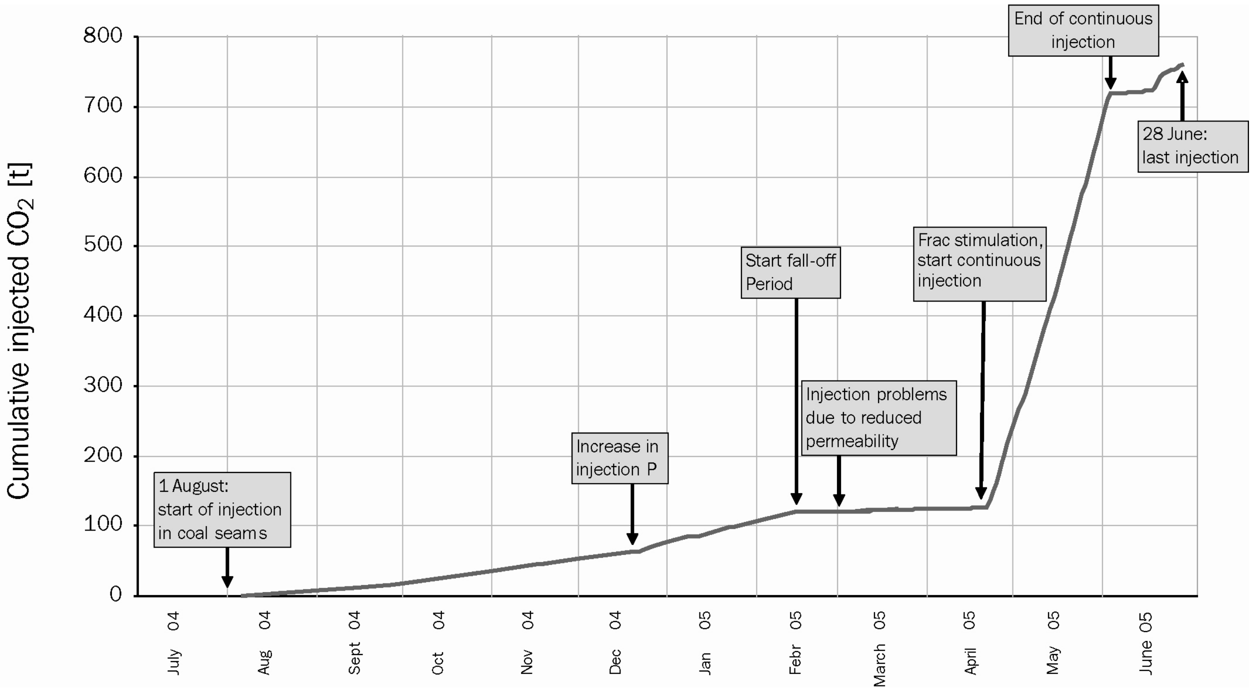


Figure 42: Cumulative amount of injected CO_2 in time in the RECOPOL project.

9 Monitoring of leakage of CO_2 to the overburden or surface

9.1 Aim of monitoring

Monitoring in this CO_2 sequestration project is applied in order to improve the understanding of storage in coal, to verify that safety and environment are not jeopardised, and to determine that the CO_2 is injected into the intended coal layers. An extensive monitoring programme was therefore set-up. The monitoring aimed at the establishment of the breakthrough of the injected CO_2 in the production well was extensively described in the previous chapters. In this chapter, there is a focus on the verification that no leakage has occurred to the overburden (i.e. nearby mine) or the surface.

Related to the environment and safety issues and the verification of the injection process a general Features, Events and Processes (FEP) analysis is used to identify possible CO_2 leakage to shallower geological formations and the surface. Some threats are listed in Table 9.1. This monitoring programme is based on FEP analyses and aims at different parts of the subsurface and the wells. Additionally, monitoring experience is gained in CO_2 sequestration projects with respect to mass balance verification, where the stored CO_2 should equal the injected amount of CO_2 such that the numbers used for emission quota and carbon credits (Kyoto protocol) are correct.

Table 9.1: Examples of FEP's identified (e.g. Hendriks et al., 2003; Arts and Winthaegen, 2004).

- Formation damage due to drilling the wells.
- Operational failure of the well.
- Fracturing or fault activation due to increased CO_2 pressure.
- Dissolution or dehydration of seal due to presence of CO_2.
- Unrecognised features in the seal like faults, joints.
- Corrosion of well casing due to CO_2.

9.2 Background

The CO_2 is injected in the reservoir in a high density supercritical phase. The pressure in the production well is low, because the water is pumped out of the well. This creates a pressure gradient from the injection to the production wellbore. The density of the CO_2 will thus lower towards the production well when it is migrating through the coal seams. It is envisaged that no immediate adsorption of the CO_2 takes place within the coal. Therefore, some of the injected CO_2 might move upwards until it reaches intra-Carboniferous clay seals and eventually the thick impermeable Miocene shale formation. Local mining experience showed that the Miocene shales are sealing and are not in hydrological contact with the Carboniferous. It is therefore expected that latter forms a cap rock to the free CO_2, and after CO_2 adsorption also as a seal for the coalbed methane. In case there would be leakage through the seal (e.g. along fractures and faults) also the shallower geological formations and the surface need to be monitored. The Silesia mine, located in shallower geological formations across the fault, is also monitored.

Direct monitoring of CO_2 can only be performed at or near the surface (and at mine galleries). Other techniques used for monitoring the injection process, the dynamic reservoir characterisation (migration through coal and methane release) and possible leakage detection are indirect measurements. All these techniques have characteristic specifications regarding spatial coverage, resolution, measurement distance and repeatability of the measurements. Because of these specifications and the objectives for monitoring, the applied monitoring techniques can focus to different parts of the storage process: Reservoir system, Background system and Surface system (Winthaegen et al., 2005). This differentiation related to the features to be monitored is shown in Figure 43.

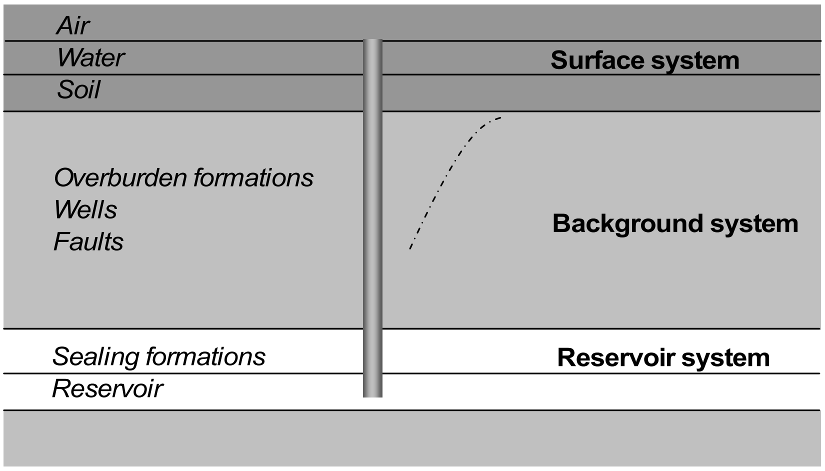


Figure 43: Subsurface profile showing the Surface system, Reservoir system and Background system (after Winthaegen et al., 2005). Also a well to the reservoir and a possible fault in overburden (dashed line) are indicated.

In order to evaluate possible effects of CO_2 injection, it is mandatory to establish the initial, or *baseline*, conditions that existed before the start of the injection operations. The baseline measurements are used to determine the reference measurements and possible variations in the measurements. Baselines were therefore verified for CO_2 concentrations in the nearby mine and in the soil gas. These baseline conditions will be compared to the measured conditions during and after injection.

9.3 Monitoring of the MS-3 well

The pressure and temperature of the tubing and the pressure in the casing of the injection well are continuously monitored. Leaking of the tubing would be detected in an early stage by in increase in casing pressure. The results show that at several occasions there was a rapid increase in the casing pressure. However, this was rather linked to air expansion due to freezing of the water than to leakage of CO_2 from the tubing into the casing.

9.4 Cross borehole tomography

As a part of the total monitoring programme in the RECOPOL project, seismic monitoring was investigated in order to image the coal layers and its overburden. Details of this survey are described in a separate report. A modelling feasibility study was carried out for optimal seismic monitoring of the injected CO_2 and to investigate the corresponding changes in seismic response. Based on the features of the target coal layers, the amount of CO_2 to be injected, the available infrastructure and limited budget the feasibility study showed that crosswell seismic acquisition yields the best resolution and repeatability compared to surface seismic acquisition and vertical seismic profiling, although only a 2D image between the wells can be obtained (Figure 44).

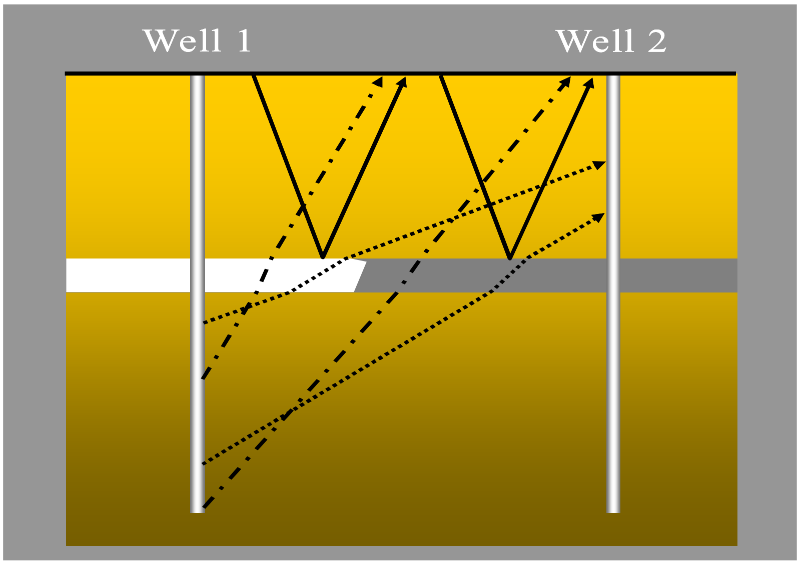


Figure 44: Schematic profile of the subsurface with a formation (grey) in which the CO_2 is injected (white) from the middle of Well 1. Three seismic methods were selected for the feasibility study: high resolution seismic (HRS) surface acquisition, Vertical Seismic Profiling (VSP), including reverse-VSP, and crosswell seismology (Winthaegen and Westerhoff, 2002). Indicated are the seismic wave travel paths of the three seismic methods: HRS acquisition (solid) applied at the surface, VSP (dash-dot) applied from the well to the surface and crosswell seismic acquisition (dot) from well to well.

In September 2003, the baseline crosswell survey was carried out between the injection and producing well covering the coal layers to be injected and a part of the overburden. It appeared that the seismic waves are weak compared to recorded unwanted waves. Possible reasons are: the overburden and coal layers very strongly attenuate the seismic signal, It was not possible to generate sufficient seismic energy in the geological formations, or a combination of the two. However based on the data, an average seismic velocity model based on move-out analysis is obtained. Using the model stacks of the receiver gathers and source gathers are derived in order to investigate travel time delays that should correspond to coal seams. The results are poor, because it is very difficult to define the first arrivals. Hence no tomographic inversion has been applied. This is a topic of current research. Also reflections are mapped and appear to agree with the locations of the coal seams present at MS-4. The reflection velocities may suggest that these are related to tube waves within the wells (probably mainly the source well, MS-4).

Further research is required to improve the signal to noise ratio of the acquired data and the results of tomographic inversion and reflection analysis. The CO_2 accumulation and migration and the CH_4 migration could not be mapped because the time-lapse survey during or after injection has not been carried out.

9.5 Soil gas monitoring

Monitoring of soil gas was performed at four locations in the surroundings of the MS-3 well. Leakage of CO_2 to the surface would have resulted in an increase of CO_2 concentration at these locations (*Figure 45*). Small wells were drilled of 2 m depth at the selected locations (***Figure 46***). This depth was chosen to exclude direct influence from the organic rich A-horizon of the soil, which is ca. 50 cm thick at these locations (***Figure 46***). IR CO_2 sensors were placed in the 2m deep tubes and connected to the registration unit in the cabin. Continuous digital data registration resulted in baseline profiles for the area near the injection well (***Figure 47***). Registration continued after the start of the CO_2 injection.

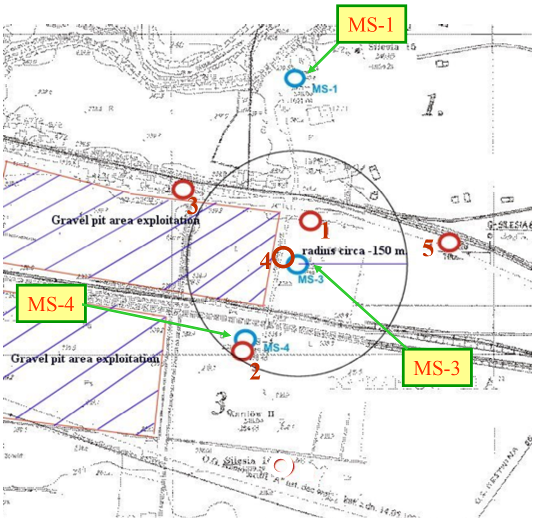


Figure 45: location of the stationary soil gas monitoring wells

The observed variation in the CO_2 concentration could largely be explained by meteorological parameters. Especially, atmospheric pressure and rain events appeared to be dominant. In addition, there are indications for a seasonal dependent influence of root respiration on the measured CO_2 concentrations. So-far, there does not appear to be a contribution from the deeper subsurface, which could possibly be linked to the injected CO_2. Spatial variation between the locations was observed. This can probably be attributed to the excavation activities in the gravel pit. Isotopic analysis of the soil gas shows that it is likely that there is influx of isotopically heavy air into the vertical wall of the pit. This results in a higher ^{13}C isotope (-15 ‰) value of the gas in the tube near the pit than the normal soil value (-26 ‰) as observed in the other wells. These isotope values appear to be stable in time.

These results give more insight in the natural soil background values of CO_2, which will be required for any interpretation of observed leakage in future storage projects. Further research should aim at comparing the RECOPOL approach in soil gas monitoring to other approaches, and look for improvements in sampling frequency and sampling grid. Also, it should be considered whether flux measurements should be added in follow-up surveys.

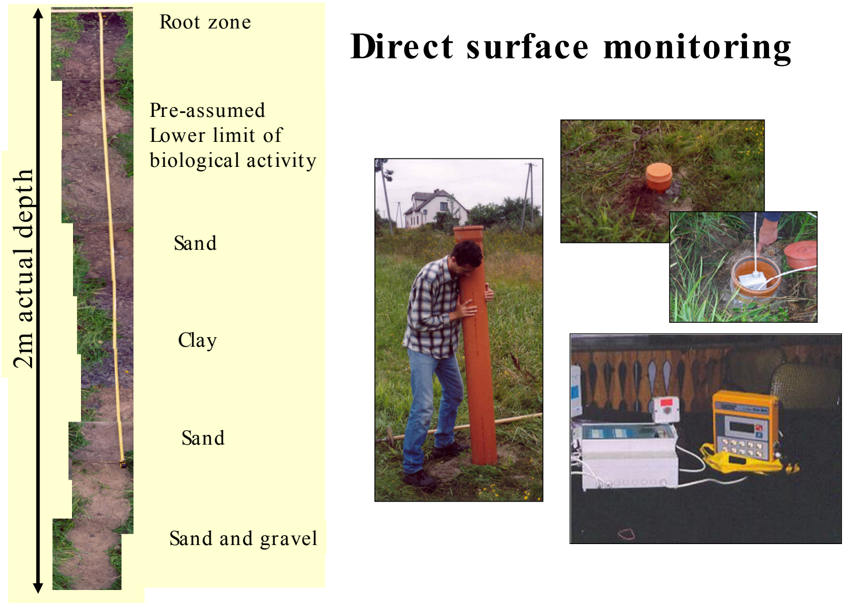


Figure 46: soil profile (left) and installation of the tubes and sensors

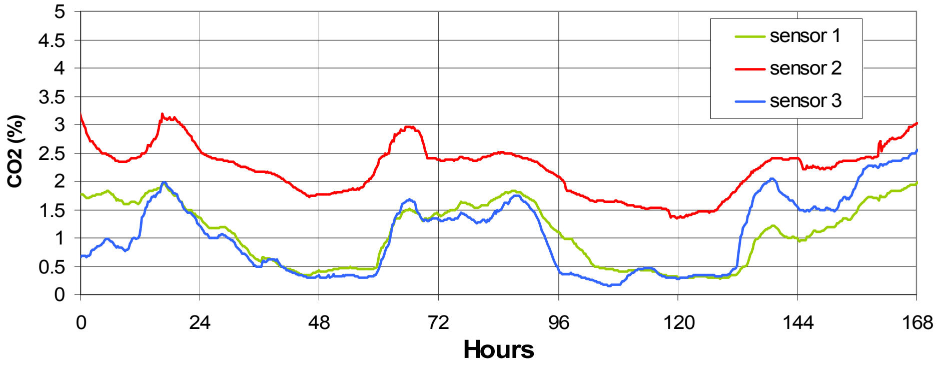


Figure 47: An example of the registered baseline soil gas measurements, over a 7 day period in April2004 (before CO_2 injection) indicating the variation in CO_2 concentration.

9.6 Mine gallery gas monitoring

The injection of the CO_2 took place in a triangular structural block, which was bounded by two normal faults (see chapter 3). The Silesia mine is located on the structural high block west of the triangular block (***Figure 48***). The coal in the Silesia mine is produced by long-wall mining. These long-walls are located close to the bounding faults, at a lateral distance of several hundreds meters of the site. Numerical models showed that it is unlikely that the injected CO_2 would leak through the fault into the long walls or mine galleries. Additionally, it should be emphasized that the total daily amount of CO_2 that is ventilated from the open galleries is much higher than the injected amounts. However, it was decided to monitor the CO_2 concentration in the long walls and galleries anyhow to be absolutely sure. Additionally, it was decided to monitor the CO_2 concentration in those galleries that were sealed off by a dam. One of these blocked mine gallery crosses the fault zone. In the unlikely event that CO_2 would migrate through the fault, it is likely that this would be registered in this gallery. Samples were taken on a regular basis and its composition analysed in the laboratory. These samples were taken before (baseline CO_2 concentration) and after the start of the injection.

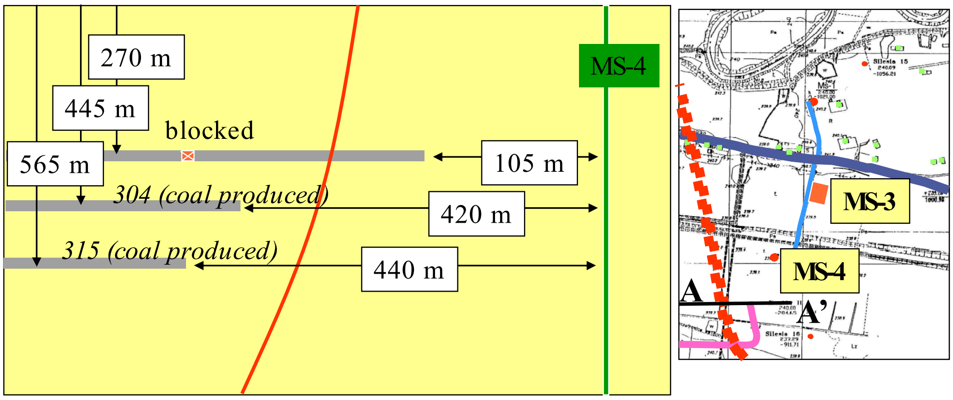


Figure 48: location of the mine with respect to the RECOPOL site

These CO_2 measurements acquired in these mine galleries show a variation in concentrations, but are usually in the range of 0.1 to 0.2 % (***Figure 49***). The higher spikes in this figure are probably the result of calibration. The concentration of CO_2 in the mine is controlled by the ventilation regime that is followed in the mine; no relation whatsoever can be found with the injection activities in the RECOPOL site.

Analyses of the samples taken from behind the dams, in the sealed galleries, show CO_2 concentrations up to 10% (***Figure 50***). These high CO_2 concentrations are most likely due to oxidation of the exposed coal in the gob zone that is connected with the sealed space. The baseline data show that the variation in the measured concentrations in the closed galleries is significant. Given this large variation, it seems unlikely that any contribution from the injection will be above this "natural" variation and can be attributed to the injection.

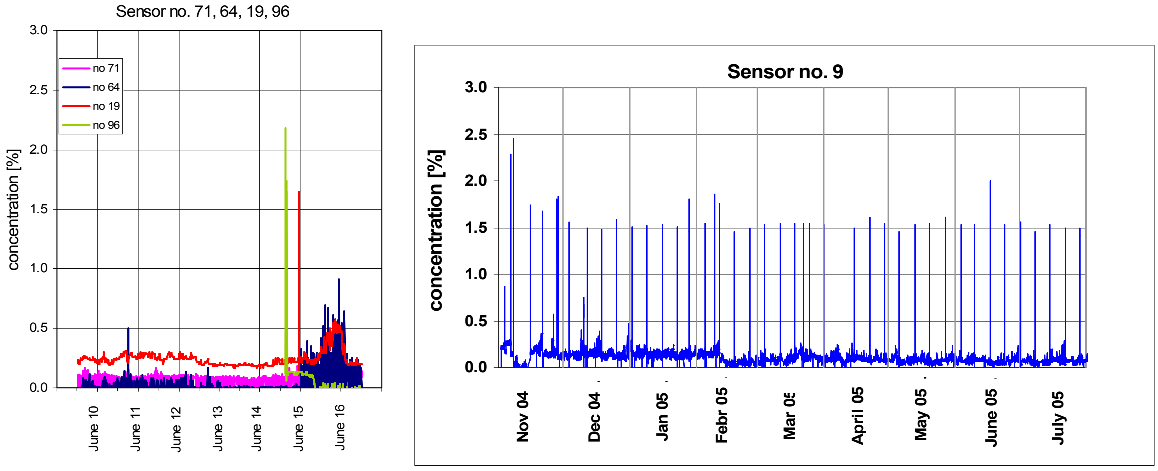


Figure 49: CO_2 measurements in the long walls, before injection (left) and after injection (right). The location of the sensors changes, following the progress of the longwall exploitation.

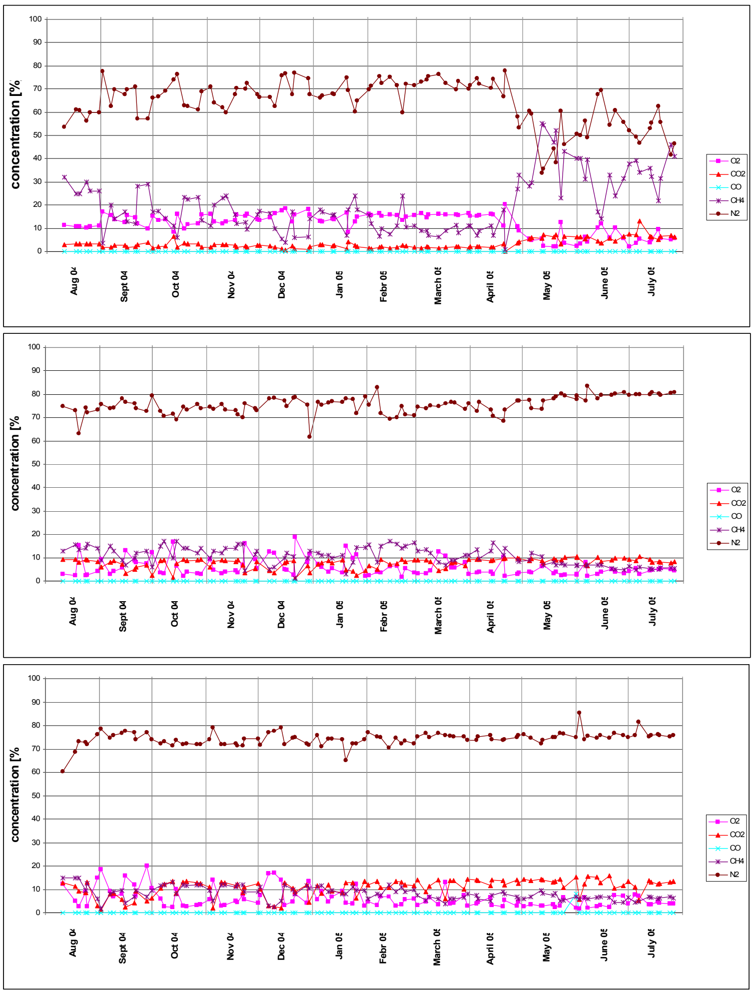


Figure 50: composition of the gas sampled at the locations of TI 417 (upper), TI 430 (middle) and TI 435 (lower), behind the dams

The observed changes in the composition from April 2005 onwards at the location of TI-417 seem, although they correspond to the start of the continuous injection, unlikely to be due to the injection activities (***Figure 50***). This can be checked by the isotope signature of the CO_2 behind the dam.

The likelihood of detecting any contribution from the injected CO_2 in the galleries is expected to be much larger by using the stable carbon isotope signature of the produced gas. This was analysed for both CO_2 and CH_4 to establish the baseline conditions. The $\delta^{13}C$ value the CO_2 of -15 to -25‰ shows a clear biogenic origin of the gas. Thus, this CO_2 most likely results from the biogenic degradation of the coal in contact with air. This signature of the gas in the galleries is significantly distinct from the signature of the injected gas (-45‰ to -48‰). Until the 11th May 2005, after the start of the continuous injection, there were no indications of the injected CO_2 (***Figure 51***).

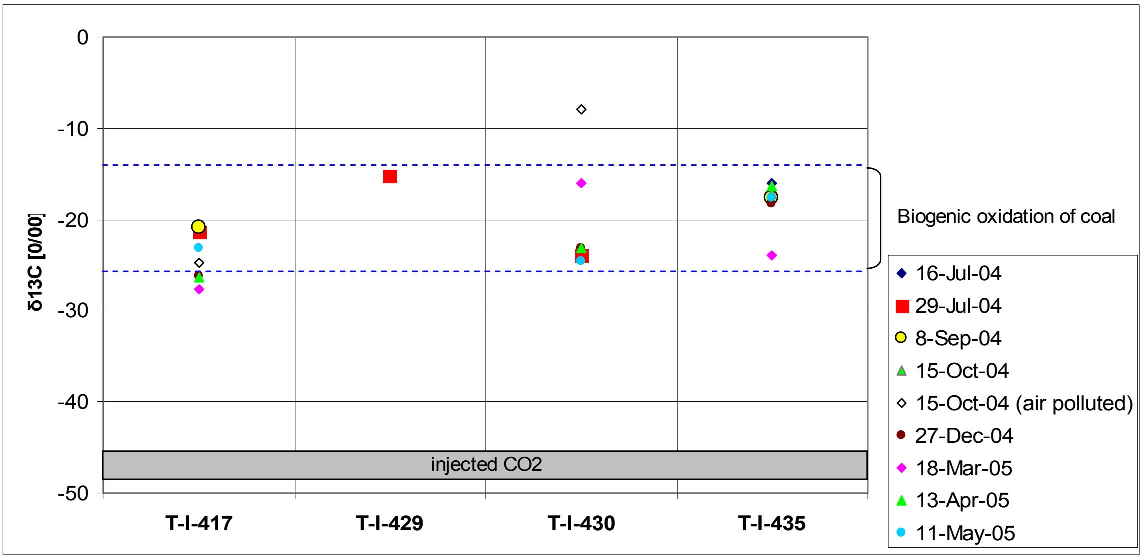


Figure 51: *$\delta^{13}C$ isotope signature of CO_2 in gas sampled behind the dams*

9.7 Conclusion

Leakage of the injected CO_2 to the mine in the overburden and/or to the surface is very unlikely. Extensive datasets were collected that can be used to show, although relatively small scale, the potential of several of these techniques for monitoring purposes. Better assessment of can be made of the baseline conditions, also in similar environments in future projects.

10 Socio-economical evaluation of ECBM applications

10.1 Introduction

The results of the field experiment may lead to follow-up projects within the Upper Silesian Basin or in other European coal basins. Therefore, the outlines for a sociological study were set-up and an economical evaluation of the Upper Silesian Basin was performed. This chapter gives an overview of the main results of theses evaluations, while they are described in more detail in separate reports.

10.2 Outlines of sociological study

The subsurface storage of CO_2 – one of many options for air pollution reduction – is a new method not applicable in Poland on industrial scale until now and not known to its citizens. That is why, necessity of conducting of wide promotional action, intended to give further information about CO_2 storage to persons who live in regions of gas storage. After the completion of the action, the research of social opinion about new method of CO_2 storage will be possible and affirmation of social consent on its full application. In the scope of the project a methodology is presented that could be applied in futures researches of the attitude of the local community towards ECBM-CO_2. Main question in the methodology is whether the subsurface storage of CO_2 perceive in social reception only in terms of benefits vs. threats or both benefits and threats. In order to give an answer, on above-mentioned question, will be possible after carry out the research of interested inhabitants. Works in frame of task, as result of records in schedule, has been divided into three stages:
- prepare the method of research,
- carry out research for reminder inhabitants' opinion,
- prepare the methodological hints for conducting informational campaign in local media and local government.

This paragraph concerns the first task of project realisation and presents the methodology and research tool (instrument).

It is proposed (submitted) to using – in realisation of the task – creative adaptation of social consultation method calls "Windmill from Royen", which include three steps of carrying out the consultation:

Stage I - Promotional Action

This stage is intended to deliver to inhabitants of regions where CO_2 is stored good knowledge about subsurface storage of CO_2, moreover limitation of uncertainty and preparation inhabitants (creation of favourable atmosphere) for survey. This is done by sending leaflets, press line activating, and publication of article in local radio and TV.

Stage II - Survey

This stage is intended to ascertain the inhabitants' attitude to ecological problems, to diagnose the inhabitants' attitude to subsurface storage of CO_2, and to verify the accuracy of the promotional action. This is done by means of a questionnaire, analysing the level of inhabitants' awareness and attitude towards the natural environment protection, the greenhouse effect, and the sequestration of CO_2.

Stage III - Social debate

A social debate will be organised. The theme and scope of debate will be established on the base of the survey results and its purpose will be to confront all participants interests and creation common policy in field of reduction of CO_2 emission, and dispel all doubts of inhabitants in field of threats (dangers). In this debate should be a participation of inhabitants of regions where CO_2 is stored, local council, members of ecological organisations, members of science organisations, enterprises interested in CO_2 storage (mines, plants etc.), and local authorities.

10.3 Country assessments

10.3.1 Poland: Upper Silesian Coal Basin

In order to be able to select potential locations for ECBM and to perform an economical evaluation, an inventory was made of information of geological information of the basin.
Information was collected and put in a geographical information system, regarding:

- CO_2 supply points
    - CO_2 supply points are major point sources of CO_2, mostly industrial operations. The database from IEA-GHG was used as the source of information.
- CBM market points
  The main question to be asked is, given its characteristics (low pressure, high quality gas) what kind of operation could use CBM gas? Examples of CBM consumers could be
    - boost gas for waste burning plants
    - local electricity production (small generators?)
    - local use for housholds (heating, cooking, etc.)
    - combinations with biogas?
    - etc.

  Possibly, the CBM can be added to the gasnet, although this will depend on the specifications of the gasnet. Probably, compression costs will be too high. The existing gas pipelines/network were added to the GIS.
- Water disposal points
  These can be any kind of disposal site that can handle saline water. In the upper Silesian Basin, the disposal points of the mines and industrial locations were taken into account in the evaluation. Possibly, water injection wells may exist, or river discharge might be allowed under certain conditions.
- Injection points
  The injection points will depend on surface conditions (spatial constraints) and subsurface conditions (amount of coal and gas, number of coal seams, fault density, etc.)
  The following information layers were constructed for the subsurface: Location of mine shafts, location of mines (names of mines, ownership, hard coal resources, exploited seams, total depth of exploitation, coal type, ash content, presence of methane), faulting rate and direction of faults, elevation of top of Carboniferous, hard coal resources, methane concessions. Also, elevation, thickness, maturity and methane content maps were made of the following seams: 401, 405 & 510.

The provided data was put in a geographical information system (GIS) for two main reasons:
1) visual presentation via the Internet
2) geographical analysis
It was soon recognised that the most important cost factors are drilling costs and transport costs of the CO_2, CBM and water. Latter costs will be strongly dependent on the transport distance from and/or to the operation. Therefore, the first step is to determine the (straight) distance between the injection point and the CO_2 supply point, CBM consumers, and water disposal. In a later stage other analyses can be performed.

The data from the GIS will be put in an economical model that will take into account the uncertainties in the values, which are obviously present, of both location specific and operational parameters.

Four parts of the complete ECBM cycle were evaluated:

- A. the static earth model: what is the situation of the earth before operations
- B. the injection operations and surface facilities
- C. the production operations and surface facilities
- D. transport of CO_2, CBM and water

10.3.2 Germany

The evaluation of the ECBM opportunities in Germany are considered in more detail in a separate report. Coal seams are available in Germany in the following areas: Ruhr, Aachen, Ibbenbüren, Münsterland and Saar-Nahe. These coals seams are situated in a depth between 800 – 1500 m and are comparable to the seams used in the RECOPOL project.The unminable coal seams of these regions amounts to about 0,924 Tt (ca. 10^{12} t) of coal. Assuming a total theoretical adsorption capacity of CO_2 of 33 m^3/t, there is a theoretical adsorption capacity of 30 Tm^3 CO_2. The effective exchange capacity of CO_2 is only 8 m^3 CO_2/t coal at several practical conditions thus the practical storage capacity is 7,4 Tm^3 CO_2. However, only a part of the coal can be achieved by the CO_2 (flooding efficiency). Under this reservoir engineering condition with 30 % flooding factor the technical storage capacity is 2,2 Tm^3 $CO_{2,}$ or 4,4 Gt CO_2. The industrial output of CO_2 in Germany is about 500 MT CO_2 per year. Assuming a further reduction of the industrial output in the next years this technical storage capacity lasts for 10 years.
The activation of the considered areas for CO_2-storage needs about 20.000 five-pattern facilities with conventional verticals wells or about 6.700 five-pattern facilities with horizontal wells of 800 – 1000 m well spacing. Each horizontal well allows the injection of 45t CO_2 per day. The following considerations are based on using horizontal wells for the injection. This assumption was made due to higher efficiency of horizontal wells.
The specific subsurface costs were estimated to amount to 6 €/t CO_2 or to about 11 €/t CO_2 for the total storage facilities covering compression, transport and storage. These figures reflect the best case considering the RECOPOL experiences. For this it is necessary to reduce the costs for the storage below 5 €/t CO_2. The cost for capture, transport and storage in sum should achieve a cost level in the range of the CO_2 emission trade, which varies in the range of 10 to 20 €/t at the moment.

Assuming that the permeability of the German coal is comparable to the Polish coal, the CO_2-storage in coal seams of Germany seems to be a promising technology. For this the aim of a "RECODEU"-project should be, to combine the findings of other projects (e.g. GESTCO) to determine a more exact figure of the available coal. Beyond this it is necessary to prove how much of this capacity can be achieved regarding geological and surface restrictions. Knowing the exact real storage capacity and distribution a comparison of the CO_2 point sources and the storage site should be done to provide the base for the evaluation of sensible transport scenarios.

10.3.3 The Netherlands

For a long time the Netherlands have relied on coal, from peat to anthracite, for a large portion of its energy demands. Despite the shift to gas and sustainable resources, it is likely that this will continue for several decades more. A large part of the coal (peat, lignite, and hard coal) used to be produced from the subsurface of the Netherlands, until the closure of the last hard coal mine in 1974. Still, the remaining coal resources in the subsurface of the Netherlands are substantial, although exploitation is currently uneconomical with conventional techniques. Current resources for brown-coal are estimated to be at least 1,700 Mt (Van der Burgh et al., 1988), estimates for bituminous coal above 1500 m depth range between 4000 and 38000 Mt. Conventional production of CBM is currently not economically feasible in the Netherlands. The recoverable volumes of coalbed methane above 1500 m depth are estimated to be up to 100×10^9 m^3. An earlier study estimated the total storage potential of subsurface coal seams in the Netherlands above 1500 m depth to range between 39 and 594 Mt of CO_2. It was concluded that ECBM-CO_2 is a promising option for reducing greenhouse gas emissions in the Netherlands and expected to be inherently safe and likely to become economically feasible (Hamelinck et al., 2001; Schreurs, 2002). A more detailed follow-up study focussed on the possibility of the initiation of a pilot project and scaled-up projects for ECBM-CO_2. A pilot project is required in order to gain necessary practical experience with ECBM production schemes, in particular with respect to drilling techniques and reservoir conditions. The south of the Dutch province of Limburg (Zuid-Limburg) was in an early stage selected as potential test area, based on the following three reasons:

- The presence of an ammonia plant in the area, that produces high purity CO_2 as a by-product;
- The presence of sufficient - and presumable CBM-containing - coal in the area;
- The mining history of the area, resulting in a high data density for at least parts of the region

A local assessment was performed of technical, geological, economical and legal aspects involved. Important item in the technical evaluation was the possibility of applying deviated drilling techniques to reduce the spatial impact at the surface (Figure 52). Several options were evaluated for the supply of the carbon dioxide to the injection wells in all sites, including transport by truck and pipeline. Legal issues were addressed by reviewing the official requirements for an environmental impact study. The required treatment system for the water produced, which is potentially saline, was also taken into consideration.

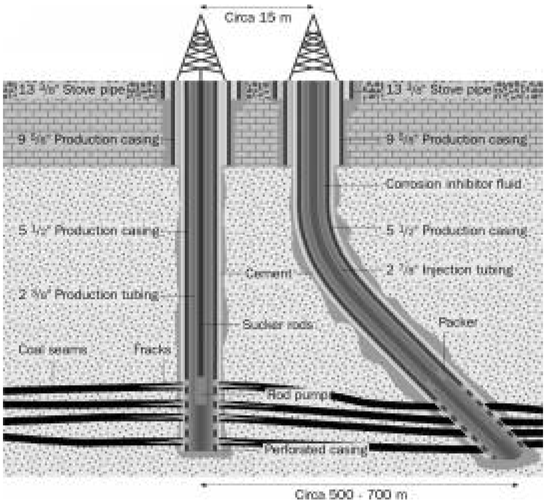


Figure 52: Schematic concept of a test site consisting of one vertical producer and one deviated injector

ECBM development is considered a high-risk venture due to the great variability in the reservoir parameters, such as gas saturation and permeability. Therefore, a phased process is required to develop a commercial ECBM project in Zuid-Limburg. Three phases were considered: a test site, a scaled-up site and a network consisting of various scaled-up sites.

For the scaled-up site and the network of scaled-up sites, CBM production costs o(break-even price) and CO_2 mitigation costs were calculated to allow comparison with alternative CO_2 mitigation options. The results clearly indicate that at present ECBM-CO_2 is not competitive with natural gas and that it needs an incentive in order to make it economically feasible. A first calculation indicates that a CO_2 price between 42 and 52 €/t, or a subsidy between 0.030 and 0.037 €/kWh, would make ECBM-CO_2 competitive with natural gas. This required subsidy falls within range with the current tariffs for renewable electricity in the Netherlands.

The results clearly indicate, despite the variation in parameters due to uncertainties or choices, that at present ECBM-CO_2 is not competitive with natural gas, even when scaling up the project. This is mainly because of the high well density and therefore large investment costs. It can therefore be concluded tentatively that ECBM-CO_2 in Zuid-Limburg needs an incentive in order to make it economically feasible, by way of a bonus for avoiding CO_2 emissions, a tax on CO_2 emissions or carbon credits in a future carbon emission trading system. Another possibility could be given by production of “climate-neutral” electricity from the produced CBM, for which a regulation came into existence in 2002.
To reduce the existing uncertainties in the process and to get insight in the actual merits of ECBM-CO_2, a test site is necessary. This test site should be developed as a standard exploration site, with the procedures as known from the oil & gas industry. When planning this actual site, environmental and legal issues should be addressed and intensive communication with the public required to bring confidence in the technology at stake.

Given the considerations above, ECBM-CO_2 could become a technique that allows the use of coal from the Dutch subsurface in future energy supply. Although it cannot compete with natural gas without an incentive, it can offer a more cost-effective local opportunity as a CO_2 mitigation alternative to other mitigation options such as renewables and other CO_2 storage options (aquifers and depleted gas fields). From this perspective, ECBM-CO_2 might become an interesting course of action, once its technical feasibility is proven, in the Dutch strategy to reduce greenhouse gas emissions.

Table 3: Summary of the results of the economical evaluation

	CO_2 stored [Mtonnes]	CBM produced [million m^3]	CO_2 supply costs [€/t]	CBM production costs [€/GJ]	CO_2 mitigation costs [€/t]
Test site	Depends on lifetime	Depends on lifetime	52-59	Not applicable	Not applicable
Scaled-up site	0.7	166	13	7	55
Network of scaled-up sites	13	3000	10	6.2	44

10.3.4 France

The evaluation of the ECBM opportunities in France are considered in more detail in a separate report. In this report a synthesis is described of the CO2 sequestration potential in coal deposit in France, that could eventually be coupled with "enhanced coal bed methane" process. From Charbonnage de France and Gaz de France documentation and from some studies of the late 90's that aimed to appraise the potential of coal bed methane in France, we had a good idea of the repartition and the quality (coal rank and CH4 content) of coal over the French territory. Last century coal exploitation does not make this assessment easier. Indeed, each coal seam has its own history and would deserve to be studied separately before being integrated in the whole which represents months of bibliographical search work.

At first sight, coal is present widely on the French territory and France seems to have a high potential for CO2 sequestration. But this potential is strongly linked to:

- the capacity of coal to receive CO2;
- the quality of coals that differ from one basin to the other one; and within one basin, from one coal seam to
- the other one;

- the volume of coal in place;
- coal "exploitability" for CO2 sequestration: is it technically feasible to exploit a given coal seam for CO2 sequestration and is there some risks for people and the environment?

Three big coal basins are considered:

1. "Bassin du Nord et du Pas de Calais" (North of France);
2. "Bassin de Lorraine" (North-east of France);
3. "Bassin du Centre et du Midi", subdivided into 8 smaller basins (center and South East of France).

Smaller basins have not been included in the three main basins: "Lons le Saulnier" basin , "Landes" basin and "Rodez" basin.

Knowing an estimate of the volume of coal in place and taking into consideration the adsorption capacity of the coal, we can assess the maximum volume of CO2 we could store within each basin. This purely theoretical calculation gives an idea of the potential of each basin (probably over estimated) and gives at least the classification of the basins regarding their CO2 sequestration potential (see table below).

Table 4: CO2 storage capacity assessment of the French coal

Basin	Volume of coal (in million m^3)	Mass of coal (million of ton)	CO_2 adsorption capacity @ 60 bars (m^3/t)	Theoretical storable volume of CO_2 (billion m^3)
Nord - Pas de Calais	13000	8000	25-35	200-280
Lorraine	5500	3700	20-30	74-111
Aquitaine & Auvergne	-	-	-	-
Blanzy-Montceau	-	-	-	-
Decize-la-Machine	160	120	15-25	1.8-3
Alès (Cévennes)	250	155	25-35	3.9-5.4
Dauphiné	250-300	150-180	30-40	4.5-7.2
Loire	-	-	-	-
Provence	610	470	15-30	7-14
Lons le Saulnier	630	420	20-30	8.4-12.6
Landes	-	-	-	-
Rodez	-	-	-	-
TOTAL	>20400	>13000		300 - 440

At first sight we can see that Nord - Pas de Calais basin has an enormous potential. It is also the most exploited field that means that a lot of galleries, more or less mapped, have been dug in this area. A feasibility study would be necessary to determine the integrity of a potential storage and its real CO2 volumetric capacity.

In the case of an eventual ECBM strategy and with some assumptions, we can do some economics on the cost of CO2 sequestration in coal seams in France. For these calculations, we assume that we adopt the same configuration than in RECOPOL base case that means one CO2 injector and one CH4 producer. The producer has a drainage area of 150 to 200 meters radius (hydraulic fracture length).

Cost of the wells varies between 1 and 2 million euros. Of course this cost - far higher than the cost of wells in USA where first ECBM productions were tested in San Juan and Warrior basins - weighs a lot in the economic balance. It could be reduced by the use of slim hole technology. For the volumetric calculations, we assumed that the produced CH4 will be replaced by injected CO2.

With a CO2 cost lower than 20 €/ton, this quick economic analysis clearly shows that CO2 sequestration in coal can only be interesting in very good conditions that means for a thick exploited coal layer and a good fracturation radius (at least 200 meters in our case). Even in such "ideal" cases, the CO2 mass that can be stored is rather small. Thus, such kind of sequestration would require hundreds of wells to be competitive with aquifer storages. However, it could be useful for small CO2 production units or countries where coal deposit are plentiful and preferred to aquifers.

In conclusion, accurate CO2 sequestration potential in French coals is not so easy because of the huge amount of data not always available and not yet synthetized and because of the complexity of these sinks partly due to the coal exploitation of the last century. This first assessment is not exhaustive but gives a good idea of the distribution of the reserves on the French territory, their size and their theoritical capacity to receive CO2. The potential is not negligible but an industrial application for CO2 sequestration, even associated with coal bed methane production, would be heavy to put in place and strongly linked to very good storage conditions. A more realistic and usable for an industrial implementation would require a case by case study.

10.4 Future technologies

The drilling costs of the injection and production wells are and are likely to be one of the most dominant cost factors in ECBM operations. In this paragraph an outlook is presented of new techniques that might reduce the overall costs in future ECBM operations.

10.4.1 Drilling techniques

The subsurface part of an ECBM- or CO_2 injection-facility consists of drilled and completed wells for CO_2-injection and CH_4-production. The drilling technique is the same for injection or production wells but the completion technique is different:

- injection well with tubing and packer for safe and gas tight CO_2-injection at high pressure
- production well with sucker rod pump for simultaneous production of water and CH_4 gas at relatively low pressure.

The following drilling techniques are considered:

<u>1. Conventional vertical well</u>

Each ECBM- or CO_2 injection-field will be explored by vertical wells as first wells to monitor the geology of the field. After this exploration phase non-vertical wells can extend the well pattern.
The costs of injection and production well are almost the same. This is due to the situation that additional expenses for the production well caused by the fracing procedure amounts to more or less the same as the additional expenses for the larger tubing and the packer of the injection well. The conventional pattern of vertical wells is the traditional five well pattern with the production well in the centre and the 4 injection wells in the pattern corners (Figure 53).

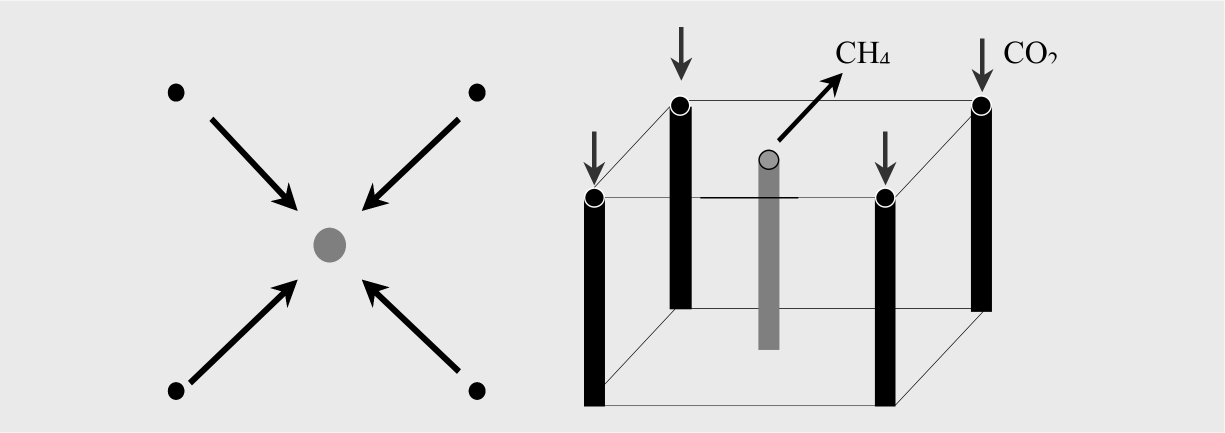


Figure 53: Conventional 5 well pattern

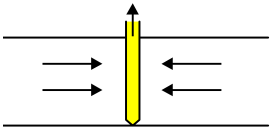
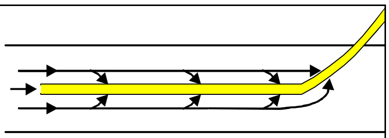
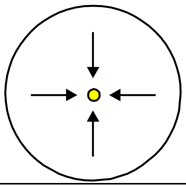
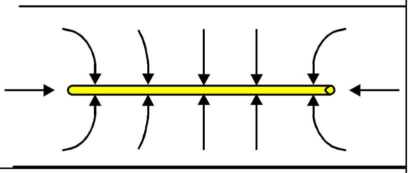
2. Deviated well

Drilling control and larger well length increases the drilling and completion costs of the deviated well. Smaller drill rig sites on surface in the cluster can decrease the costs. The slanted penetration of the coal seams package by the deviated well results in a higher injectivity of well because the filtration area of gas flow is increased. The production well should be more or less vertical because the rod pump needs clearness and low friction in the production tubing.The drilling and completion costs of the deviated well are higher than the costs for the conventional vertical well. The saving due to the possible reduction of surface installations is estimated to be able to compensate the higher drilling and completion costs.

3. Horizontal well

Horizontal wells increase the well productivity resp. injectivity considerably by transforming the filtration state from the radial symmetric form (flow limitation in well bore near zone) to the linear form (ideal flow state). The significantly increasing of the filtration area leads to a strong decreasing of the pressure gradient. The flow scheme of vertical and horizontal wells is illustrate in Table 5.

Table 5: Effectiveness of Horizontal Wells

Flow Pattern x - z		
x - y		
Injectivity/Productivity Index	1 x	3 x (2 x … 10 x)
Drilling Costs	100 %	150 %

The oil and gas industry prefers horizontal wells in explored reservoirs for higher economy. There are criteria's of decision and design of horizontal wells under specific reservoir engineering aspects. One of this is the thickness of reservoir layer. The smaller the thickness the higher is increase of injectivity / productivity. For this it seems very reasonable to use horizontal wells for coal seams with thickness of 2 – 3 m. Using horizontal wells can reduce the needed number of wells by increasing the injectivity significantly (3 – 10fold). A very welcome consequence of this is the reducing of CAPEX.
The production well with sucker rod pump has to be nearly vertical. The well scheme is shown in Figure 54 as the cluster.

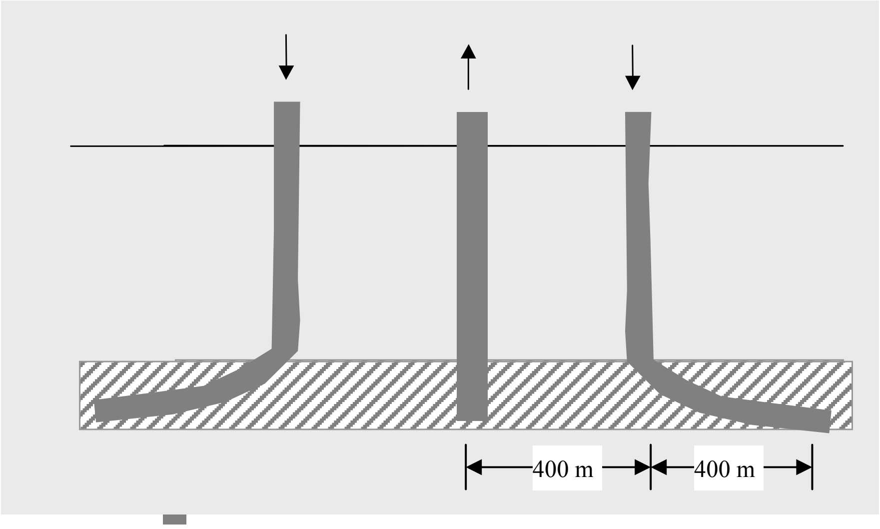


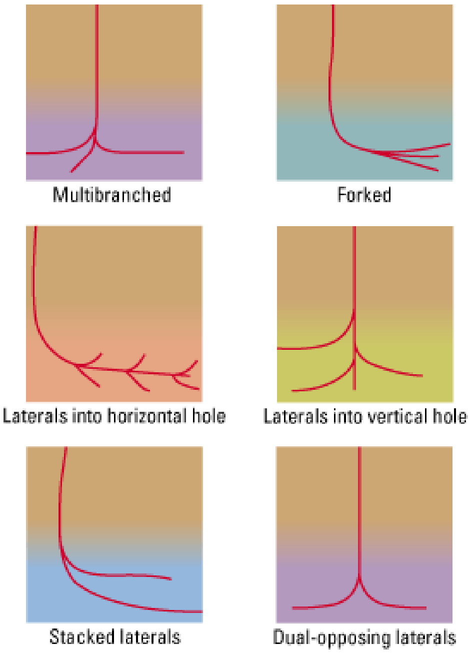
Figure 54: Horizontal well cluster

The well area can be increased to a 160-acre pattern with 800 m spacing this lead to a reduction of well number to ¼ of the original amount.

The drilling and completion costs of horizontal wells are calculated by 50 % more than vertical wells in average.

4. Multilateral Well

By drilling several horizontal well sections starting in the main borehole (vertical) or in the horizontal section (***Figure 55***) the conventional horizontal well drilling (described in article 0) can be extended.



Multibranched

Forked

Laterals into horizontal hole

Laterals into vertical hole

Stacked laterals

Dual-opposing laterals

Figure 55: several multilateral well types, from http://www.glossary.oilfield.slb.com/DisplayImage.cfm?ID=341

The drilling costs exceed the costs of the conventional horizontal well by about 25 % per lateral. Thus the 4-lateral well costs about the 2,5fold of vertical well or the 1,5fold of horizontal well.

On the other hand the geological- and reservoir engineering conditions are very complicated for the multilateral well in thin coal seams. The risk of unsuccessful well is relatively high. Therefore multilateral wells for ECMB-or CO_2-injection facilities require detailed knowledge of the local geology.

Latest drilling techniques involve so-called “fish-bone” drilling (***Figure 56***). This technology, currently operated by CDX, involves drilling from one site covering an area up to 1,200 acres, compared with 16 well sites needed when using the conventional drill and frac CBM recovery method. Drilling from just one site hole saves the construction of all the access roads and other facilities needed for the 15 extra well sites. Up to 5,000 ft from the central bore hole can be reached (Hayes, 2003).

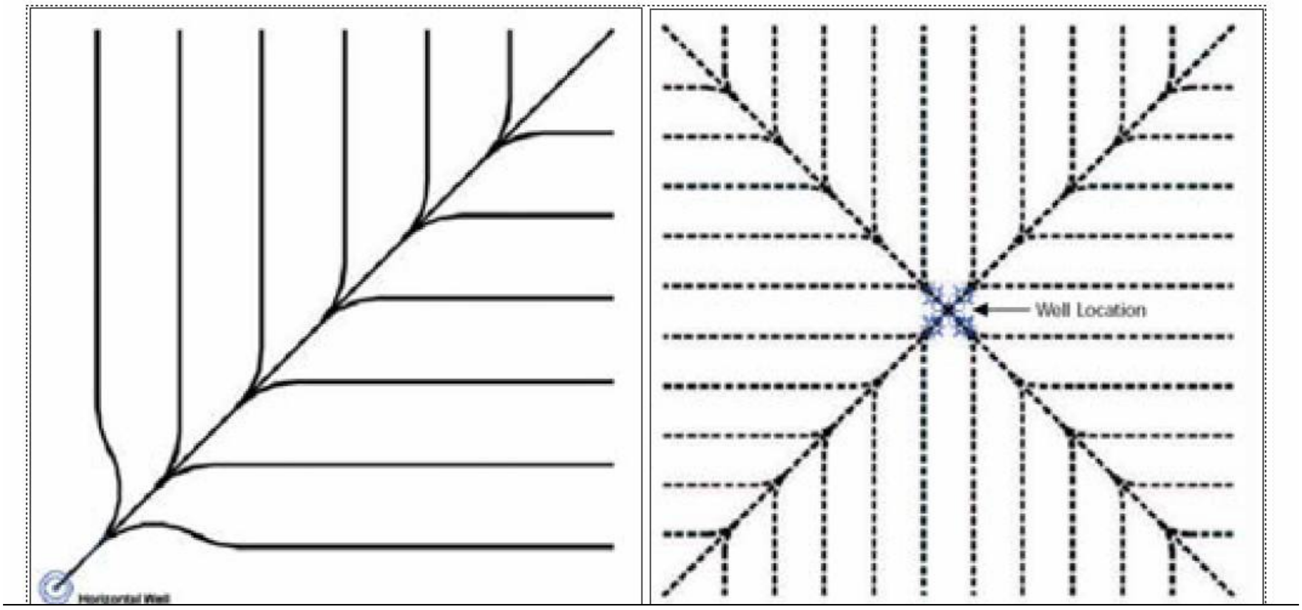


Figure 56: Left: Z-pinnate Horizontal drilling and completion System configured in the shape of a leaf (single pinnate pattern). Right: Multiple pnnate patterns can be nested and drilled from one well site (after Hayes, 2003)

10.4.2 Costs saving potentials

The well drilling represents the highest cost position in the CO_2-injection project (≥ 60 %). Asking how to reduce costs is a primary question.

But the required safety conditions of the CO_2 storage project request a high quality of drilling and completion techniques. There isn't an effective costs saving potential in drilling and well equipment. The maximum cost saving potential regarding the drilling is estimated to 10 %.

More saving potential exists in the well design, in the transformation from the vertical to horizontal wells. The theoretical cost saving potential amounts to 50 %. This theoretical value is not achievable because the technology isn't proved by a practical application for the CO_2 Injection yet and in a multi well pattern vertical wells are needed for the CH_4-production. Thus the saving potential by using horizontal wells for the CO_2 injection is estimated to 30 % in comparison to the conventional vertical wells.

A further potential can be given by the discount during drilling of numerous wells in the same time period by one drilling company. Saving well site organisation effort (de-mobilisation, camp a. o.) can reduce the costs by 10 – 20 %.

Concluding the maximum saving potential of subsurface well technology can be around 50 % of recent well costs.

10.4.3 Surface facilities

A necessary precondition for the injection of CO2 into coal seams or other geological formation is the availability of suitable surface facilities as pumps resp. compressors, heaters, measurement devices etc.. In the frame of the project DBI had developed a basic engineering, which describes the fundamental requirements on CO2 injection facilities. In the project the interfaces for the CO2 injection were given. Air Liquide had delivered the CO2 as a liquid in tanks. The CO2 had to be pressured up to 110bars. Later in the project course a pressure of 150bars was agreed. The facilities were designed to meet these requirements.

In preparation of the main configuration of future surface facilities it's important to know where CO2 occurs in a significant amount (e.g. power plants), how it can be separated (e.g. by membranes), transported and which will be the conditions (temperature, pressure, purity etc.) of the CO_2 at the injection site. Depending on these conditions different configurations of the surface facilities can be suitable to meet the various requirements.

10.4.4 Smart field developments

A workshop was organized by Delft University of Technology on visions and impressions on SMART field development and ECBM. This was intended to have an idea of ideas that may help in the future development of ECBM. Several topics were discussed, such as "closed loop reservoir management", the use of drilling, stimulation and completion techniques to increase the injectivity and productivity, increasing sweep efficiency. A detailed report on the workshop is included in a separate report.

11 Conclusions

11.1 Main observations

- Several months of injection showed that injection without stimulation is difficult under the local field conditions.
- The differential pressure between the injection and the reservoir pressure required is much higher than originally anticipated
- The injectivity in low permeability coal could be increased to substantial volumes by fraccing the coal and by using the proper injection equipment.
- Unexpectedly, a slow rise in the CO_2 content in the production gas was observed since November 2004 which could be attributed to the injected CO_2. There is a clear response of the production well on the injection activities. This early results require detailed analysis of the design of the test and the used models. Faster breakthrough of small amounts of CO_2 than expected by modelling
- The injected amounts after stimulation of the injection well provide a good basis for a future upscaling of the operations. Continuous injection rates of water of 50 l/min are reached at elevated pressure (21 MPa).
- Enhancement of gas due to the injection of CO_2 is likely. However, despite fairly good in situ gas content of the coal, the recovery rates are very low
- Permeability of the coal is decreasing in time during injection of CO_2, most likely due to swelling of the coal
- Changes in the coal properties during injection, leading to higher frac pressures, are probable
- The laboratory results allow major improvements in the understanding of the process
- Strength of ECBM
    - Value added storage technique, therefore likely to attract interest from industry
    - Has some safety advantages over e.g. aquifers
    - Large potential reserves
    - Usually near industrial areas and methane market
- Weakness of ECBM
    - Limited opportunity
    - Currently limited process understanding
    - Expensive (although there is some offset)
    - Small window of opportunity
    - Technically unproven – still many uncertainties
    - Higher operational pressures than comparable aquifers (cost)
    - Seam faulting
    - Never define what is “unminable”
- Opportunities for ECBM
    - Niche regions have sinks and source close (esp. Eastern Europe
    - Existing gas network and local markets for gas and storage
    - Fiscal credits and CO_2 credits under emissions trading system
- Threats for ECBM
    - Early breakthrough/swelling
    - Conventional Natural gas availability
    - Public opinion – permitting issues
    - Other storage options with potentially more capacity
    - Local land use competition

11.2 Comments on organization and management of the project

At the end of the project an internal review was performed within the consortium on the organization, management and outcomes of the project. As an organisational scheme it was chosen to divide the work into a set of seven work packages. The major items in the project were divided over these work packages. The following items were identified (table 12.1). An internal review of the separate items was held within the consortium. Results of this evaluation are summarised in table 9.1.

11.3 Future research

The following topics should have the priority for future research on ECBM-CO_2

1. Physical process / fundamental and advanced understanding
2. Well development
3. more extensive field projects (in more situations)
4. overcome swelling
5. which geological environments are the best (how niche is niche) – jewel picking -
6. multiple approach (different storage options combined)

11.4 Concluding remarks

Advances were made in the understanding of the process that allows improvements in the dedicated numerical simulators. Enhancement of methane production was proven, although the underlying process is not fully understood. Further field experiments and laboratory studies should be undertaken to gain further knowledge of the processes involved. The permeability of the coal remains a critical factor, even though it is shown that the injectivity in low permeability coal could be increased to substantial rates. The injected amounts provide a good basis for a future upscaling of the operations. It is expected that in the Upper Silesian basin locations can be found with higher permeability, thicker seams and higher gas content, providing a better prospectivity for gas production. With the experiences of this project, field optimization can be performed to enhance production in future sites. Since the process appears to be diffusion controlled, an optimum distance should be chosen between the wells that guarantees sufficient contact time between the injected CO_2 and the *in situ* coal. Other well completions, such as horizontal or "fishbone" drilling, need to be researched to assess their impact on injectivity and productivity. To enhance the recovery factor even further, dedicated operational schemes, with varying injection and production intervals, should be planned. Operational flexibility in the applied pressure and flow rates is highly recommended to manage the swelling effects.

Conclusively, the consortium showed that it is possible to set up the first on-shore CO2 storage pilot in Europe and to handle all "soft" issues (permits, contracts, opposition, etc.) related to this kind of innovative projects. The experience gained by a broad group of people is invaluable for the further development of CO2 sequestration in virgin, deep seated coal seams in Europe. The lessons learned in this operation can possibly help to overtake start-up barriers of future CO2 sequestration initiatives in Europe. One of these barriers is the public concern of the safety of these kinds of projects. Further and future activities within the RECOPOL project are therefore focused on the monitoring of the injected CO2 in order to detect any possible, but unlikely, emission of injected CO2 to the surface.

Table 6: Results of internal review of main project items

Coordination	Complications in the co-ordination were the international character. Handling of these complications were, in general, considered to be satisfactory. It was recognised that the character of the field experiment requires a dedicated co-ordination of the field test alone. Communication and cooperation between the different fields of expertise was considered good.
Geology	Geological characterisation was considered to be satisfactory. In future projects, focus can change to more specific requirements, such as stress field evaluation.
Lab work	Extensive lab programme undertaken, new techniques and new information developed. Co-operation was considered to be good and valuable. Results documented some unexpected results that can be used to improve the models. Translation to modelling and field conditions of the findings still has to be undertaken. Ways of future research identified (upscaling, sorption processes, water content, kinetics, etc.).
Numerical simulations	The pre-operational simulation provided useful data for development plan, despite that the models are not yet fully developed and calibrated to enable production and injection operations and response to be predicted with confidence. This exercise has been excellent in developing these models further, but further development will be required. In future, sensitivity studies should still be included with the notion that these studies are not currently conclusive.
Field test	The realisation of the field test as such is a major achievement, also taking into consideration that permitting of such an activity has never been undertaken. As such, this project provides a reference point for future projects. From a technical point of view, the target of continuous injection has not yet been achieved. Considerable experience has been gained in the design and operation of CO_2 injection equipment in coal seams. For future tests, more site specific data is required at the outset to adequately design equipment. Maintain flexibility in the design as long as possible. More time is required in order to allow for a proper phasing of the project, given this aspect. Well testing should be improved and undertaken as early in the project as possible. Provisions for extending test should be made, in case of inconclusive results. Stimulation (fracturing) from the start should be considered to improve injectivity. Other well completions (horizontal drilling) need to be researched to assess their impact on injectivity.

Table 6 (continued)

Monitoring	The importance of monitoring was underestimated during the proposal stage. Within the project, this was recognised in an early stage and a monitoring programme was introduced into the programme. The monitoring programme provided valuable input to the project. The application of crosswell seismics was ambitious and remains unproven.
Effective time and budget	Given the character of this project, i.e. it is a field pilot project and not a paper study, more contingency and flexibility within the time and budget needs to be allowed.

12 Dissemination of results

12.1 Local

Information panels (in Polish and English) were placed on the street side of the RECOPOL site with an explanation of the activities and an overview of the consortium (***Figure 57***). Also, contact information was indicated for further information.

Figure 57: Information panel at the RECOPOL site

12.2 International

<u>Expert panel</u>
An international restricted workshop was held in March 2003 with experts in the operational and research field of ECBM (***Figure 58***). Minutes and documentation of the expert panel are reported in two separate reports.

Figure 58: Attendees of the RECOPOL expert review meeting, with from left to right: Henk Pagnier, Bernd Krooss, Xavier Choi, Frank van Bergen, Scott Reeves, Khaled Gasem, Pawel Krzystolik, David Law, Karl-Heinz Wolf, Jack Pashin, Bert van der Meer and John Gale (Luke Connell took the picture).

Open workshop

As part of the projects final dissemination activities, a workshop was organised by TNO, Central Mining Institute and IEA GHG. The workshop looked at the opportunities for carbon capture and storage (CCS) in Central and Eastern Europe with specific focus on the results of the RECOPOL project.

The workshop was held in the ski resort of Szczyrk in Southern Poland on 10-11 March 2005, which was still experiencing plenty of snow in what had been expected to have been spring time conditions. The presentations were given in both English and Polish with translations provided.

Figure 59: Winter scenes at the venue for the RECOPOL workshop, Szczyrk, Poland

Day one of the workshop included an international perspective on carbon capture and storage, a look at the requirements for the reduction of harmful emissions from power plants in Poland, an overview of worldwide CO_2 Enhanced Coal Bed Methane (CO_2-ECBM) projects and the potential for CCS in Central and Eastern Europe.

The first day also included a trip to the site of the RECOPOL pilot project. A short tour of the site was arranged to see the injection and production wells (Figure 60 and Figure 61).

Figure 60: The site tour includes the CO_2 injection well MS-3

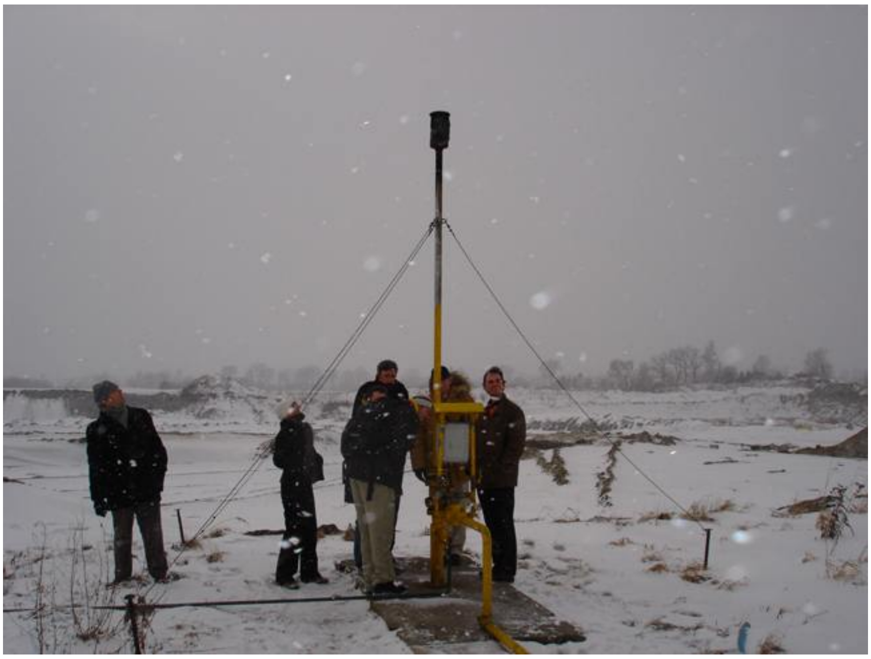


Figure 61: Flaring of the produced methane

The international review of ECBM on day 1 presented the 5 ECBM projects world-wide. There has only been one commercial scale project which was in the U.S.A. (San Juan Basin). Then there are a series of smaller pilot projects in Canada (Alberta-ECBM project), Japan (Hokkaido project), Poland (RECOPOL project), and China (Qinshui Basin). These smaller projects consist of either a single injector/producer well or a single injector and a single producer well. The general consensus from the international projects is that whilst there is a requirement to buy CO_2 to inject into the coal as is the current situation, the projects will not be economical, even those projects with favourable coal conditions (i.e. high permeability). If in the future there was a charge to dispose of the $CO_{2,}$ then the economics would change benefiting ECBM projects.

The second day of the workshop provided an opportunity for the project consortium to present the latest results from the RECOPOL project. The RECOPOL consortium consists of the following research institutes, universities and industrial partners: TNO-NITG (co-ordinator, the Netherlands), Central Mining Institute (Poland), Aachen University of Technology (Germany), Delft University of Technology (the Netherlands), Institut Français du Pétrole (France), CSIRO (Australia), DBI-GUT (Germany), Gaz de France (France), Gazonor (France), Air Liquide (France), Advanced Resources international (USA), IEA Greenhouse Gas R&D Programme, JCoal (Japan), Shell International, and the University of Mons (Belgium).

The RECOPOL results were presented during the second day of the workshop:

- **Geological characterisation of the Upper Silesian Coal Basin (USCB)**. This looked at the stratigraphy and lithology of the strata, tectonics and the resources of the reservoir. There was plenty of information available from years of observations conducted in the Brzeszcze and Silesia coal mines.
- **CO_2 injection well test, planning, performance and analysing**. The conclusion of this part of the project was that the wells had been successfully completed and the perforations were located in the right place (i.e. in line with the coal seams). The plans for the project were modified to ensure successful injection. The permeability of the coal at the test site was low which is not ideal for an ECBM project. Favourable high permeability conditions such as those seen at the commercial scale project in the U.S.A. are not common elsewhere around the world. To improve injectivity into coals other technologies might have to be used, the presentation was reserved regarding fracturing due to the associated dangers but mentioned the use of horizontal wells.
- **Determination of the change in permeability of coal by bottom hole pressure survey and fall-off test**. The tests concluded that the decrease in permeability during injection was most likely due to coal swelling. A future challenge will be to understand the mechanisms of coal swelling so it can be prevented or its impacts reduced.
- **Reservoir modelling of coal bed methane operations.** Simulation was undertaken to investigate all the phases of the planned ECBM pilot test. From the beginning of the project it was recognised that the presence of the injected CO_2 at the production well (i.e. breakthrough) would provide the maximum amount of information on the potential of ECBM in the Silesian coal. With this in mind the distance between the injection and production wells was determined to allow breakthrough within the timeframe of the project. The indication of breakthrough, identified by the rise to 8% CO_2 in the produced gas is earlier than the simulation models suggested. However, the models are two years old and the early breakthrough could provide useful information on the adsorption of CO_2 in the coal seam.
- **Isotopic evidence of CO_2 influx from MS-3 to MS-4 well.** The main purpose of stable carbon isotopic analysis was to determine the origin of the CO_2 at the production well. This form of analysis identifies the naturally occurring CO_2 from the injected CO_2. Being able to determine between the two would provide evidence as to whether the injected CO_2 had reached the production well or whether it is only the naturally occurring CO_2 that is present. This presence of injected CO_2 was identified at the production well in December 2004.

- **Sociological and psychological problems related with social reception of CO_2 storage**. This focused on three stages of social/public consultation that could be applied in future projects. The three stages identified were: promotional campaigns, surveys and public hearings/debates.
- **Monitoring techniques applied for CO_2 injection in coal**. The monitoring undertaken as part of the pilot study should help to improve the understanding of CO_2 storage in these coal layers. The measurements from the various techniques utilised should aid the development of a subsurface model that predicts future behaviour of the stored CO_2 and the coal after field abandonment.

A poster session on day 2 provided further information on the RECOPOL project including the geological model, the site development of the production and injection wells, an evaluation of the injection data, monitoring and GIS techniques and the evaluation on the ECBM potential of the Upper Silesian Coal Basin.

The final sessions of the day were split into two areas: Laboratory Experiments and the Sustainable Usage of Coal. These two sessions presented more results from the RECOPOL project and also provided an opportunity for a review of other research on CO_2-ECBM from around Europe.

The overview of the RECOPOL project given by the co-ordinators of the project, announced the significant outcomes from the RECOPOL project as:

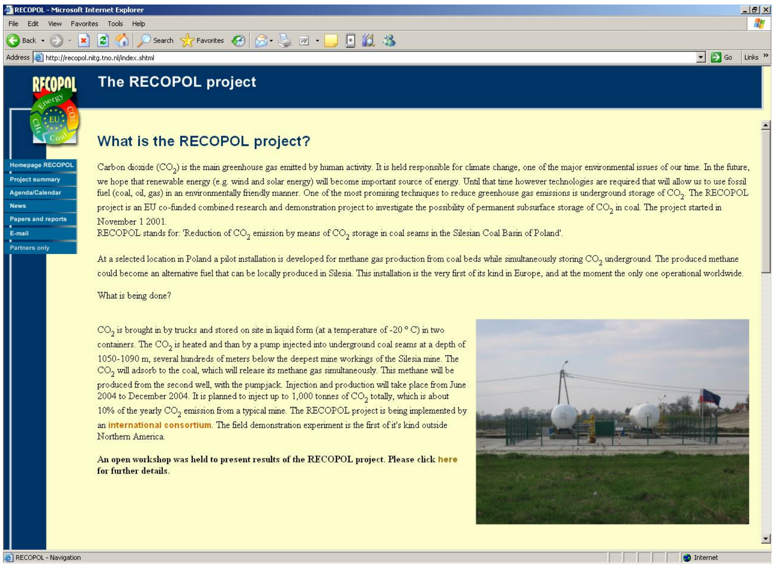
- Lab results allowed major improvements in the understanding of enhanced coal bed methane,
- CO_2 was successfully injected in to the coal bed but CO_2 induced swelling of the coal was significant and the injectivity was lower than expected,
- Onshore storage of CO_2 can be an option in this region,
- Higher pressures were required for CO_2 injection but development of the design of the pilot project were altered accordingly,
- The experience gained through the RECOPOL project will help the development of future projects although each region will have different regulatory requirements and will not necessarily be able to follow the route of this project.

Greenhouse issues

Three articles on the progress of the RECOPOL project have been posted in the January 2004, January 2005 and September 2005 issues of Greenhouse Issues of IEA GHG. In addition an article on the technical workshop was posted in the June 2005 issue. Additionally, a paper on the RECOPOL project was presented at the GHGT-7 conference (organised by IEA GHG) held in Vancouver, Canada 2004. Proceedings for this conference will be available in September 2005. Currently all papers from the conference are available on the conference web site at www.ghgt7.ca. An abstract for a paper for the next conference, GHGT-8 to be held in Trondheim, Norway in June 2006 will be submitted for oral presentation.

Internet

Further, the Internet homepage of the project was frequently updated and responses were received. The address is www.nitg.tno.nl/recopol or recopol.nitg.tno.nl (Figure 62).



The RECOPOL project

What is the RECOPOL project?

Carbon dioxide (CO_2) is the main greenhouse gas emitted by human activity. It is held responsible for climate change, one of the major environmental issues of our time. In the future, we hope that renewable energy (e.g. wind and solar energy) will become important source of energy. Until that time however technologies are required that will allow us to use fossil fuel (coal, oil, gas) in an environmentally friendly manner. One of the most promising techniques to reduce greenhouse gas emissions is underground storage of CO_2. The RECOPOL project is an EU co-funded combined research and demonstration project to investigate the possibility of permanent subsurface storage of CO_2 in coal. The project started in November 1 2001.
RECOPOL stands for: 'Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland'.

At a selected location in Poland a pilot installation is developed for methane gas production from coal beds while simultaneously storing CO_2 underground. The produced methane could become an alternative fuel that can be locally produced in Silesia. This installation is the very first of its kind in Europe, and at the moment the only one operational worldwide.

What is being done?

CO_2 is brought in by trucks and stored on site in liquid form (at a temperature of -20 ° C) in two containers. The CO_2 is heated and than by a pump injected into underground coal seams at a depth of 1050-1090 m, several hundreds of meters below the deepest mine workings of the Silesia mine. The CO_2 will adsorb to the coal, which will release its methane gas simultaneously. This methane will be produced from the second well, with the pumpjack. Injection and production will take place from June 2004 to December 2004. It is planned to inject up to 1,000 tonnes of CO_2 totally, which is about 10% of the yearly CO_2 emission from a typical mine. The RECOPOL project is being implemented by an international consortium. The field demonstration experiment is the first of it's kind outside Northern America.

An open workshop was held to present results of the RECOPOL project. Please click here for further details.

Figure 62: Opening page of the RECOPOL website

IEA GHG has continued to maintain a link from its web site www.co2captureandstorage.info to the RECOPOL project web site. The RECOPOL project data sheet has also been maintained throughout in IEA GHGs CCS Practical R&D Database that is hosted on its web site. The RECOPOL project details are presented on the web site along with all relevant projects on CO_2-ECBM underway in the USA, Japan, China and Canada.

12.3 Accompanying reports

2005

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RECOPOL – Operations. Krzystolik, P., Skiba , J., and Jura, B. (CMI), 2005

Summary of AL activities in the RECOPOL project. De Smedt, G., Wentink, P. and Hasanov, V. (AL), 2005

Seismic monitoring of CO_2 storage in the RECOPOL project. Winthaegen, P. (TNO)

CO2 sequestration potential in coal deposits, in France. Grabowski, D. and Saysset, S. (GdF), 2005

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12.4 Publications

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Appendix 1
Laboratory experiments - results

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A.1 Coal Properties (RWTH, CMI)

	VRr (%)	Lipt. (%)	Vitrinite (%)	Inert. (%)	Moisture Cont (%)	Ash (%)	Min. Mat (%)	Vol. Matter (%)	Density (%)	TOC (%)
Brzeszcze 106-405	0.740	10.00	74.00	16.00	1.44	13.58	14.80	29.16	1.34	70.22
Brzeszcze 105-364	0.780	10.00	36.00	54.00	2.22	17.03	18.56	37.83	1.26	70.18
Brzeszcze 405-510	0.750	8.00	39.00	53.00	1.85	4.57	4.98	34.17	1.33	68.80
Silesia 155-315	0.680	7.00	70.00	24.00	7.00	20.05	21.85	40.13	1.38	60.73
MS1_364	0.80	12	54	34						
MS2_357	0.84	8	84	8						
MS3_364					1.83	14.55				
MS4_364	0.84	2	65	33	1.72	13.14				
MS5_364	0.83	7	88	5						
MS6_402	0.81	4	86	10	1.69	49.03				
MS7_401	0.80	12	61	27						
MS8_405	0.88	14	15	71	1.42	19.36				
MS9_405	0.83	13	40	47	1.00	13.05				

A.2 Sorption Parameters (RWTH)

- RWTH

					Langmuir parameters (DAF)			
Sample	**gas**	**state**	**P_{max} (bar)**	**T (°C)**	**K_L (bar)**	**m_{inf} (mmol/g)**	**m_{inf} (m^3/t)**	**VR_r (%)**
Brzeszcze 405 LW 106								0.74
	CH_4	dry	216.75	45	20.26	0.85	20.01	
		moist	215.23	45.3	20.71	0.71	16.73	
	CO_2	dry	190.75	45.3	10.58	2.92	68.96	
		moist	162.40	45.3	17.15	2.03	48.07	
Brzeszcze 364 LW 105								0.78
	CH_4	dry	226.53	45	18.85	1.06	24.96	
		moist	221.63	45.5	24.90	0.72	17.09	
	CO_2	dry	215.80	45.3	10.69	3.80	89.86	
		moist	204.63	45.3	23.00	3.69	87.18	
Brzeszcze 510 LW 405								0.75
	CH_4	dry	183.98	45	15.34	0.93	22.00	
		moist	171.43	45	22.10	0.37	8.66	
	CO_2	dry	187.85	45.3	10.39	2.52	59.64	
		moist	223.13	45.3	23.32	1.54	36.35	
Silesia 315 LW 155								0.68
	CH_4	dry	186.50	45.3	14.12	1.14	26.93	
		moist	226.43	45.4	19.66	0.42	9.88	
	CO_2	dry	157.48	45.3	13.51	3.09	72.99	
		moist	162.40	45.3	39.32	1.85	43.77	

- TUD

  Sorption capacities from flooding experiments:

	water saturation (%)	**amount of sorbed CH_4 (mmol/g)**	**amount of sorbed CO_2 (after CH_4 inj.) (mmol/g)**	**amount of initially injected CH_4 produced (%)**
Brzeszcze 501	10.2	0.58	0.42	72.74
Brzeszcze 501	dry	0.45	1.03	30.18
401 seam (MS3) CO_2/N_2 exp	6.1	0.31	n.a.	37.97

A.3 Permeability (IFP, TUD, RWTH)

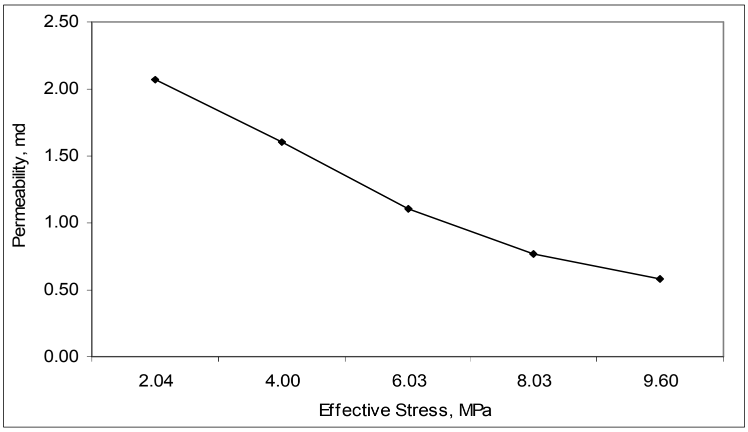
- IFP

  Average values for coal seam 364 and 401:
  - from core **2.27 mD / 1.44 mD**
  - from well test **0.51 mD / 0.73 mD**

  Average values for coal seam 405:
  - from core **0.08 mD**

- TUD

  Permeability dependent on effective stress.
  401 seam: ~ **2 mD at 20 bar to ~0.6 mD at 96 bar**



- RWTH

  Permeability measurements with H_20 (fluid pressure=60-70 bar).
  405 seam: **1 µD** (constant for varying confining pressure, poorly cleated)
  364 seam: **2 mD to 0.2 µD** (dependent on confining pressure, very well cleated)

A.4 Porosity

- IFP

  Average value for 364 (from logs) **0.07 (Range from 0.02 to 0.16)**
  Average value for 401 (from logs) **0.1 (Range from 0.02 to 0.16)**
  The core values measured on cores used for the Pc curve and cuttings were **0.04** and <**0.03**
  Average value for 501 (from logs): No log analysis was done for this coal seam since the decision to include this seam was taken after log analysis was done. One value of porosity was measured **0.02**

A.5 Pc-curves

- TUD

  From Silesia Mine not good enough. Instead, comparable Pc-curves from Warndt-Luisenthal (Saar coal district), of same coal rank, **will be delivered by W.J. Plug.** Note, these values are confidential for publishing till January 2006, but can be used for modeling.

A.6 K_r Curves

- IFP

  As for the Pc the Kr input for the simulation ought to be:
  - for the 364 and 401 coal seams shapes using Burdines's method with $\lambda = 2.97$
  - for the 501 coal seam shapes using Burdine's method with $\lambda = 3.32$

  The only end-point estimation we can make is the S_{wi} value which we think should be high (between 0.4 and 0.5). The reason is the SANS experiment which implies a high rugosity. Ultimately, this also implies a different shape of the K_r curves, thus a tortuosity of 0.5 instead of 1 to be used with Burdine's.

A.7 Diffusion coefficient

- IFP

  The diffusion coefficient for 364 & 401 coal seams by our calculations should be: $9*10^{-10}\ m^2s^{-1}$

  The diffusion coefficient for 501 is probably lower (conclusion drawn from inspection of the CT images). A value cannot presently be given.

- RWTH

  CO_2 diffusion coefficient on water saturated 405 seam:

  D_{eff}=$1.18\text{-}1.43 *10^{-9}\ m^2s^{-1}$

A.8 Characteristic Times of Diffusion

- IFP

  For the characteristic times to be used for coal seams 364 and 401, the characteristic times were given in prior reports (**between 50 and 60 days**), depending on what the half-length average is considered from the image analysis of length distributions between fractures.

  For coal seam 501, given the fact that the diffusion coefficient is unknown, it is difficult to provide an exact value.

- RWTH

  Relative sorption times (or characteristic times) for slow and fast sorption processes; for CO_2 and CH_4 on dry and moist coals; at 32 and 45°C.

	ratio in sorption time (fast/slow)		**ratio in fast sorption process (CO_2/CH_4)**	**ratio in slow sorption process (CO_2/CH_4)**
CO_2_dry_45°C	7	dry_45°C	1.7	4.2
CO_2_moist_45°C	11	moist_45°C	3.6	13.5
CO_2_dry_32°C	15	dry_32°C	4.1	5.6
CH_4_dry_45°C	17			
CH_4_moist_45°C	40			
CH_4_dry_32°C	21			

A.9 K and PHI distributions

- IFP
  - For coal seam 364 & 401

    Initial porosity value: any value from **0.02 to 0.16** except for the cell where the well is declared which takes a core value (**0.02/0.04**)

    Standard deviation **0.02**
    Correlation Factor **0.1**
    Mean Porosity **0.07**

  - For coal seam 501

    Initial porosity value: any value from 0.02 to 0.16 except for the cell where the well is declared which takes a core value (**0.02**)

    Standard deviation **0.02**
    Correlation Factor **0.1**
    Mean Porosity **0.1**