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1. Project execution

1.1. WP 1 Improving storage understanding and performance

1.1.1. Objectives

Workpackage 1 focuses on laboratory experiments on coal and (improved) modelling of the ECBM field experiment in Poland. Also, the new field experiment in the Velenje mine in Slovenia is included in this work package.

The main objectives of the work package are:

- to gain better understanding of the adsorption kinetics and diffusivity of gases into the coal/matrix as this is a key parameter of ECBM that has received little attention to date.
- to develop accurate models able to predict the long term effect of CO₂ injection (cap-rock and adsorption to coal).
- to investigate how to influence the accessibility to the coal fracture system (macro-scale, e.g. horizontal wells) and the coal matrix (micro-scale, e.g. improving pore accessibility).

1.1.2. Laboratory experiments

1.1.2.1. Desorption kinetics and hygrometry

A new method of humidification of coal has been established. This method allows performing measurements on coal with a precise value of humidity level. A clear trend has been established between excess sorption capacity and humidity level of the coal sample. In terms of influence of water on sorption rates, the experiments have shown no difference on the time for reaching equilibrium while CO₂ uptakes between steps decrease considerably from low humidity level to high humidity level. This indicates clearly that water has a considerable influence on diffusion on coal. This is generally explained by the fact that water is a good swelling agent for the coal. More sorption rate experiments at constant uptakes for each step could give more information on the diffusion parameters.

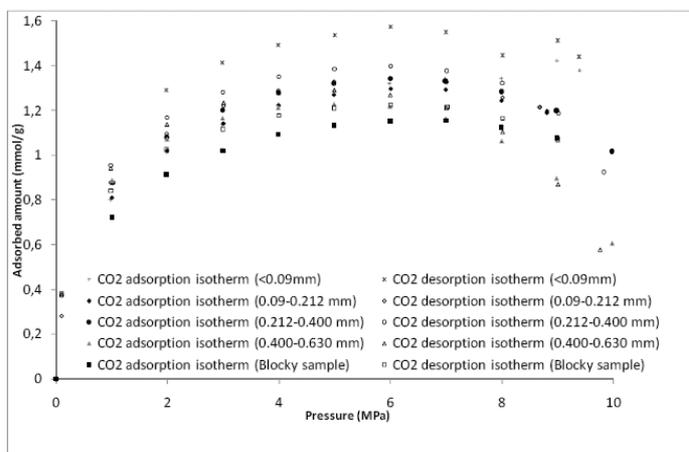


Fig. 2 CO₂ sorption isotherms on different grain size fractions. All measurements performed on dry coal at 318 K.

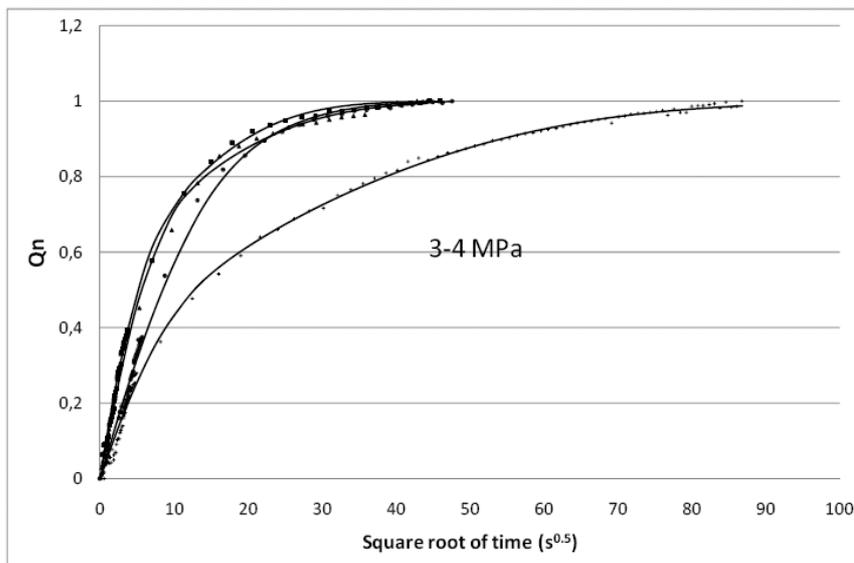


Fig. 8 Experimental and simulated (lines) CO₂ adsorption equilibration curves for each grain size fraction for step 3-4 MPa (black square: 0.09-0.212 mm; black triangle: 0.212-0.400 mm; black circle: 0.400-0.630 mm; black cross: blocky sample).

In conclusion, a gravimetric apparatus was adapted to carry out adsorption and desorption rates experiments. The use of a pressure regulator during these adsorption rate measurements allows us to maintain pressure constant which is one of the more restrictive hypothesis of simple diffusion model available in the literature. Sorption rate experiments were performed up to 10 MPa on coal crushed in different grain size fraction. Influence of grain size was clearly shown by the experimental results obtained. Pressure influence shown by these results has been discussed. A bidisperse model proposed by Ruckenstein et al. has been used to modelled experimental measurements and gave accurate results.

1.1.2.2. Mechanical transport

In order to determine CO₂ penetration of matrix blocks and related behaviour, the following activities have been performed.

- Strain development in unconfined matrix samples of RECOPOL coal (of about 1 x 1 x 1 mm) at 40°C and 8 MPa CO₂ pressure has been measured in a high pressure optical cell (under a microscope) as a function of time. Both air dried and moisturized samples (see below) were used. The effects of methane and argon were also investigated.
- The results of the strain development experiments have been used to determine penetration rates and diffusion coefficients of CO₂ into matrix blocks.
- Experiments on granulated RECOPOL matrix material have been performed to investigate the effect of stress on CO₂ uptake.
- Experiments have been performed to measure directly, for the first time, the transport properties of coal matrix blocks and to attempt to distinguish between permeability and diffusion effects.
- Consideration of implications for ECBM.

1.1.2.3. Influence of water on pore accessibility

Field experiments and laboratory studies have shown that swelling of coal takes place upon contact with carbon dioxide at underground pressure and temperature conditions. Understanding this swelling behavior is crucial for predicting the performance of future carbon dioxide sequestration operations in unminable coal seams conducted in association with methane production. Swelling is believed to be related to adsorption on the internal coal surface. Whereas it is well established that moisture influences the sorption capacity of coal, the influence of water on coal swelling is less well-defined.

Laboratory experiments were undertaken by partner UU to investigate the effect of moisture on coal swelling in the presence of carbon dioxide, methane and argon. Strain development of an unconfined sample of about 1.0-1.5 mm³ at 40°C and 8 MPa (and at other pressures) was observed in an optical cell under a microscope as a function of time. Both air dried and moisturized samples were used. Results confirmed different swelling behavior of coal with different substances: carbon dioxide leads to higher strain than methane, while exposure to argon leads to very little swelling. The experiments on moisturized samples seem to confirm the role of moisture as a competitor to gas molecules for adsorption sites. Adsorption of water could also explain the observed swelling due to water uptake at atmospheric pressure. A re-introduction of carbon dioxide, after intermediate gas release, results in higher strains which indicate a drying effect of the carbon dioxide on the coal. The results of this study show that the role of water can not be ignored if one wants to understand the fundamental processes that are taking place in enhanced coalbed methane operations.

Main conclusions can be summarized as follows:

- 1) Microscopic observations confirmed that strain develops in unconfined coal samples as a result of introduction of CH₄, scCO₂ and water at a temperature of about 8 MPa and a temperature of 40°C.
- 2) Point (1) confirms that water and gas molecules both compete for adsorption sites.
- 3) Because adsorption and swelling are related, point (2) implies that swelling will be less for moisturized coals than for dry coals.
- 4) We recommend that these studies be extended to other coals of different rank and composition. The results of these studies could lead to conclusions on how to improve the access of gas and scCO₂ to pores in a coal matrix.

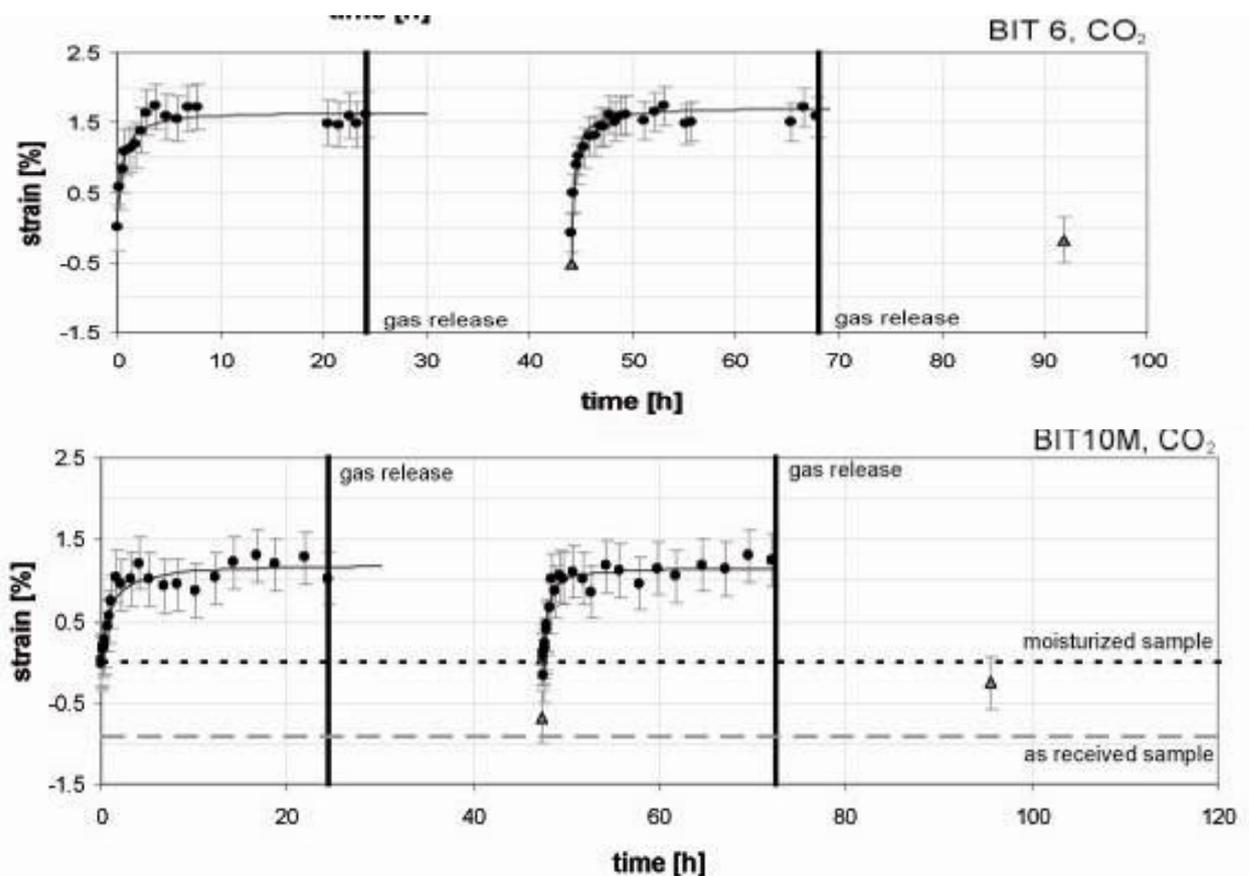


Figure 1.2 Development of strain with time of air dried (top) and moisturized (bottom) bituminous coal samples under CO₂ pressure. The gas is introduced at 0h. The line represents the best fit through the data. The measurement point after equilibration to atmospheric pressure is indicated by the triangle.

Also, the effect of water was investigated (by partner SKLCC) by comparing the effective permeability of wet and dry coal. The effective permeability was calculated from the volume flux in the downstream compartment using Darcy's law for compressible media:

$$k_{\text{eff}} = \frac{2Q\eta P_2 L}{(P_1^2 - P_2^2)}$$

where k_{eff} [m^2] being the effective permeability coefficient for gas. The effective permeability coefficient for Ar (ranging from 0.05 ~ 0.7 nDarcy) was considerably lower than single phase Ar permeability coefficient (20 to 317 nDarcy) and the absolute water permeability coefficient (18 to 41 nDarcy).

It was reported that under gas pressure dry coal swell more than wet coal. The similar phenomena were obtained for Yangquan coal block (Figure 1.3). However a reversed phenomenon was observed for dry and 0.6% moisture coal (Figure 1.4). It seems that small amount of water helps coal swelling. It also can be attribute to the shrinkage of dry coal which was further dried by contacting with swelling gas. To clarify this further studies are necessary.

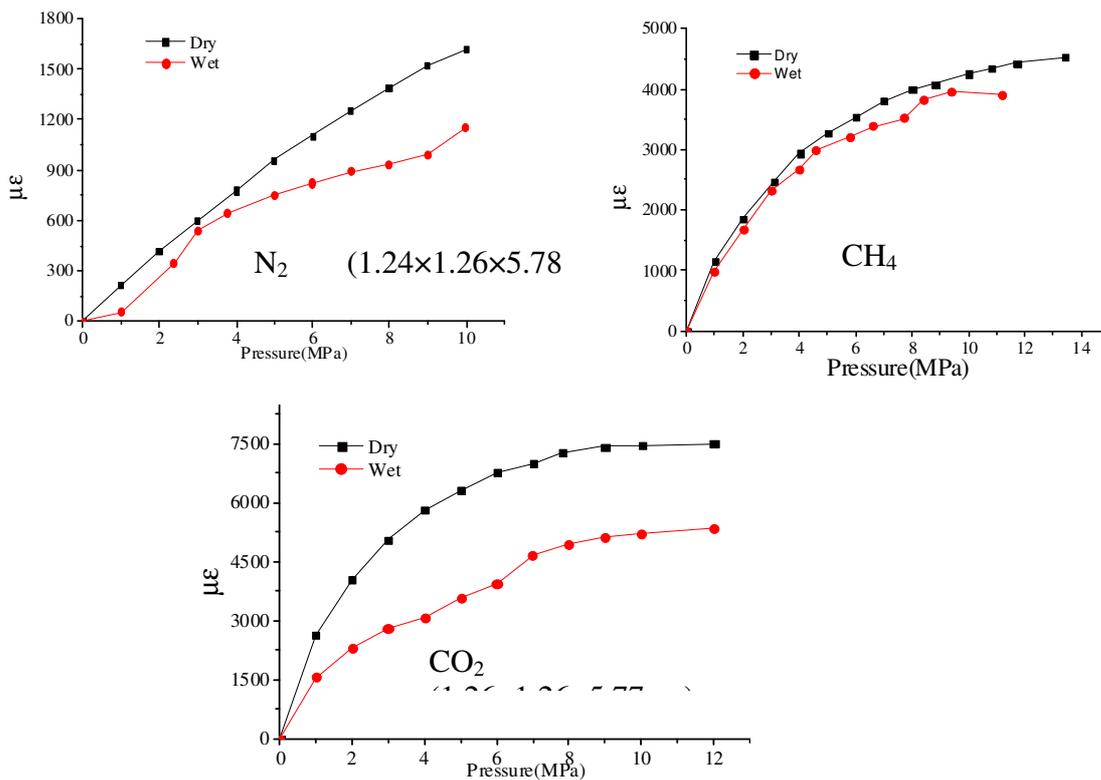


Figure. 1.3 Swelling isotherms for dry and wet (@4%water content) coal blocks under CO_2 , CH_4 or N_2 pressure at 45°C

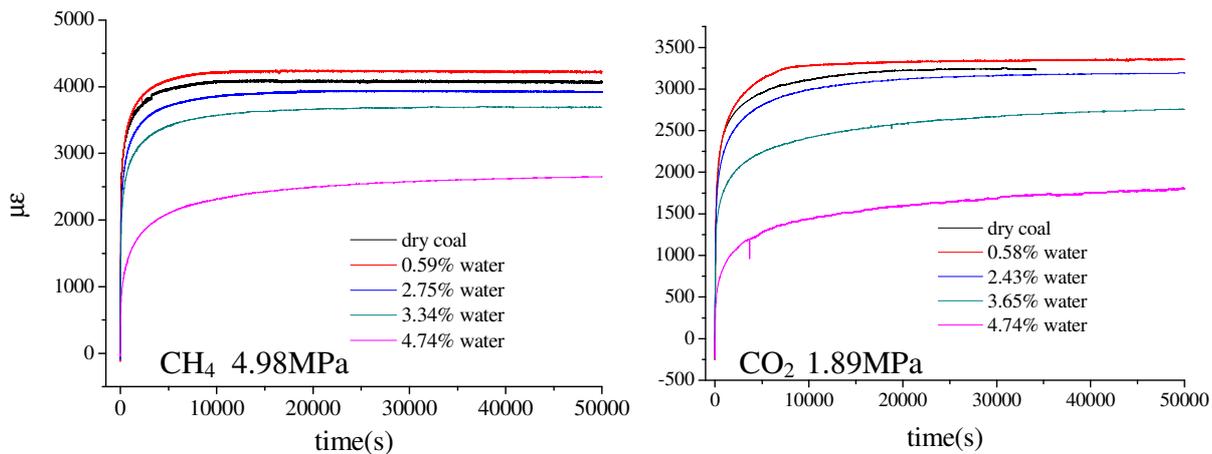


Figure 1.4. Swelling profiles of wet Yangquan coal block samples

Also, the permeability to Ar, He and CO₂ of a Chinese coal (Yangquan) sample was measured. Experiments were conducted to establish the relation between swelling ratio and adsorbed amount. Also, the dependence of swelling and sorption behavior on temperature was determined. Experiments designed to study the effect of water showed that under gas pressure dry coal swell more than wet coal. The dependence of sorption on particle size was studied. In relation to flue gas injection the reaction of coal components with CO₂, SO₂ and O₂ was investigated.

1.1.3. Field experiments

1.1.3.1. Field experiment in Poland

The field experiment in Poland was handled in a separate workpackage (WP2, Chapter 2).

1.1.3.2. Field experiment in an active coal mine

A successful 4-spot ECBM micro-pilot was conducted in the Velenje coalmine bridging the gap between large field and laboratory. One CO₂-injection well and three observation wells were drilled in the Velenje coalmine to study the behaviour of CO₂ in coal under in situ conditions. The wells were 30m long, cased up to 25m and fitted with plastic liners. The last 5m of the liners were perforated by 8 mm holes at 3-5 cm distance distributed in a spiral form. The effective diameter of each well was 90mm (including the liner). A total amount of 5.7 kg CO₂ was injected in the central injector during seven different pressure steps ranging from 1-12.5 barg. The pressure and production response was monitored in three observation wells, which were drilled 1m above, 3m left and 3m right from the injector (see figure 1.5).

The results were evaluated with numerical modelling (see below).

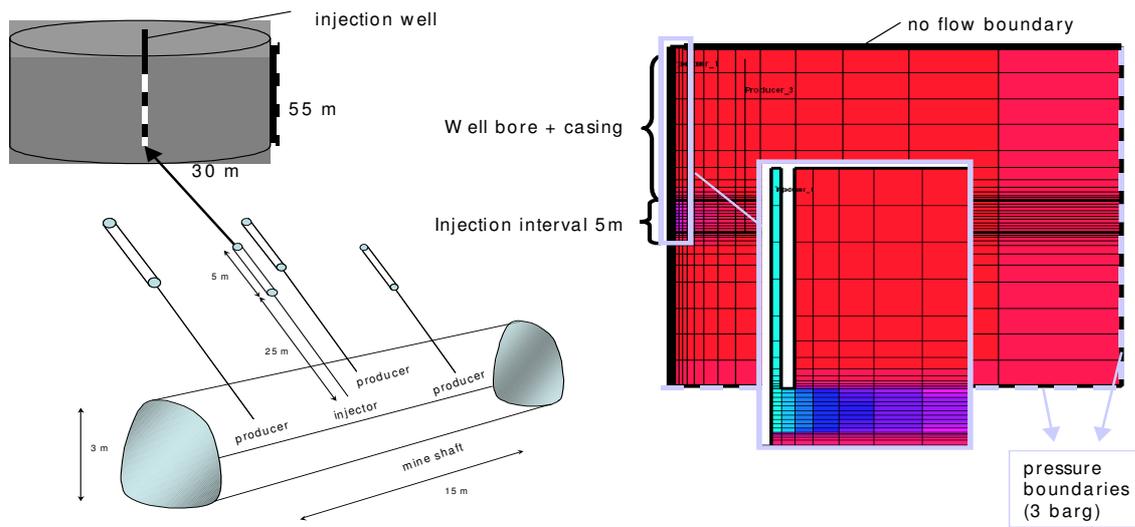


Figure 1.5: Schematic of mine experiment and simulation grid

1.1.4. Numerical modelling of field experiments using the input from the laboratory experiments

1.1.4.1. Model development

A new coal-swelling model (Bustin, 2008)¹ has been implemented in Shell's proprietary reservoir simulator (MoReS). The parameters of the model were based on typical experimental values obtained from the MOVECBM lab work and other data available in the literature. Figure 1.6 shows the swelling model applied to the RECOPOL field. It can be observed that the permeability can drop several orders of magnitudes, when CH₄ is replaced by CO₂. Figure 1.6 also shows the same plot for the Velenje mine experiment. Note that in the Velenje experiment pressures are much lower. In this range we are at the steep part of the Langmuir isotherm, thus sorption dominates the coal swelling. One can observe that the impact of swelling is extreme in the Velenje coal.

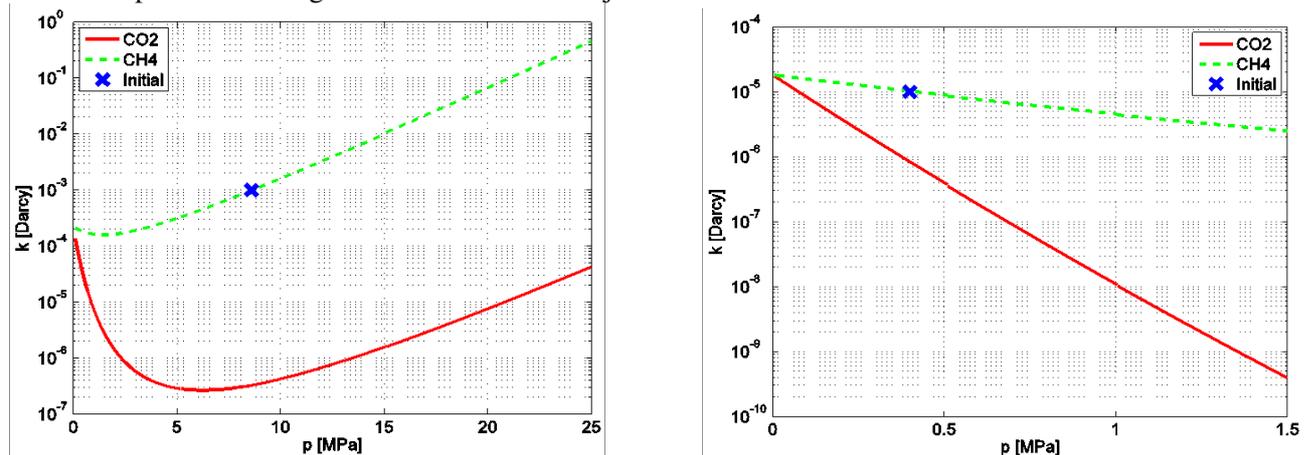


Figure 1.6: (left) Permeability change as a function of pressure (RECOPOL field test). The cross shows the initial reservoir conditions. The dashed line shows the permeability change as a function of CH₄ desorption or adsorption (i.e. a function of pressure). The solid line shows the permeability reduction when all CH₄ is replaced by CO₂. (right) Permeability change as a function of pressure (Velenje mine)

¹ R. M. Bustin and X. Cui and L. Chikatamarla, Impacts of Volumetric Strain on CO₂ Sequestration in Coals and Enhanced CH₄ Recovery, AAPG Bulletin, No. 1 (2008) 92

Additionally, a new model has been developed that couples reservoir simulations with a geo-mechanics code. The model can be used to assess the potential leakage of the stored CO₂ when field data are available to provide the input data required by the model. A CBM reservoir simulator SIMED (Stevenson et al., 1994)¹ is used to simulate the two-phase flow of the injected CO₂ and pore water, the diffusion of CO₂ into the coal matrix, adsorption of CO₂ in the micro- and meso-pores, and the desorption of methane that has been replaced by the more preferentially adsorbed CO₂. The change in effective stress caused by the matrix swelling/shrinkage and changes in reservoir pressure are modelled using a finite element geo-mechanics analysis code FLOWMEC (Choi, unpublished). Permeability is updated based on changes in effective stress. Mechanical failure such as tensile and shear failures can also be modelled. The cubic law is used to model fluid flow in the newly formed fractures.

1.1.4.2. Numerical modelling of field experiment in Poland

A reservoir model was constructed, which represents a triangular area of 1.35 km². Coal swelling was included in the model. Because matrix permeability is very low, there is no matrix/matrix transport. Therefore, a single porosity model proved to be sufficient. The kinetics of the reactions determine the sorption rates and are based on methane desorption from coal cores.

Results show that CO₂-injection rates of the simulation were matched to the field rates. The corresponding bottom hole pressures (BHPs) of the field test and the simulation matched in the period after the frac-job. Figure 1.7 compares the CO₂-injection rates and corresponding BHPs. It can be observed that a good match was obtained. The skin effect around the injector together with the permeability reduction due to swelling could explain the initial low injection rates and slow pressure fall-off after the experiment.

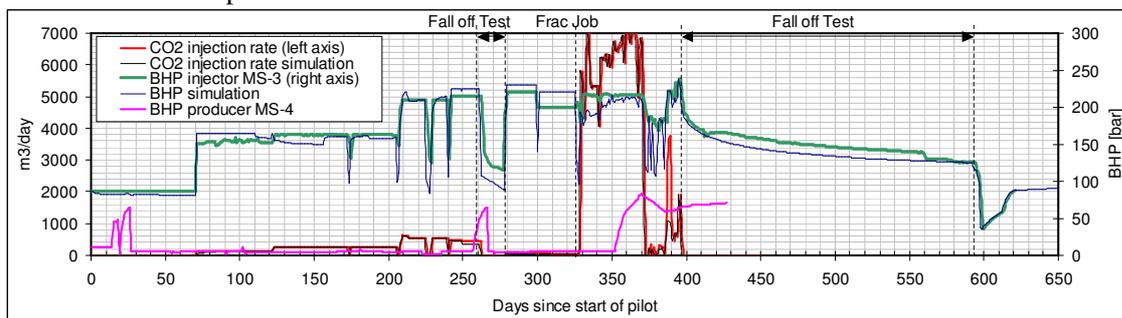


Figure 1.7: CO₂ injection rate and pressure (MS-3); comparison between simulation model and field.

The response of the CO₂-injection on the methane production was observed in the producer MS-4. Two simulations were conducted:

1. without any CO₂ injection to determine the CBM baseline
2. with the CO₂ injection matched to the field rates.

Figure 1.8 shows the production response of the field and the simulations. It can be observed that the response of the simulation is close to the field data. The methane production is clearly enhanced with respect to the CBM baseline, but CO₂ starts to break through very early in the producer too. Field rates are close to the simulated rates. The massive breakthrough of CO₂ after the frac-job and significant methane enhancement can also be observed in the model. The early breakthrough can be explained by the gravity override of the CO₂ in the cleats. Note that to model this effect sufficient grid blocks need to be used in the z-direction, especially in the vicinity of the cap-rock. Vertical grid spacing was typically on cm scale near the cap-rock.

¹ Stevenson, M. D., Pinczewski, W. V., Meaney, K. and L. Paterson, 1994: "Coal Seam Reservoir Simulation"; APEA Journal, V. 34, p. 114-120.

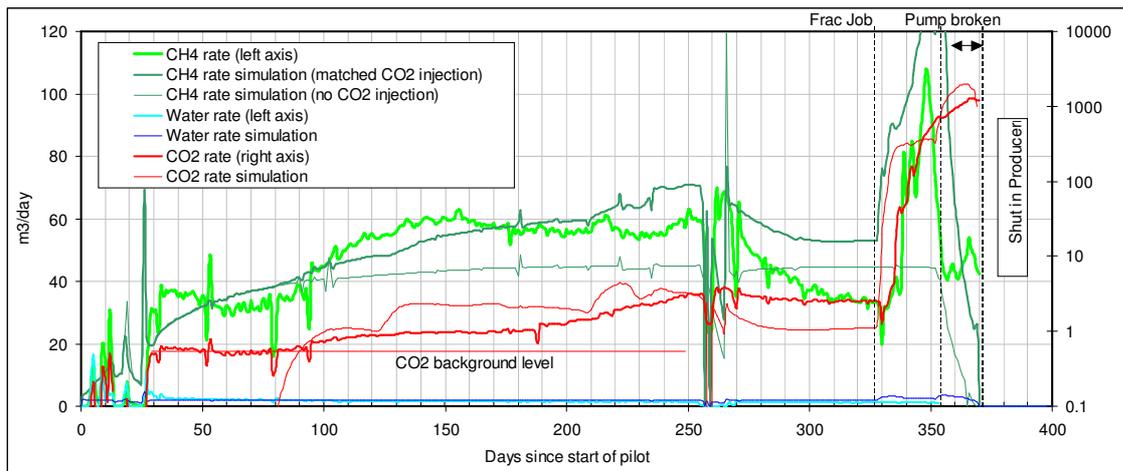


Figure 1.8: Water, CO₂ and CH₄ production (MS-4); a comparison between field data and simulation response.

At the end of the pilot (1000 days) the injector MS-3 was back-produced for 100 days. Very small water rates of 0.01-0.1 m³/day were observed in the field, while the gas production was in the order of 60 m³/day with 70% CO₂ and 30% CH₄ initially. At the end of the field test, the composition had shifted towards 40% CO₂ and 60% CH₄. The simulation could explain the small water production. However, smaller water and gas production rates were observed in the simulation: 0.0001 m³/day and 10 m³/day, respectively. It turned out (figure 1.9) that all the water around the well bore was swept away by the CO₂ and the reduced permeability caused by the coal swelling prevented the water to flow back. The initial CO₂ concentration in the simulation was close to 100% indicating a perfect sweep.

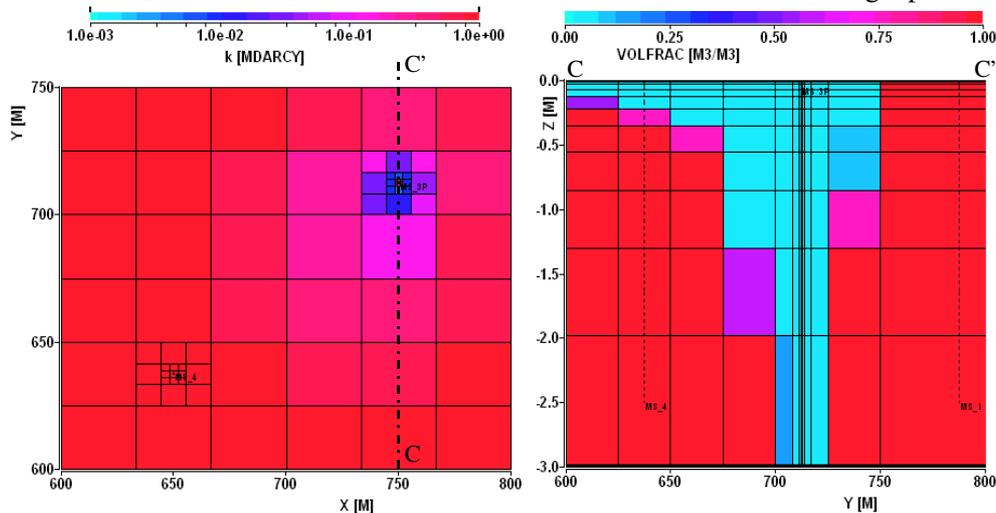


Figure 1.9: Permeability (left) and water saturation (right) at end of the project and or concentrations

The simulation probably over-predicted the CO₂ adsorption around the well bore. This also increased the amount of coal swelling, which explains the lower water and gas rates in the simulation.

Possible explanations for the lower CO₂ and higher CH₄ concentrations observed in the field are:

- an imperfect sweep

- a slower adsorption of CO₂ (kinetic effect)
- a contribution from other coal seams.

These possibilities will be further investigated.

1.1.4.3. Numerical modelling of field experiment in active coal mine in Slovenia

The CO₂ injection was simulated with Shell's reservoir simulator MoReS. For this purpose, a radial grid was constructed consisting out of 20 grid blocks in the radial direction and 36 grid blocks in the z-direction. The grid was refined near the well and further refined near the injection interval. This refinement was necessary to correctly model the permeability reduction near the well bore due to swelling. The CO₂ in the well bore was also modeled by including the well bore and casing in the grid (figure 1.10). A no flow boundary was applied near the mineshaft and two pressure boundaries were applied to the far field (30m from well) both were set to 3 barg, which is equal to the backpressure from the coal-formation observed in the observation wells.

The CO₂ mass-flow into the well was matched to the historic mass-flow of the mine experiment. The corresponding pressure build-up and fall-off were simulated. The permeability was adjusted to match these pressure responses. The following parameters were used for the swelling model: $E = 5$ GPa, $\phi_0 = 0.01$, $\nu = 0.3$, $C_p = 0.3$ MPa⁻¹, $k_0 = 0.01$ mD and $\gamma = 22$ cc/mol. Simulations were also conducted without a swelling and compaction model. A reasonable agreement was found between the simulation with swelling and the experiment (figure 4.2). The pressure steps could be reproduced and the pressure fall-offs have the same magnitude. However, the shapes of the pressure fall-offs differ. If no swelling model is applied, the pressure fall-off is much faster and the curves cannot be matched at all.

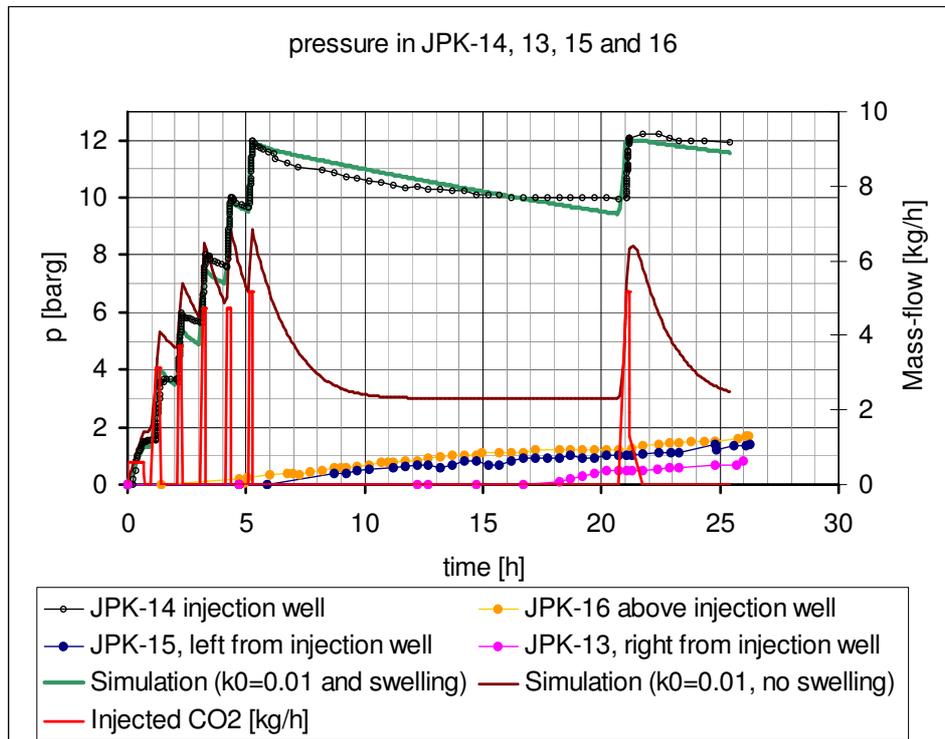


Figure 1.10: Pressures of wells (simulation and experiment) and CO₂ injection rate.

Coal swelling reduced the permeability significantly sealing the well and leaving a pressure of 12 barg on the injector after the experiment. However, weeks after the experiment improved pressure communication between the injector and observation wells was observed indicating that CO₂ injection had created new fractures in the coal. There are several possible explanations for the formation of

these fractures: The CO₂ had dried the coal causing cracks or the stress caused by the adsorption of CO₂ lead to fractures.

The swelling model of Bustin [6] was successfully applied using typical experimental values for coal giving us confidence in the modeling. In this sense, the mine experiment allowed us to bridge the gap between field pilot and lab experiment.

1.1.4.4. Conclusions on numerical modelling

The new reservoir simulations allowed us to better understand the results of the ECBM field test in Poland and the mine experiment in Slovenia.

- The low water production observed in the back-production of the former injector in Poland could be explained by an effective CO₂ sweep that carried away the water during the injection. Furthermore, the reduced permeability caused by coal swelling prevented the water to flow back towards the injector.
- The CO₂ injection test in the Velenje coalmine could be adequately simulated with Shell's simulator MoReS and the permeability reduction was successfully modelled with the swelling model of Bustin. However, the improved pressure communication between the wells, which was observed weeks later, could not be modelled. The modelling of this effect will require the coupling of a geo-mechanical simulator and reservoir simulator, because the creation of fractures depends on the stress fields. In task 1.5, this gap in the current models is addressed.

1.2 WP 2 Monitoring of gas migration in coal resevoirs and assessment on caprock integrity

1.2.1 Objectives

Coal holds an enormous volume of methane and provides a large potential storage medium for CO₂. The complexity of the system makes, however, the implementation of larger scale projects more complicated than other subsurface options, like depleted gas fields. Still, large parts of the world have abundant unminable coal.

In the EC RECOPOL project CO₂ is injected in coal seams in Kaniow (Upper Silesian Coal Basin in Poland). The aim of work package 2 is to monitor the migration of the injected CO₂ in coal and to monitor released CH₄ from the coal. The monitoring is performed to verify if the CO₂ behaves as predicted within accepted boundaries. Therefore also the cap rock over the coal seams will be monitored. A system will be devised, including time-lapse profiling, and varying monitoring techniques. These techniques differ in applied locations and sampling, but together should result in an optimal, dynamic image of the subsurface. The WP also includes the site preparations.

1.2.2 Operations of the field pilot

Several operational periods can be defined during production and injection and between the last injection in June 2005 and the abandonment of the well in October 2007, as represented in Figure 2.1. In this area, coal seams with thicknesses between 1 and 3.5 m occur throughout the entire depth interval in further sand- to claystone dominated sedimentary sequence. Synsedimentary tectonics resulted in faults with a north-south orientation that are expected to be sealing. The pilot site is located on a large block that was upthrust during the Alpine orogeny. The thickness of the overburden in the area is about 250 m, mainly consisting of sealing shale deposits of Miocene age that unconformably and discordantly overly the Carboniferous deposits. The high-volatile bituminous coal (vitrinite reflectance ~ 0.8-0.85 %Rr) varies significantly in maceral composition, but is mainly vitrinite dominated. Permeability is different per individual seam: the upper two seams had a value in the lower range (~ 0.4 – 1.5 mD) of the regional variation (1 – 2 mD), whereas the permeability of the deepest seam was very low (~ 0.01 – 0.05 mD). Reservoir simulations indicated a permeability in the order of 1 mD for matching the water production. Total gas content of the cores was up to 10 m³/ton (dry ash free, i.e., corrected for moisture and mineral content of the coal), with CH₄ concentrations of usually 95 % or higher, with some percentages of N₂ (0.5-3 %) and CO₂ (1-3 %) and traces of other gases. Desorption tests, however, took several months and showed very slow diffusion out of the coal matrix.

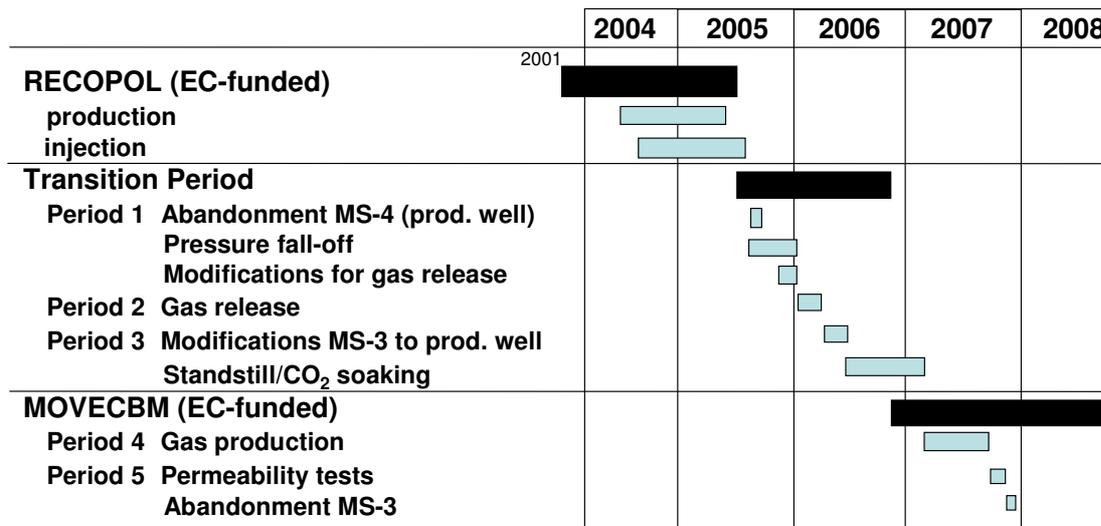


Figure 2.1 Overview of the main operational activities in the period of 2004-2008.

An existing coalbed methane well, remnant of CBM exploration and production activities undertaken in the 1990's, was cleaned up, repaired and put back into production in May 2004 to establish a baseline production. A new injection well (the MS-3 well) was drilled 150 m away from the production well (the MS-4 well). Initial injection of CO₂ took place in August 2004 in three seams in the depth interval between 1000 and 1100 m. Several actions were taken to establish continuous injection. This appeared not to be possible because the injectivity was decreasing in time, probably due to swelling of the coal. Continuous injection was eventually reached in April 2005 after stimulation of the reservoir by a hydraulic fracture treatment. In May 2005, approximately 12-15 tons per day were injected in continuous operations. About 760 tons of CO₂ have been injected into the reservoir from August 2004 to June 2005. Breakthrough of the injected CO₂ was established, which resulted in the production of about 10% of the injected CO₂ by the production well in this period. As such, a total of 692 tons of CO₂ were stored in the reservoir. The results of the gas production showed that, although the recovery of methane was still low, the production of methane increased significantly compared to baseline production due to the injection activities.

Injection was stopped on June 28, 2005 because of the end of the project funding for field operations. The well was shut-in during Period 1 for observation of the pressure fall-off. From the beginning of November 2005 modifications on the field equipment were made in order to be able to decrease the pressure at the wellhead (aim of period 2). Several tests were undertaken in this period, often followed by modifications to the equipment, until January 11, 2006 (start of period 2). Unfortunately, no permeability could be derived from the curve. However, the slow pressure decline indicated of permeability reduction due to swelling. In period 2 the pressure on the MS-3 well was lowered through gas release. Pressure, temperature, gas production and composition were measured during the gas release. During the gas release, the water in the well was rising as a result of continuous inflow of water during the shut-in period, although at declining rates. The stabilization pressure of the reservoir was estimated to be in between 6.0 to 8.0 MPa, which approaches the original reservoir pressure in August 2004 of about 8.5 MPa, before injection activities were undertaken. This implies that the reservoir is returning back to hydrostatic conditions. When the well was depressurized on January 16, 2006 the gas production rates were rapidly declining to about 30-40 m³ per day. The production rates were declining as the water is rising in the well, thereby hampering further gas release. The reservoir gas composition showed a concentration of about 40% CH₄ and 60% CO₂. The CH₄ concentration appears to increase very slowly. During the gas release in this period 1322 m³, or 2.5-3.0 tons CO₂ were produced back from the reservoir. Gas production ceased with the shut-in of the well in March 2007 when production rates were low and declining. During Period 3 the injection tubing and packer were retrieved from the MS-3 well and the production tubing and pump string were installed. In June

2006 a pump jacket was installed on the MS-3 well, enabling active water pumping and thereby gas production from the coal (Figure 2.2).



Figure 2.2 Picture showing the conversion of MS-3 well from injector (left) to producer (right)

Period 4 started in March 2007 with pumping of water and gas from the MS-3 well, one year after the shut-in. Both water and gas production rates were very low (70 m^3 per day for gas, $< 0.10 \text{ m}^3$ per day for water) and declining over the production time. The gas composition showed a predominance of CO_2 over CH_4 during the gas release that changed gradually into a predominance of CH_4 over CO_2 during the production phase (60% CH_4 , 40% CO_2). The cumulative amount of CH_4 and CO_2 produced in this period are 4134 m^3 and 4157 m^3 (~8 tons), respectively. The composition of the original reservoir water was highly saline. After injection of the CO_2 the pH decreased slightly from about 6.5 to a value of about 6 while the bicarbonate concentration was increasing, up to 400 mg/l in May 2005 indicating that the CO_2 was dissolving into the water. In the first phase of the active production the water shows a high bicarbonate concentration of more than 3000 mg/l, about 50 times higher than the background value (~ 50-70 mg/l) and more than 7 times higher than measured in the production water of the MS-4 well in May 2005. Clearly, some of the CO_2 has dissolved into the water. The drop in pH is, however, not so dramatic which shows the buffering capacity of the highly saline water. The dissolution of minerals into the water as a result of the lower pH seems to have been limited, as there is no pronounced increase of calcium or magnesium concentrations. During the abandonment phase (Period 5) several tests were performed that confirmed that the perforations in the well were still open. The MS-3 well was finally abandoned in November 2007.

Considering the storage of CO_2 in the reservoir it can be concluded that the experiment has been very successful. CO_2 injection rates of ~ 15 tonnes per day were reached. The mass balance of the injected and produced CO_2 shows that the total volume of CO_2 produced was only a fraction of the amount that was injected (Figure 2.3). Alternative explanations of the fate of the injected CO_2 have also been considered. Migration of CO_2 into overlying sandstones would have resulted in a higher volume of produced CO_2 when the pressure in the well was lowered. Migration into the overburden is considered unlikely, given the sequence of Pennsylvanian sediments in the overburden with shales and tight sandstones. A monitoring program was set-up around the injection site, including soil gas sensors and measurements in a nearby coal mine. The soil gas monitoring did not indicate any changes out of the ordinary in CO_2 concentrations, fluxes or isotope signature. The mine was positioned on the opposite side of the western bounding fault of the tectonic block where the site is located. Analyses of gas samples taken in the mine showed changes in the isotopic signature but this change was definitely inconclusive with regard to CO_2 migration through the fault because of other influencing factors in the mine. It can be concluded that the CO_2 was taken up by the coal and is currently adsorbed, unless some of the CO_2 has migrated into the overburden. However, this migration is considered unlikely, given that the pressure in the well went back to hydrostatic conditions and because the monitoring of the site did not give any indication of migrated CO_2 . The CO_2 is strongly fixed to the coal, as pressure release by water production did not result in release of the CO_2 . The release of pressure in the reservoir

probably added to the fixation by closing of pores. Also, coal swelling due to the adsorption of CO₂ may have eventually sealed the coal matrix. This result gives confidence in the long-term stability of the injected CO₂.

CO₂ mass balance over project lifetime	
• Injected:	760 [t]
• Produced during injection, mainly after the frac job	68 [t]
• Produced during first phase of back-production	2-3 [t]
• Produced during second phase of of back-production:	8 [t]
• Stored/fixated in the reservoir:	682 [t]
• about 90% of injected CO₂	

Figure 2.3 Mass balance of the injected CO₂

Also, the enhancement effect on the methane production has been shown during the injection phase. An increase in production of ca. 55 - 70% was obtained compared to estimated baseline conventional production. It was expected that the adsorption of CO₂ into the coal would be associated with release of more CH₄ than was currently observed from the production because of the higher affinity of coal for CO₂. This is the process that is generally considered to be responsible for the enhancement of the gas production in ECBM operations. Instead, the actual results showed a slow stabilization of the composition of the gas, with 40% CO₂ and 60% CH₄ at low production rates.

A lot of knowledge has been gained in the understanding of the processes that are taking place in the reservoir, especially related to coal swelling. Coal swelling occurred before the hydraulic fracture treatment was executed but also afterwards during periods where the continuous injection was temporarily stopped. Part of the permeability could be recovered once continuous injection was established. The slow fall-off curve of the first period in the post-injection period also indicated a low permeability due to swelling of the coal. The rate of water inflow in the MS-3 well during the production period (Period 4) was much lower than could be expected, even considering the low production rates of water in the MS-4 well. This could be explained by the low permeability as a result of the swelling, but history matching showed that a sweep of the water by the injected CO₂ is more probable [3]. The resulting composition of the gas after a 1 year soaking period, 60% CH₄ and 40% CO₂, could not be readily explained. These results suggest that while significant amounts of CO₂ are able to diffuse into the coal, there is hardly any diffusion of CH₄ out of the coal. The often reported exchange ratio of 2 molecules of CO₂ for 1 molecule of CH₄ could not be confirmed in this study and is considered as too simplistic under field conditions. The gas transport in the matrix is considered a crucial factor for the performance of the operations. In first instance, this requires that the matrix blocks come in contact with the injected CO₂. It seems likely that the presence of water in the coal during the injection prevented good contact with the matrix blocks, as there was probably a bypassing due to a gravity override of the CO₂ on top of the water phase [4]; Also, bypassing is expected when the diffusion kinetics are much slower than the flow in the cleats which may cause an early breakthrough even in dewatered coals (Figure 2.4).

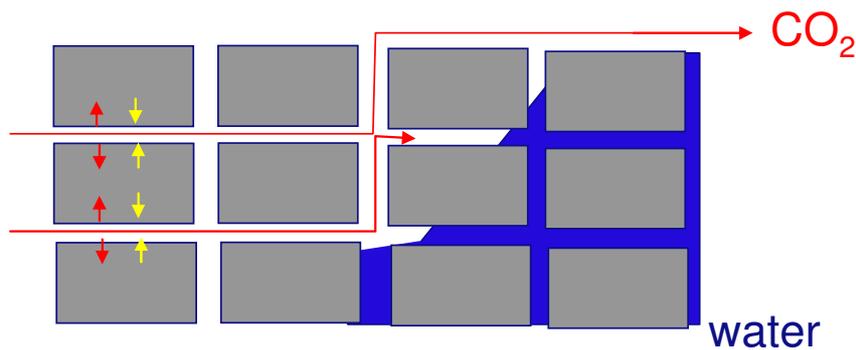


Figure 2.4 Schematic picture of part of the coal seam, representing a view on the face cleat surface. Because the transport time for the CO_2 in the cleats is much faster than the transport of the matrix, much of the CO_2 can already pass the matrix before the CBM can be released. Also, gravity override can occur if the cleats are still filled with water.

The field experiment in Poland has confirmed earlier observations from other field tests that the coal-water- CO_2 system is complex. It must be emphasized that only a limited number of field experiments have been realized today under different geological and operational conditions and the technology is still far from mature. Further, it is recognized that the heterogeneity in composition, transport properties and geometry in individual coal seams makes every coal basin unique. Extrapolation of experimental results from the Upper Silesian Coal Basin to other basins is difficult and dedicated field studies are mandatory to comprehend the processes between the coal and the CO_2 under local conditions. A lot has been learned, especially considering the coal swelling under field conditions.

The injected CO_2 is stored in the coal, the larger volume presumably being adsorbed on the coal. The CO_2 is fixated, since it is difficult to produce it back even when the pressure is reduced by pumping. This gives confidence in the long-term stability of the injected CO_2 .

The volumes that can be injected in low permeability coal seams ($< 2\text{mD}$) by a vertical well is likely to be less than 100 ton per day (depending on well completion, cumulative coal thickness, etc.), or about 30,000 ton per well per year.

It can be expected that the CBM production will be 1.5 to 2 times higher because of the interaction with the CO_2 . It is recommended to perform ECBM operations as a secondary production phase after an initial CBM production phase. This way, the CO_2 can be injected in dewatered coal seams.

1.2.3 Seismic monitoring

Production and/or injection of gas, oil or water affect the subsurface in several ways. Obviously, the bulk density and seismic velocities of strata are modified, whereas micro seismicity could be induced. From the Gassman equation (Gassman, 1951) it is known that only a few percent of change in the gas saturation can significantly alter the seismic velocity of rock volumes. Changes in density and velocity due to injected fluids will therefore affect the amplitude and travel times of seismic waves.

Two classical partially multi-component seismic surveys were performed at the pilot site in time-lapse. Besides monitoring the subsurface, the second purpose of the active survey was to provide data to aid the processing and interpretation of the passive seismic survey. The first active seismic survey was performed before reproduction of the injected CO_2 in April 2007, and a second survey was executed during the reproduction in August 2007 (Figure 2.5 a & b). Time lapse processing of the seismic data (Figure 2.5 c) comprised correcting for various factors caused by changes in acquisition parameters (e.g. geometry and equipment) and field conditions (e.g. groundwater table variations).

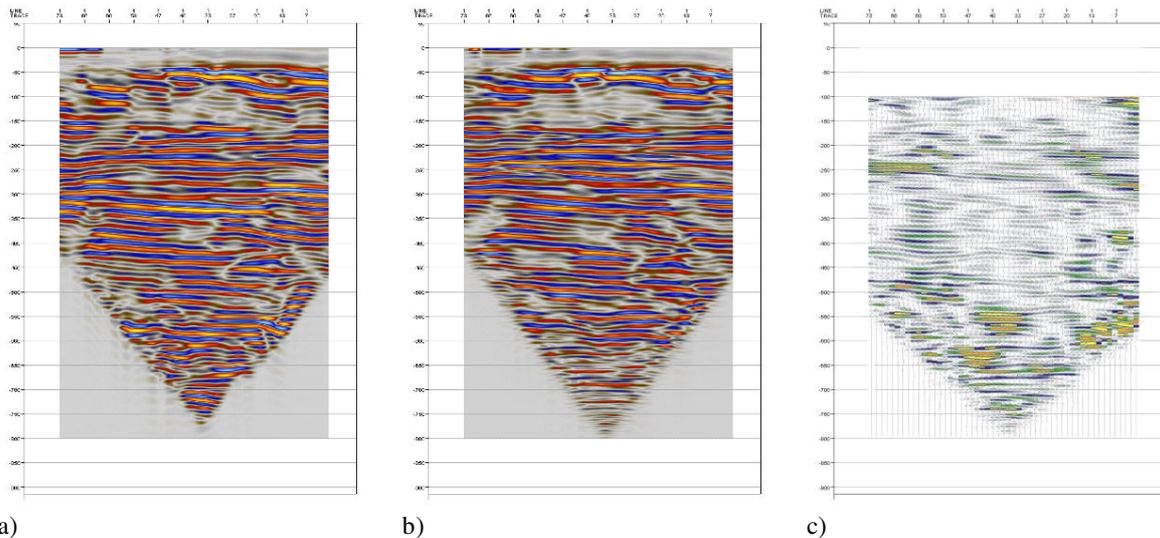


Figure 2.5: a) & b) are stacks and recorded respectively in April 2007 and August 2007. c) represents the difference panel of the stacks. The zone where the CO₂ has been injected, and reproduction is taking place from is located between 650 and 700 ms TWT. The horizontal distance is about 100 m, which was due to access restriction in the field.

The differences identifiable on Figure 2.5 c) can not simply be interpreted as being caused by the CO₂ injection or reproduction. Due to restricted field access the seismic survey was confined to a small zone. The short offsets caused generally inferior data with strong noise bursts on the edges of the data. Therefore, the data and its difference seems to be less reliable near the edges.

Also a passive seismic survey was tested. This can be used to identify and, if present, locate the development of micro-fractures in the subsurface due to the production of gas and water. Communication with the recording equipment was enabled via a satellite uplink. This provided the possibility of direct quality control and of improving data quality by enabling tuning of certain acquisition parameters (e.g. gain and sampling interval) in real time without the need for human presence at the location. In this way the possibility was created to diagnose and reinitialize parts of the system remotely. Throughout the monitoring phase the passive seismic monitoring system performed well with regard to reliability and environmental impact.

1.2.4 CO₂- cap rock interactions near in-situ conditions

Seven samples representing potential cap rocks have been selected to be subject to investigation of CO₂-rock interaction. In order to obtain more general and locally independent insights, the samples from different areas revealing varying lithologies have been considered. The samples “Emscher” and “EST 25593” represent marls; the sample “L930” is a dolomitic marl, whereas “D5” represents a carbonate. The three remaining samples can be characterized as shales. The “Kaniov”-shale represents the potential cap rock from the RECOPOL/MOVECBM storage site. The samples are listed in Table 2.1.

Sample	Depth [m]	Basin	Formation	Lithology	Age
Emscher	128	Münster Basin, Germany	Emscher	Marl	Upper Cretaceous (Coniac)
EST 25593		Bure, France		Marl	Jurassic
D5	813	Münster Basin, Germany	Emscher	Carbonate	Upper Cretaceous (Turon)
L 903	930	Officer Basin, Australia	Hussar	Dolomitic marl	Neoproterocoic (Cryogenic)
L 1114	1114	Officer Basin, Australia	Hussar	Shale	Neoproterocoic (Cryogenic)
Kaniov	1025	Upper Silesian Basin		Shale	Upper Carboniferous
S08		North Sea		Shale	Mesozoic

Table 2.1. Information on the investigated sample set.

Major goal of the study was to determine the mineralogical and petrophysical impact of supercritical CO₂ on the samples. In order to achieve intense fluid-rock interaction, all samples have been subject to CO₂ diffusion and/or breakthrough experiments under *in-situ* conditions. Additionally sample “L1114” has been subject to a CO₂ sorption experiment. Table 2.2 reveals absolute permeabilities of the samples investigated, prior and after CO₂-interaction. All samples exhibit absolute permeabilities significantly below 100 nD (10⁻¹⁹ m²), thus revealing their high potential to act as effective cap rocks. The “Kaniov”-shale from the RECOPOL/MOVECBM storage site is characterized by the lowest permeabilities (0.1 to 0.7 nD) followed by the Australian samples “L930” and “L1114”. Considering the samples whose permeabilities have been measured prior and after CO₂-interaction, absolute permeabilities after CO₂-treatment are increasing, except for sample “L1114”.

Sample	Applied Method	Abs. k [nD] prior to CO ₂ -interaction	Abs. k [nD] after CO ₂ -interaction
Emscher	pB	34	43
EST 25593	pB	4	
D5	pD	7	12
L 930	pD	0.5	
L 1114	pD	2.2	1.3
Kaniov	pD	0.1	0.7
S08	pD	9.3	

Table 2.2. Absolute (H₂O) permeabilities prior to and after CO₂ interaction: “pB”=after gas breakthrough test; “pD”=after gas diffusion test

Regarding the interaction experiments, both, “Emscher” and “L1114” samples have been treated by multiple induced CO₂ interaction processes. It has to be noted that each of these treatments have been performed on raw sample material and not sequentially. Based on the reaction characteristics, the sample set can be separated into two groups: virtually inert and reactive ones. The samples “EST 25593”, “D5”, “L903”, and “L1114” revealed to be inert, i.e. the mineralogical composition of those samples exhibited no significant response with respect to CO₂-water-rock interactions. Differently, samples “Emscher”, “Kaniov” and “S08” experienced highly significant mineralogical alterations.

Among the reactive samples, three reaction schemes have been observed:

1. The “Emscher” sample revealed a loss of anorthite, acting as a Ca-source whereas calcite and quartz contents increased.
2. The “Kaniov” sample exhibited consumption of Kaolinite while Muscovite and Quartz were generated.
3. Although the “S08” sample represented a Kaolinite-Muscovite-Quartz shale prior to CO₂ treatment, similar to the composition of the “Kaniov” shale, the “S08” sample revealed a reversed reaction scheme compared to the latter sample (figure 2.6).

The fundamental difference between the experimental setups of both samples is that the “Kaniov” plug has been saturated with brine, whereas the “S08” plug was saturated with tap water. The chemical constitution of the brine represents a potential potassium source required for the generation of muscovite, observed in the “Kaniov” sample. Roughly, the observed reaction schemes fit into known models. It has to be noted that the mineral alteration took place on a very short time scale (30-70) days, indicating that cap rocks at operating storage sites may be subject to significant alterations. However, regarding the low absolute permeabilities prior and after CO₂ interaction (< 1 nD), it is evident that significant mineral alteration do not inevitably deteriorate the sealing integrity of a cap rock.

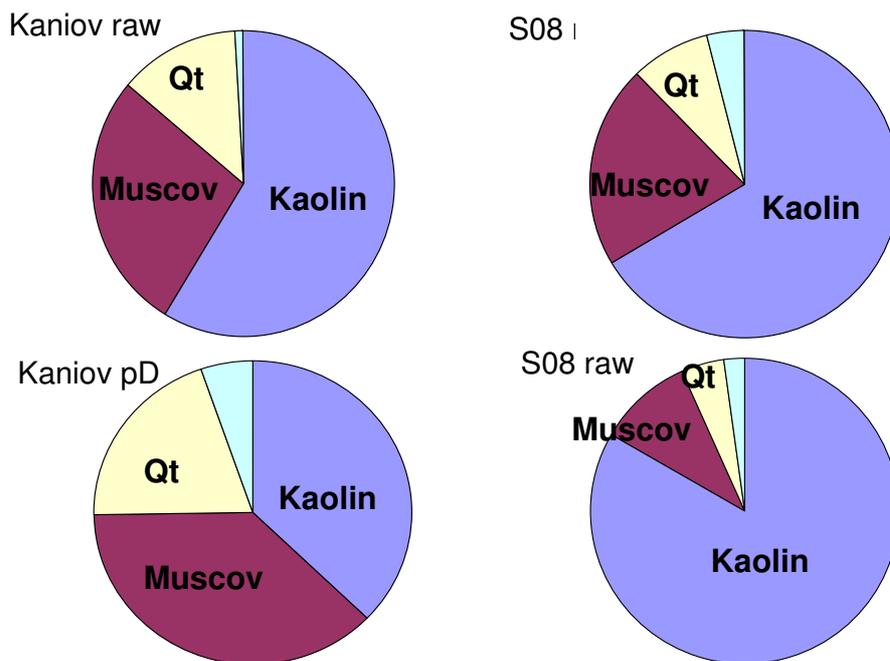


Figure 2.6. Mineral composition of the “Kaniov” and “S08” samples prior (raw) and after (pD, “post diffusion”) CO₂ interaction.

1.3 WP 3 Wellbore integrity

1.3.1 Objectives

The objective of this work package was to better understand the well material degradation mechanisms and how to monitor them by sensor systems, for proper risk analysis and identification of remedial actions. For that purpose, laboratory characterization, in-situ measurements and modelling studies were conducted in parallel.

The properties and behaviour of the reservoir seal (onshore and offshore) are critical for the long-term safety of CO₂ storage systems. Man-made features that penetrate the natural seal, such as wells, could introduce preferential leakage paths to shallower formations, for instance potable aquifers, or even to the surface. These paths have to be avoided. The important mechanisms or features that could potentially lead to upward migration or leakage are:

- Defects at the interfaces between casing and cement, or between the formation and the cement.
- Long-term deterioration of cement plugs and sheath by wet CO₂ under in-situ conditions (post-abandonment), which could lead to changes in cement properties (i.e. permeability).

The above two mechanisms would increase the casing exposure to CO₂ and corrosion will be accelerated. Based on this analysis, the activities in WP 3 Wellbore integrity pursued three complementary directions:

- Assessment of the completion integrity and its monitoring versus time.
- Modelling of the completion deterioration versus time and the evaluation of leakage rates.
- Characterization of completion materials (cement and casing) under down-hole conditions.

1.3.2 Assessment and monitoring of the completion integrity through time-lapse logging

In principle, the integrity of a well is determined by three layers: steel casing, cement and near wellbore. In order to evaluate the status of the MS-3 CO₂ injection well at Kaniow, its steel casing and cement sheath were investigated in detail during the well abandonment stage. In addition, changes observed between two time-lapse logging runs were analysed.

The MS-3 well was logged a first time on May 26, 2006 using UCI (high-resolution ultrasonic steel corrosion evaluation), Isolation Scanner (IS, ultrasonic steel and cement evaluation) and CBL-VDL (sonic cement evaluation). A second logging session was carried out on October 20, 2007 (i.e. 512 days later) again using the UCI and Isolation Scanner.

The Isolation Scanner provided maps of acoustic impedance (Z) and flexural attenuation (α) with a resolution of 10° and 1.5 inches (approx. 15.5 mm around the azimuth and 38.1 mm along the depth of the well). It also provided a measured wavespeed in the annular medium at each depth – see [1] for further details on the measures. Z and α were independently verified for consistency with each other and against their expected value at the top of cement, at 15.5 m. Therefore they are not likely to show any significant bias when comparing both runs.

The log interpretation revealed interesting changes during the 17 months between runs. First, the data were reliable, with good repeatability and consistent response between sonic (CBL) and ultrasonic (IS) analysis (Figure 3.1, right plot). Secondly, the casing shows a uniform, slight (0.4%) increase in thickness, well below the posted tool precision (Figure 3.1, left plot). This is probably because of two

favourable conditions in the well, which was exposed to either dry CO₂ or water with low CO₂ content (because of extremely slow release from the formation). A passivating siderite layer may have also reduced corrosion rates to levels below the detectable limit. The negligible increase in thickness may be an artefact caused by the increased acoustic impedance and the presence of a fluid-filled micro-annulus. The logs show no evidence of pitting. Furthermore, the logs suggest superficial cement carbonation along the whole well: the carbonation was probably caused by a ballooning fluid-filled micro-annulus, in turn caused by the high injection pressure. The evidence also confirms that the micro-annulus shrank back in size after the end of injection and that coal creeping/swelling provides a good hydraulic seal. Finally, cement bonding across the coal seams is markedly better, resulting in higher (+30%) apparent acoustic impedance matching the gamma ray log.

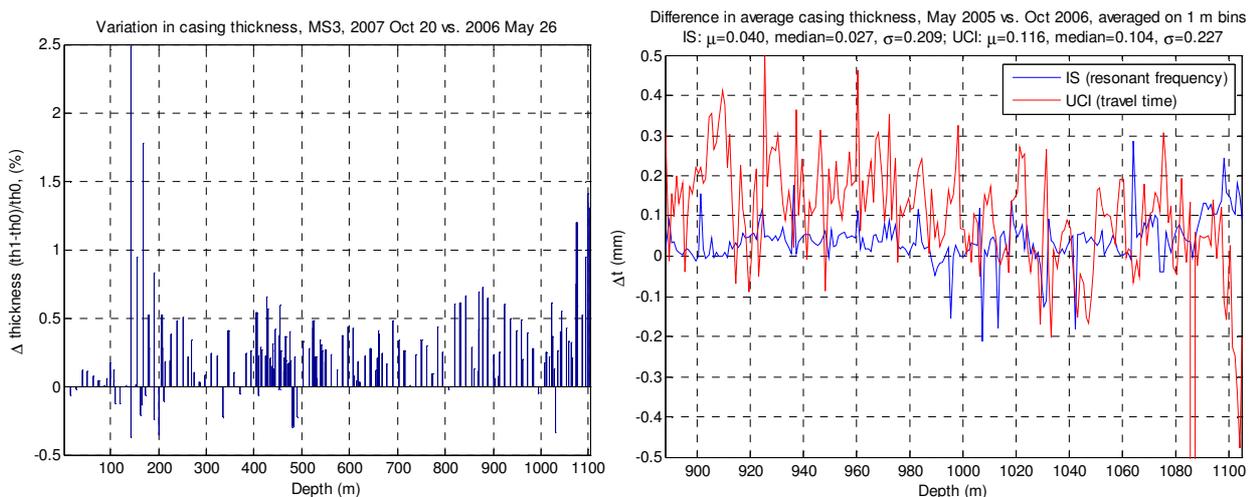


Figure 3.1 Distribution of casing percent thickness changes between logging runs measured by the IS and averaged at each casing joint (left plot), and comparison of IS and UCI absolute thickness changes for a section at the bottom of the well (right plot).

1.3.3 Completion integrity modelling

A report was prepared by EPS to recommend the best way to model the mechanical behaviour of the coal seams. This is necessary to predict the failure mode of the cement sheath when exposed to changes in temperature or pressure (such as cold fluid injection or overpressuring).

The impact of coal poromechanical behaviour (elastic properties, sorption-induced strain) was reviewed in the report in the context of well integrity for CO₂ storage in coal-beds. Mechanical coal properties gathered from the existing literature were briefly listed and the integrity of the cement sheath in front of a coal reservoir was then investigated in the case of the injection of a cooler fluid (i.e. CO₂).

The coal swelling induced by the adsorption of CO₂ in the coal matrix appears beneficial with respect to well integrity: coal swelling tends to close any micro-annuli that may exist or appear either at the cement-casing and/or cement-coal interfaces. The report details the constitutive laws and constants that should be implemented in a software module to predict completion mechanical integrity. It was chosen to publish the detailed technical specifications instead of providing a code to improve legibility and portability.

1.3.4 Performance and risk analysis

The objectives of a risk assessment study (performed by OXAND) are, on the basis of the available data: (i) to evaluate the performance of well integrity and identify risks and quantify their associated criticality values and (ii) to treat the risks by selecting one or more options for decreasing risks and implementing them. Quantification of criticality values requires evaluating the two components of the risk: the probability of a hazardous event to occur, and the severity of this event.

At the beginning of a study, all data relevant to well integrity (e.g. drilling report, cement logs, description of geology) are collected and interpreted. Data help to characterize the geometry and properties of well components (casing, cement) and of the wellbore for later modeling of the well system. The methodology is based on a systemic approach to the well. Practically, this means that well integrity performance is assessed according to the possibility that a function performed by the well (confinement of injected CO₂ in this study) will fail. The functional analysis is required to identify the contribution of each well component to the function, and how this function could be defeated (i.e. what could lead CO₂ to leak to the surface).

For a given well, interpreted data are used to build the static model describing the system (Figure 3.2):

- Geology (input for characterizing the wellbore environment): type, depth and mechanical properties of geological formations;
- Casings: material, diameters, thickness, overlaps, shoe depths, centralization in the bore hole;
- Cement sheaths: thickness, rathole length, conditions (e.g. zones of free pipe, microannulus), vertical and horizontal permeability values.
- These data are then implemented into the numerical leakage simulator SIMEO™-STOR, and completed by data relative to the dynamic model:
- Degradation processes and properties: kinetics and impact of corrosion, cement leaching and/or carbonation;
- Defining the initial and limit conditions applied to the static model: pressure and temperature profiles along the wellbore with time; flow condition between cement sheaths and geological formations (i.e. possibility for the injected CO₂ to migrate from the well to geological formations)

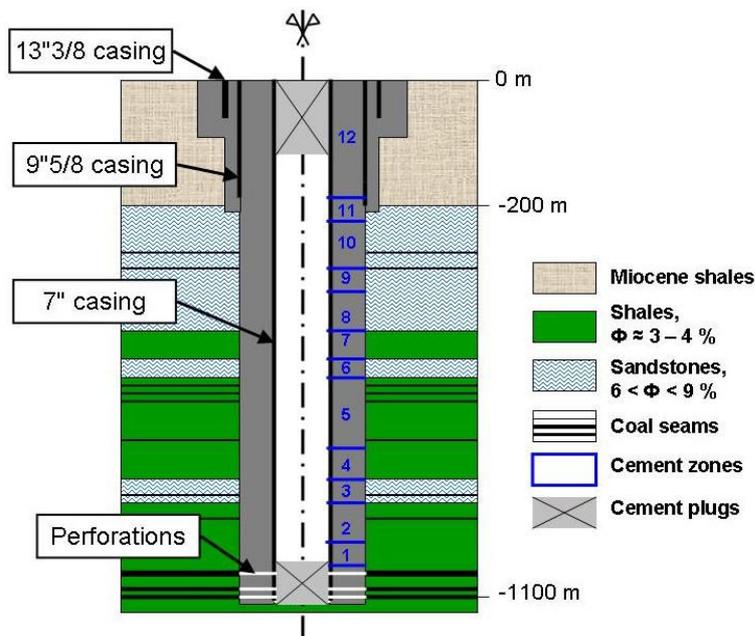


Figure 3.2 Graphic representation of the MS-3 well with all cement zones defined for calculations.

Both static and dynamic models take into account parameters' uncertainty (like uncertainty associated to cement permeability, to degradation mechanisms, to initial and limit condition, etc.) by the use of probabilistic distribution laws.

The next step consists in building different probabilistic scenarios issued from the dynamic model. These scenarios describe specific geometrical and mechanical hypothetical states of the well for the simulations (during injection and/or abandonment phases). Depending on the probabilistic distribution laws that describe each parameter, the probability of occurrence of each scenario can therefore be assessed.

Each scenario is then simulated over the given period (1000 years in this study), using a coupled model (a two-phase flow model and ageing degradation model). One output of the model is the CO₂ leakage mass (expected nil if well integrity is efficient to avoid any CO₂ migration to the surface or to shallow aquifers). For each scenario that corresponds to a well integrity failure (i.e. a scenario for which a CO₂ leakage is not nil), the leaked mass obtained is converted into a severity level according to the consequence grid. The combination of this severity level and of a scenario's probability allows quantifying the risk level or "criticity value".

After simulations, a risk mapping is built from the criticity values of all scenarios. From this risk mapping, specific recommendations can be proposed that contribute in ensuring that the overall risk level remains acceptable. The acceptable level is defined by the operator based on the stakes associated to the project. Within the MOVECBM project, criticity values were not assessed. Recommendations are thus based on the estimation of CO₂ leakage mass.

MS-3 well integrity from CO₂ leakage issues was modeled for a period of 1000 years after abandonment. In this study, a total of 50 scenarios were defined that represent 'most likely' CO₂ leaks (parameters set to values most relevant to the current well), and the impact of some parameters was quantified via a sensitivity study. For the sensitivity study the parameters considered were associated to (i) storage conditions, (ii) well geometry (e.g. cement permeability, micro annulus) (iii) degradation mechanisms associated to the presence of CO₂ (e.g. corrosion, cement degradation) and due to the well environment. As an example of the results of the simulations, Figure 3.3 presents, for a scenario, the cumulated mass of CO₂ that leaks at the surface over time.

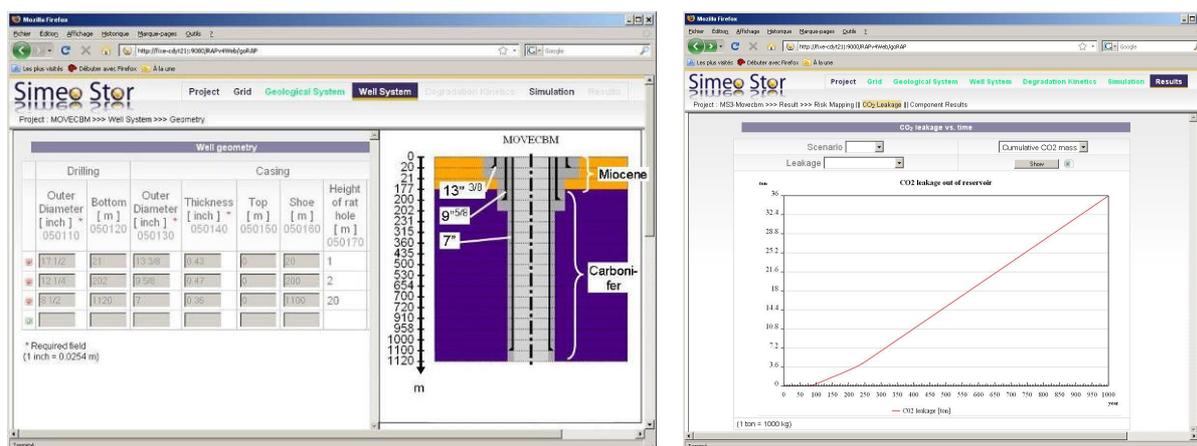


Figure 3.3 System boundaries and cement segmentation for the system description of the MS-3 well (left picture) and example of CO₂ mass leakage out of reservoir vs. time for one of the scenarios (right picture). Pictures are extracted from Simeo™ Stor.

For all scenarios, the cumulated CO₂ mass released within the abandonment period remains relatively low compared to the actual CO₂ mass that was injected. This efficient confinement of the CO₂ is explained, among other things, by low reservoir pressure during storage, and the overall good quality

of the cement sheath (low permeability values, even in the presence of a thin microannulus). Permeability of cement zones of greater quality (lower permeability) has a great impact on gas migration (i.e., decrease of the mass of released CO₂) compared to cement zones of lower quality, even small zone of great quality cement.

To complete these results, the sensitivity study however highlighted some parameters that could favor CO₂ leakages: (1) greater leakages are associated with scenarios where cement permeability was assumed to be the greater, as well as reservoir pressure; (2) the development of microannulus with time creates preferential pathways from the reservoir to the surface favors upward migration of the CO₂ within the wellbore, (3) particularly if degradation kinetics are fast.

1.3.5 Cement analysis

EPS (Schlumberger) performed lab measurements to characterize mechanical and petrophysical properties of the cement used in the Kaniow MS-3 well. For this purpose, the cement slurry (mixed using fresh water and cement powder samples from the wellsite) had to be optimized to reduce settling, which would have caused unacceptable vertical variation in set cement properties. The cement was then cured in an Ultrasonic Cement Analyzer – a device that monitors compressional wavespeed during setting. This variable is related to the elastic constants of cement (Young's modulus and Poisson's coefficient) and – to a lesser extent – the strength of the material, which is normally characterized by the Unconfined Compressive Strength. The cement reached a final speed of just over 3,000 m/s, consistent with similar formulations (5% inerts by volume of blend and 0.5 water-cement ratio).

Separately, cement samples will be cured at 40°C for 12 days, then cored and exposed to wet supercritical CO₂ for 3 weeks. A series of characterization measures will then be performed (SEM-EDS, XRD, TGA, UCS and scratch tests) to compare its performance to neat class G Portland cement, which has been extensively characterized over the past years. At the time of writing the results of CO₂ exposure were not available yet, due to a late arrival of cement samples.

1.3.6 Casing integrity

Despite a large research effort on CO₂ corrosion, the electrochemical degradation mechanism of steel is still uncertain. Addition of complicating factors like protective surface films on steel, the use of corrosion inhibitors, changes in pressure and temperature, composition of formation waters, steel type, the corrosion history of the casing material and the presence of Portland cement, increases the complexity of the degradation phenomena and monitoring methods.

TNO performed an experimental study under high pressure CO₂ conditions using several electrochemical techniques: Open Circuit Potential (OCP) monitoring, Linear Polarization Resistance (LPR), Electrochemical Impedance Spectroscopy (EIS) and Electrochemical Noise Measurements (ECNM). The aim of this study was to investigate the usefulness of these electrochemical methods for monitoring the corrosion under CO₂ storage conditions. For this purpose, a custom-made high pressure thermostated electrochemical cell was made (Figure 3.4) which allowed to in-situ monitor the corrosion of the casing steel materials (API N80 and J55 steel) in an electrolyte with similar composition as the formation water of the well, under pressurized CO₂ conditions (80 bar CO₂ @ 45°C). Using this configuration, several 5 to 10 day duration tests were performed.



Figure 3.4 Electrochemical cell used for the corrosion experiments.

After the duration tests the samples were examined using Scanning Electron Microscopy (SEM) and Surface profilometry. The corrosion products in the electrolyte were analyzed using inductively coupled plasma (ICP) measurements.

The experiments show that there is strong variation in the observed corrosion mechanism after the CO₂ exposure time in the HPT set-up. Some samples showed “uniform” corrosion, others were passivated due to the formation of ferrous carbonate (siderite) layer on the surface.

The observed corrosion phenomena correlate well with those observed at the surface of the tubing material (N80 steel) which was field tested in the CO₂ storage facility of MovECBM in Poland for approximately one year. Precipitation of FeCO₃ results in the formation of a partial siderite film that may impede continuous corrosion. In addition, the observed development of blisters is probably associated with the release of hydrogen gas at the steel surface beneath the siderite layer. Corrosion of the inner tubing steel has effectively been linked to the water level in the tubing during operations.

The results obtained from the electrochemical monitoring techniques can be summarized as followed. Open-circuit potential (OCP) measurements is a very simple tool which can be used to distinguish between the two observed corrosion mechanisms but is not useful to determine the corrosion rate. The results from electrochemical noise measurements (ECNM) are difficult to analyze; however, the ECNM current noise and voltage noise graphs can be used to detect pitting corrosion. The samples tested in the HPT set-up showed no pitting and similarly none was observed in the field test. It was found that both Electrochemical Impedance Spectroscopy (EIS) and Linear Polarization Resistance (LPR) measurements are useful techniques to monitor the CO₂ corrosion. In addition the LPR results can be used to calculate the corrosion rate. The corrosion rates from LPR correlate well with those obtained from the ICP and the surface profilometer measurements.

1.3.7 Impact

The impact of the work performed in WP 3 Well Integrity on the Geological Carbon Storage industry has been high. First, the experiments on the type of corrosion experienced in CO₂ injection wells have allowed to confirm that uniform corrosion and blistering are the main phenomena (with little or no pitting observed) and that a siderite layer offers some protection. The experiments also allowed identifying EIS and LPR as two promising methods for corrosion monitoring in-situ. Furthermore, the time-lapse logs showed the value of high-resolution imaging of steel and cement to characterize CO₂ effects. In particular, they confirmed that only negligible corrosion phenomena happened to the steel, that there is some evidence of a (tiny) CO₂ leak between cement and steel (that carbonated the cement over 1 km), and that coal – because of creep or swelling – compresses cement on the casing guaranteeing a good seal in the absence of a strong injection pressure. This is the first time that a leak path during injection has been identified and quantified.

Finally, simulations allowed for the quantification of possible long-term leaks and to characterize risk. Given the cement quality and low CO₂ pressure, the risk was confirmed negligible, and the abandonment and monitoring practices recommended by local regulations were deemed sufficient.

1.4 WP 4 Environmental monitoring and risk assessment and safety (HSE)

1.4.1 Objectives

A critical component of long term geological sequestration of anthropogenic CO₂ will be the ability to adequately monitor a chosen site to ensure public and environmental safety. Near surface monitoring is particularly important, as it is possible to conduct sensitive and direct measurements at the boundary between the subsurface and the biosphere (i.e. surface water or atmosphere). While discontinuous surface monitoring is often performed, continuous monitoring is preferable if one hopes to observe a leak in its early stages to allow for rapid remedial action. Also, natural trends (i.e. natural background values and their variation) can better be determined. Based on this assumption, the core of these WP activities are focused on the development of low cost and innovative tools for the continuous monitoring of CO₂ concentration and flux. This is done to:

- control post-injection conditions (baseline);
- detect and measure any seepage to the biosphere, identifying potentially hazardous leakages of CO₂;
- observe CO₂ migration in (and around) the storage reservoir;
- test and calibrate site performance simulations;
- perform analysis, modelling and interpretation for a generic protocol for future storage projects.

The WP also includes public perception and guidelines for site certification.

1.4.2 Surface measurements

In the first year of the project, according to the activities planned in tasks 4.1 and 4.2, a soil gas and flux survey was carried out in May at the Kaniow site. During this survey more than 150 samples were collected in an area of about 40 km² (i.e. a radius of 4 km; Figure 4.1) with a decreasing sample density from the injection MS-3 site to the boundary of the area. Each measurement station was georeferenced using a Global Positioning System (Garmin mod. GPSmap 76s). The coordinates were recorded using the UTM34 coordinate system format and WGS 84 world projection.

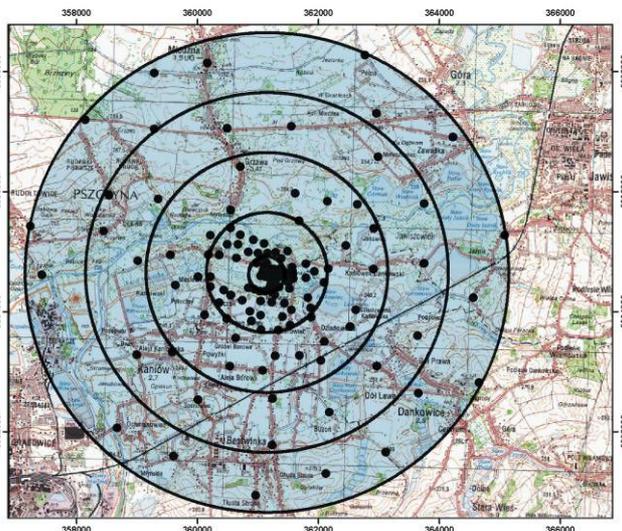


Figure 4.1. Sampling points of soil gas and flux measurement conducted during the first years of the project.

Statistical treatments of the data suggest that the studied area is characterized by soil gas values very close to the background expected in clay soil. In contrast, the high standard deviation values suggest the presence of outliers probably caused by biological degradation phenomena of CO_2 and CH_4 and/or linked to other origin for helium anomalies.

The CO_2 map shows higher concentrations in the western sector and lower concentrations in the central-eastern part of the area. In correspondence with MS-3 some high (up to 10%) CO_2 values were detected (Figure 4.2b). The CO_2 flux map shows an anisotropy direction (SW-NE), as well as generally low values and some small anomalies in the central part of the area. (Figure 4.2a). In general detected values both for CO_2 and CO_2 flux can be explained as linked to shallow origin (i.e. biological degradation of organic matter).

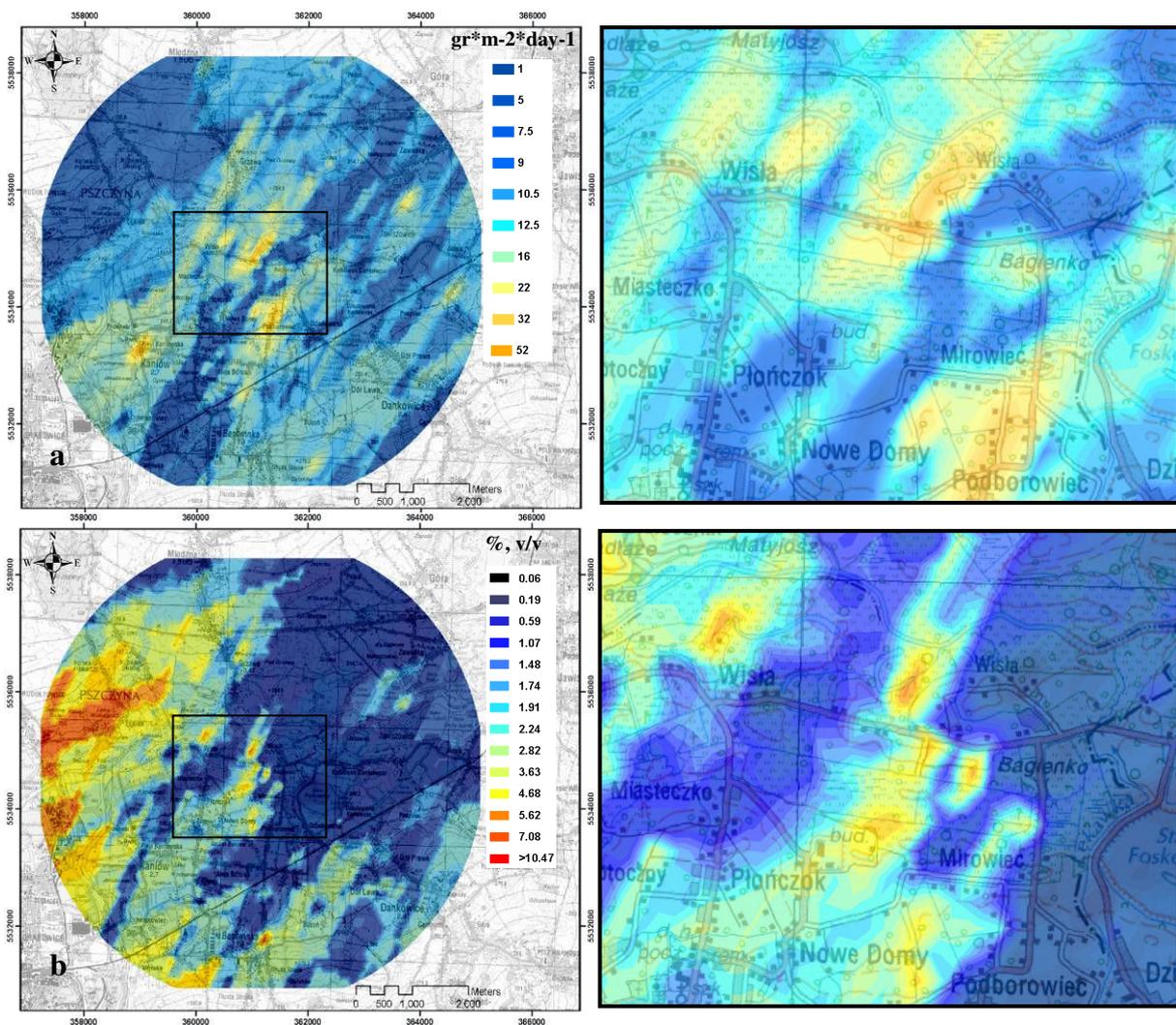


Figure 4.2. Regional and detailed map of CO_2 flux (above) and CO_2 concentration (below). It is possible to observe that only small anomalies can be detected around the Kaniów site.

CH₄ concentrations are generally low. A number of very high values occur in the area, probably due to biological degradation. These values were excluded in the creation of the map to obtain a more readable figure. The anomaly in the centre of the map is linked to several high CH₄ samples occurring in a restricted area (Figure 4.3a). Helium is probably the most interesting parameter. This figure shows that the entire investigated area is characterized by helium concentrations similar to air (5.22 ppm). Only three samples, close to the injection site, show anomalous values (up to 22 ppm) (Figure 4.3b).

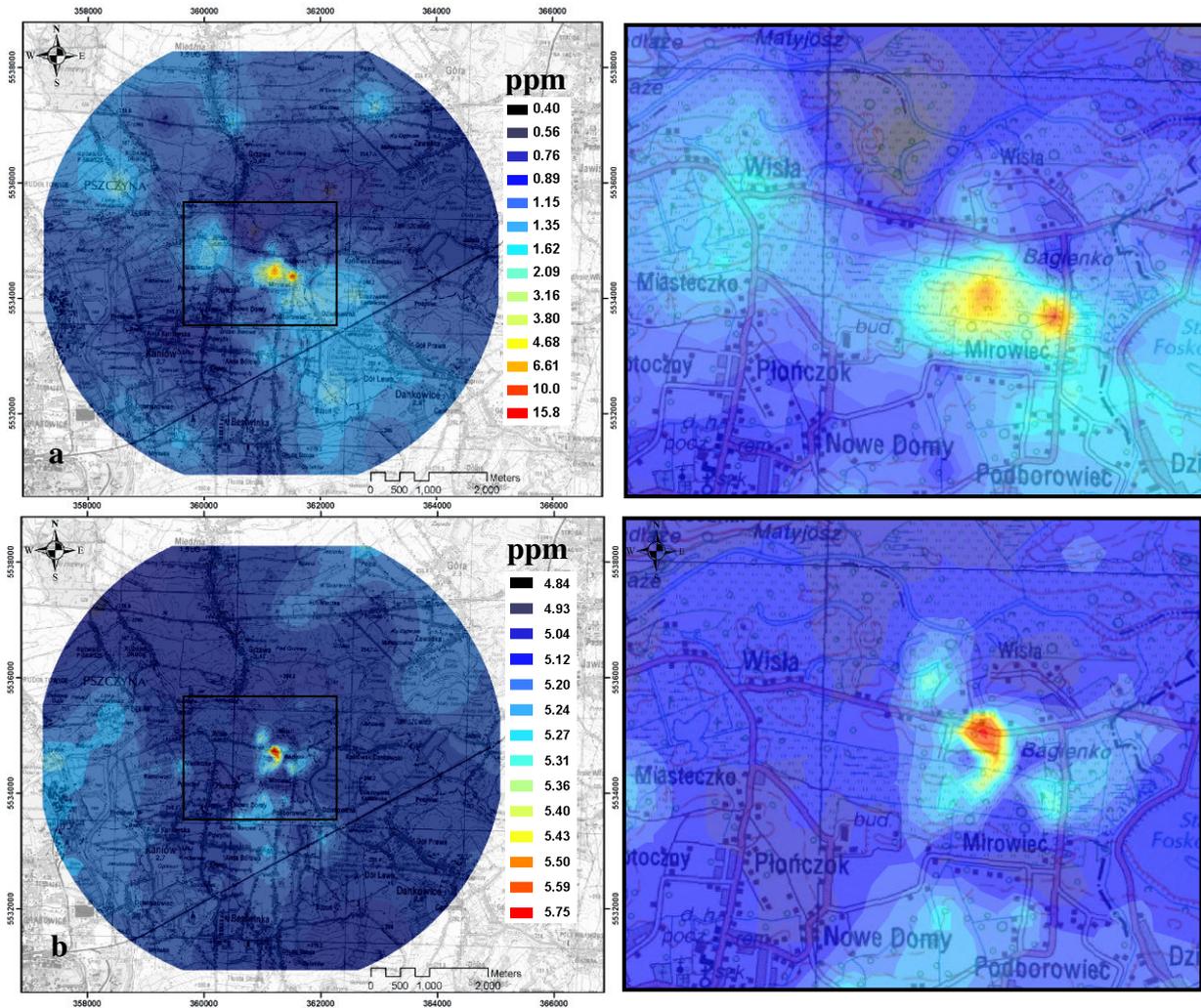


Figure 4.3. Regional and detailed map of CH₄ (above) and He concentration (below). It is interesting to observe that all around the studied area the concentration of both gases are very low. In contrast close to the Kaniow site strong anomalies were detected.

During the 2008 survey a total of 135 samples were collected as follows:

- 114 samples (57 with Rn and Tn) along a 1400 m soil gas profile;
- 9 samples in a different mining area (far from the Kaniów site);
- 12 samples close to the MS-1 injection well.

Figure 4.4. shows the distribution of these sampling points.



Figure 4.4 - Sampling points location for soil gas and flux survey. Green points represent the 1400 m long soil gas profile with radon measurements. Blue points in the same zone represent the randomly collected points close to MS-1 and the other blue points are located in the comparison mining area.

The soil gas profile carried out during the second year of the project was done in substitution of the detailed soil gas survey previously planned. This profile was done across the MS-1 injection well and across two known faults recognised in the area.

Obtained results (Figure 4.5) highlight that the injection well could be a preferential pathways for deep gas migration. The domain of this phenomenon is restricted in the area close to the wells. Radon values highlight the faulted zones and confirm its potential as “fracture tracer” according to numerous examples in the international literature (Ciotoli et al., 2007, Baubron et al. 2002).

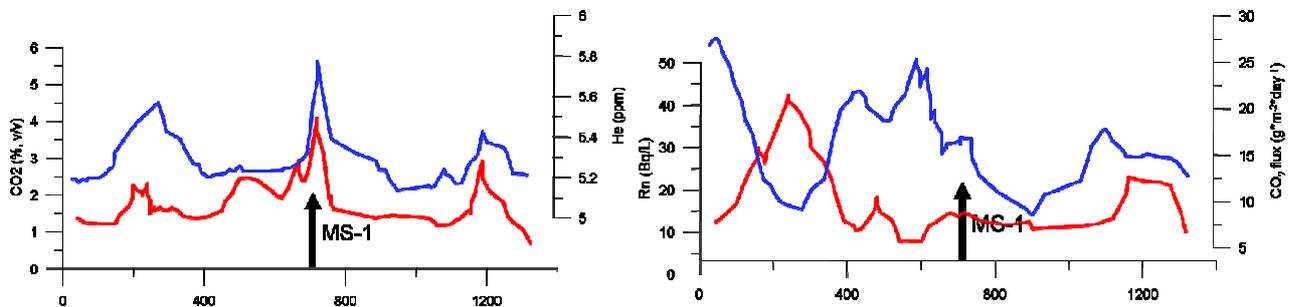


Figure 4.5 - The blue lines indicate changes with the distance of helium concentration and CO_2 flux while the red lines show the variations of carbon dioxide and radon. It is interesting to note the increasing of CO_2 and helium in correspondence of the injection well, while there are no appreciable changes in CO_2 flux and radon.

Anomalous values were also detected in a few samples randomly collected around MS-1. High concentration of CH_4 , He and CO_2 in these samples is in agreement with the 2007 survey and confirms the restricted spatial domain of the phenomenon.

Additional samples were finally collected in another mining area in order compare the anomalies detected close to the MS-3 and MS-1 sites with samples collected in a similar geological scenario. In particular it was important to understand if in other mining zones in which CO₂ is not injected, helium anomalies can be comparable with those detected in the Kaniow site. The investigated area is characterized by low soil gas values, with helium concentrations generally lower than those measured at MS-1/3 sites. In this area also samples collected directly from the ventilation well were analysed. These samples highlight only the presence of HC (CH₄ > 1000 ppm) and low anomalies of helium (about 5.55 ppm).

1.4.3 Automated monitoring system

The surface measurements described above was integrated by the development and test of a monitoring system able to collect data for dissolved gas, soil gas, soil temperature, soil humidity, air temperature and air humidity. However, due to the water table level, only soil gas can be collected on site. Figure 4.6 shows the scheme of the monitoring system.

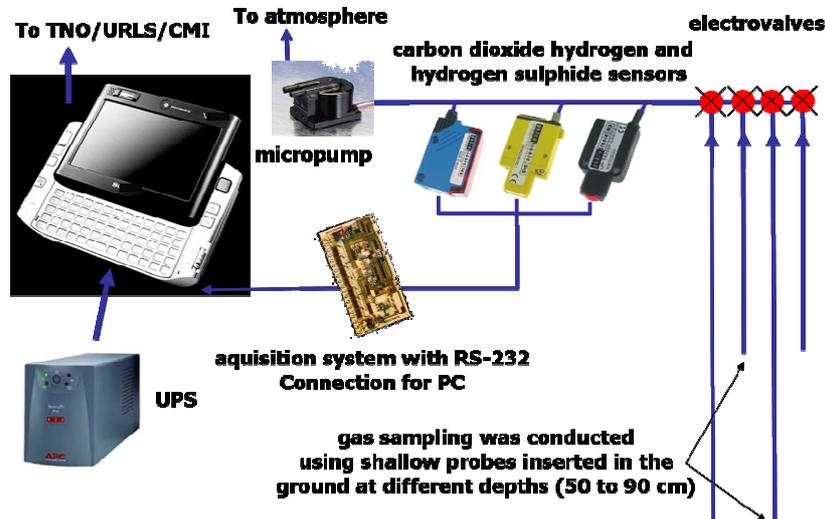


Figure 4.6 - Scheme of the developed monitoring system

Soil gas and flux concentrations were measured by using two different IR sensors for CO₂ (range 0-30% and 0-100%) and two electrochemical sensors for H₂ and H₂S. Four monitoring probes were inserted to the ground at different depths in order to have the possibility to also calculate the CO₂ flux values. For these reason each monitoring point is constituted by two probes, installed at 50 and at 90 cm of depth respectively (Figure 4.7).



Figure 4.7 – On-site installation of the monitoring system. It is possible to see the four probes (two for each monitoring point).

The system operated between March and July 2008 (closure of the site) in the vicinity of the MS-1 well. The first monitoring point continuously collected data for all parameters. In contrast, the second point was affected by technical problems after about 2.5 months, probably linked to the presence of water in the probes. Figures 4.8 and 4.9 show the results obtained by MS.

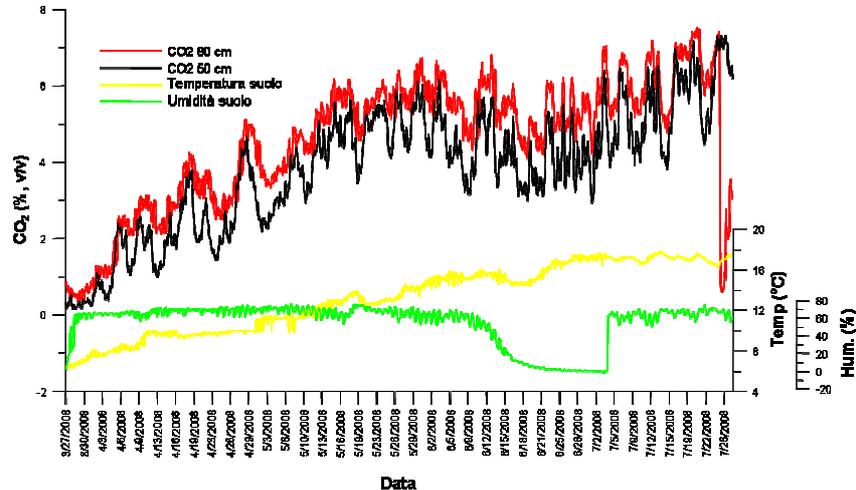


Figure 4.8 - Results obtained during 4 months of monitoring in the Kaniow site. It is possible to note how the values of CO₂ in both depth seem linked with those of temperature, confirming a likely source organic carbon.

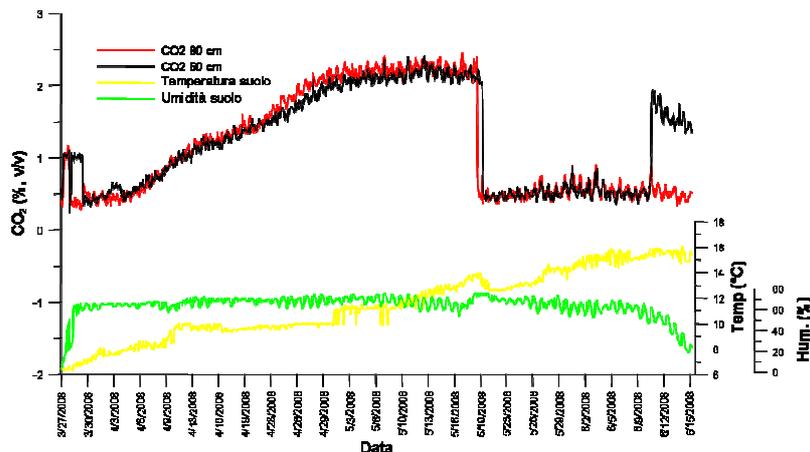


Figure 4.9 - Results obtained during 3 months of monitoring in the Kaniow site. It is possible to note how the system has highlighted problems probably related to the presence of water in the probes after 2,5 months of sampling.

Collected data were statistically analysed both using mono-variate and multi-variate techniques. Time series analysis graphs (Figures 4.10 and 4.11) show respectively the measured data, the trend, the cyclicity and the residual values. It is interesting to note that both probes show the presence of a periodicity in the results (daily). This could be linked to the temperature difference between night and day. It is also interesting to note the difference of residual variation between the probes. This variation is more evident in the shallow probe than in the deeper probe. This phenomenon is probably attributable to the increased influence of weather parameters on the shallower probe. The cross-correlation between the different parameters of the monitoring system revealed the presence of correlation only between CO₂ and temperature. Figure 4.12 shows this elaboration for the monitoring point 1 for each depth of measurement. It should be noted the presence of a peak of maximum correlation respectively at the lag -4 and the lag -3. This result would seem to indicate that in the deeper probe CO₂ results was affected by the influence of temperature changes with a delay of 4 hours while in the shallower probe this delay drops to 3 hours.

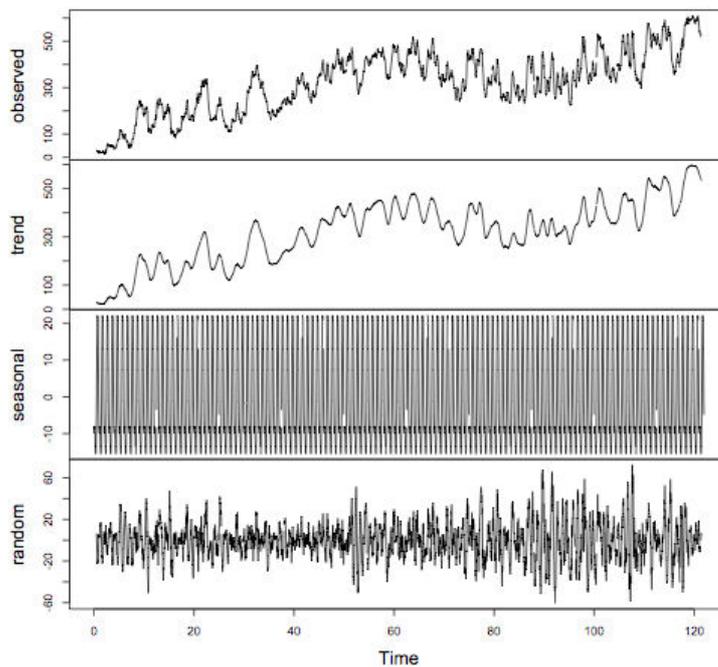


Figure 4.10- Random graphs show the residual value between observed measurements and trend. Small residual variations in correspondence of observed peak confirm the “consistence” of the peak. In contrast large residual variation could be due to “small scale” phenomena.

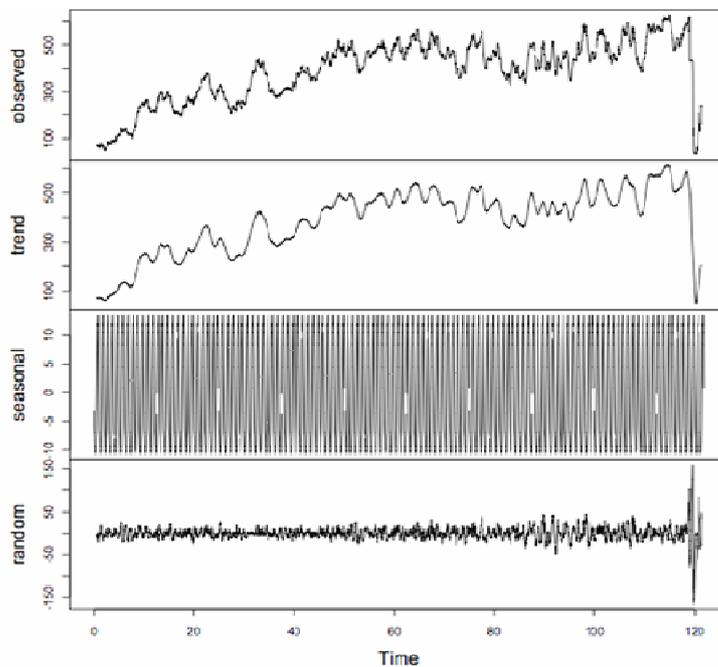


Figure 4.11 – Time series graph of the deeper monitoring point. It is possible to observe that the random graph shows (residual value between observed measurements and trend) smaller residual variations with respect to the shallower point. This means that observed peaks can be considered as “true peaks” linked to a lower influence of the atmospheric parameters.

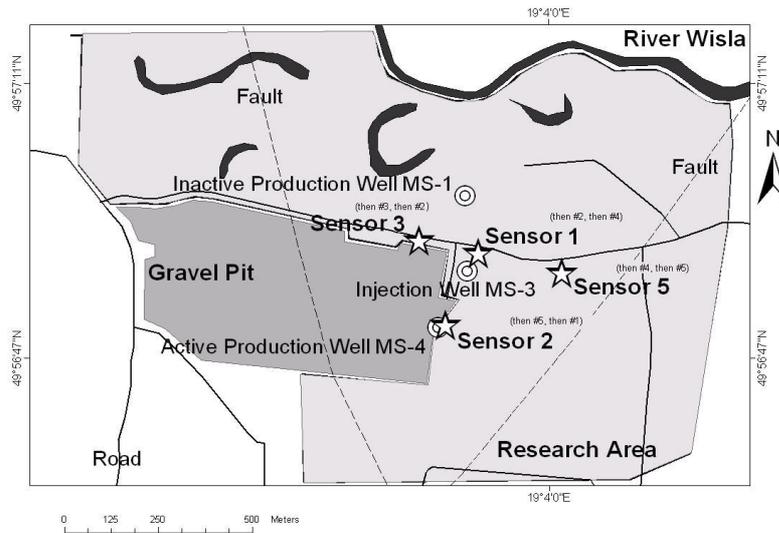


Figure 4.13. Storage site with the positions of the sensors between April 04 and October 05

In Figure 4.14 an example is shown where the obtained model derived from the learning data set is applied to a control data set. The variance intervals comply with 99% of the variance of the random residuals of the model. In general, the model is in good accordance with the measured time series, with two exceptions: the period between day 490 to 493 and during the day 495. The weather conditions during recording the control data set were less stable and characterized by higher precipitation. The two mentioned deviations from the modelled time series were preceded by strong rain events, which led to elevated soil moisture contents during the following days, most probably influencing the soil gas concentrations.

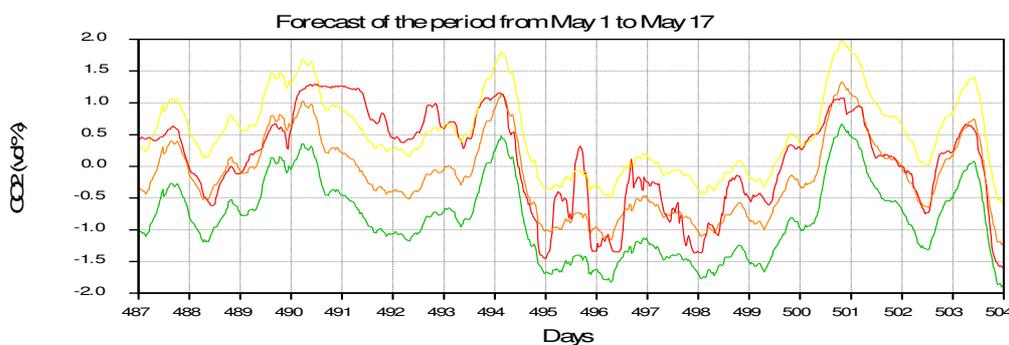


Figure 4.14. Control data set with modelled (orange), measured (red), lower (green) and upper (yellow) variance.

Soil moisture was already considered a parameter of considerable impact on CO₂ soil flux in previous studies.

The present study represents an initial step to the prediction of natural CO₂ baselines, necessary to establish automatically operating monitoring stations implying CO₂ seepage alarm systems for CO₂ storage locations. The study indicates such systems are feasible. The results exhibit the demand for further refinement of the model. They also exhibit the need to consider the monitoring strategy in terms of seepage pathways and predictive monitoring power.

The results of this study give rise to the following suggestions for future research projects:

- Consideration of precipitation/soil moisture as an additional model calibration parameter
- Measurement of longer time series (>1 year) to obtain more comprehensive and more representative control and learning data sets

- Additional measurement of the influencing parameters (temperature, pressure, humidity) in the subsurface, close to the IRGA; precipitation measurement, for instance, cannot indicate the period of the resulting elevated soil moisture concentrations. This can only be achieved by direct measurements of this parameter. Furthermore, low-period temperature changes during meteorological unstable periods may have a minor influence on the subsurface temperature and therefore on respiration activity and subsurface CO₂ concentration. Therefore, the *in-situ* temperature may exhibit a more significant correlation with CO₂ subsurface concentrations.
- Maintaining stationary conditions during measurement campaigns. Neither the position nor the depth of the sensors should be changed during the long-term campaigns.

It is expected that comparison of different techniques may lead to the development of different prediction tools exhibiting distinct condition-dependent advantages, enabling a condition-dependent application of the best suiting available approach.

Considerations on monitoring station positioning lead to the following conclusions:

- In principal, locations exhibiting very low natural background emissions exhibit little seasonal influence; therefore their baselines are quite stable and thus to predict more reliably
- Monitoring stations should be placed in zones exhibiting enhanced leakage risks, e.g. zones of enhanced He- or Ra-flux
- The aforementioned aspects are contradictory in a way, as zones exhibiting preferential leakage pathways are likely to emit enhanced natural CO₂ fluxes
- Monitoring stations which recorded concentrations in the range of 1 to 4% revealed considerable differences with respect to data scattering; locations exhibiting lower scattering are to be preferred as monitoring locations, as their baselines are to predict more reliably
- Consequently, monitoring location selection is a compromise between zones of enhanced leakage risks and zones of low CO₂ baseline concentrations and low scattering
- Thus, prior to stationary monitoring extensive site-specific evaluations and lateral surveys are required, in order to define the most suitable monitoring locations

1.4.5 Integrated risk assessment, including mining operations

The risks due to leakage from storage of CO₂ in geological reservoirs fall into two broad categories: global risks and local risks. The first was not taken into account as this a demonstration project on a small scale. Here, only hazards connected with local risk events are considered. The risk assessment methodology is based on the following:

- ALARP (as low as reasonably practicable) principle for determining criteria of acceptability of risks occurring in the production processes,
- elucidation of a scenario for the dangerous event,
- selection of the proper prevention methods at every stage of the scenario,
- determination of shares of different systems in risk reduction.

Because presence of CO₂ in high concentrations in underground workings causes rapid circulatory insufficiency leading to coma and death special attention should be turned on different independent methods of prevention (different independent protection layers). Mining ventilation departments have great experience in control different gas hazards, and use all kinds of protective barriers.

In the vicinity of the MS-3 injection well two storage tanks were present with a capacity of 30 tones each one. If a downward leakage from a tank or a surface transportation system module occurs, the CO₂ would undergo a large temperature reduction and form a bank of “dry ice” on the ground surface; the sublimation of the gas from this bank represents an area source term for subsequent atmospheric dispersion, with an emission rate dependent on the energy balance at the bank surface. Modelling shows, that the plume of CO₂ exceeds maximum 100m during one hour at weather conditions with wind speed below 2 m and a temperature from 10 to 20 C°. Concentration of CO₂ in the plume does not exceed 10000 ppm ie. allowable threshold. Higher concentrations are only in the immediate nearby of the dry ice cone. It is expected that as a consequence severity may be serious not due to CO₂ concentration, but due to incorrect handling with solid frozen CO₂.

Leakage could occur through undetected faults, fractures or through leaking wells where the release to the surface is more gradual and diffuse. In this case, hazards primarily affect drinking-water aquifers and ecosystems where CO₂ accumulates in the zone between the surface and the top of the water table. In this scenario, there may also be acidification of soils and displacement of oxygen in soils. Additionally, if leakage to the atmosphere were to occur in low-lying areas with little wind, or in sumps and basements overlying these diffuse leaks, humans and animals would be harmed if a leak were to go undetected. Due to results of soil gas monitoring the event frequency of CO₂ leakage was low.

Carbonate hardness of water decreases with time as a result of CO₂ injection, because the formation water is expected to acidify when coming into contact with CO₂. Due to small quantities of daily pumped water (1 to 1,5 m³), the severity of consequences are defined as minor. On this scale of water production, the undertaken prevents methods were adequate to monitored hazards.

1.4.6 Public acceptance study performed near the injection site

It should be mentioned that the analysis performed – in the scope of perception by the local community related to capture and storage of CO₂ – was under the condition of a demonstration project (with special focus on monitoring and verification). Here, not the situation is considered in which the technology of geological storage of CO₂ is put into practice on industrial range.

Summing up the issues related to the social acceptance for activities carried out in frame of the MOVECBM project in the light of conducting monitoring and risk assessment:

CCS technologies, especially geological storage of CO₂, lack of experience on local level connected with putting into practice, make it difficult specifying the scale (range) of social resistance, potential conflicts and interest groups. Important is a correct preparation of putting into practice of new technological solutions which should take into consideration winning social acceptance.

The official standpoint of ecological and non-government organizations, declaring both on international forum and national level, indicates that potential applying of CCS technologies should not be subject to “boycott” from the side of such type of organizations. Even so, these organizations emphasize first of all demonstration nature of activities taking so far in that area and express doubts concerning especially safety of applying such kind of technological solutions in long-term perspective. In the situation of activity planning connected with putting into the practice CCS technologies, especially geological storage CO₂, the special attention should be on information transparency, especially those for non-government organizations. Crucial becomes also assuring participation of non-government organizations representatives in social consultations.

The analysis shows that there is a low level of knowledge concerning CCS technologies. Very important is dissemination of information, e.g. by carrying out an information campaign on wider territorial area (national or regional) with using such kind of information resources as: television, radio and press. Information actions on local level should be in a large degree carrying out in a form of information meetings with experts. Especially important is direct (face-to-face) contact with residents which guarantee proper passing information.

On local level, crucial issues do not concern safety only, but also further economic development of the area. Alternative directions of development of the territory and potential “loosing chances” of local community results from putting into the practice CCS technologies have to be taken into consideration. It demands first of all precise specific economic benefits (profits) for local government and local community connected with applying such kind of technological solutions.

On local level very important is precisely specifying obligations for local governments and also assuring adequate forms and financial resources for their realization.

1. Crucial issues are building and exploitation essential infrastructure for transport and storage of CO₂, especially in the context of areas with high population density and also spatial limitations connected with their exploitation.
2. Also becoming important is carrying out social consultation on wider territorial (area), which include neighbouring administrative units (e.g. neighbouring poviats) and at sub-region or region level. Of course in this case can be applied different forms of conducting social consultation, even so

it seems that putting into the practice such kind of technological solutions should be based on some kind of consensus achieved on region scale (range). Potential social consultations concern applying geological storage CO₂ should be carry out with participation of local government representatives from different levels of administrative units, ecologists and non-government organizations, independent experts and residents.

3. Social consultations should be carried out first of all by local governments and independent experts. It seems, that a great role is attributed to independent experts, not only as participants, but also organizers or co-organizers of social consultations. Not without importance is the fact, that in carried out social opinion polls researchers (independent experts) and non-government organizations are perceived as reliable information source. The role of potential investors in such kind of activities should be limited to co-organization of social consultation.
4. In the case of geological storage of CO₂ important is relatively early taking up social consultations with residents. Consultations should be taken up on the stage of decision about location of potential investment (investment activities). It seems that starting dialog with the local community on later stages can arouse social resistance. These issues are connected with proper types of consultation, i.e. on a two-way process (exchange information with society) as well as dialog assuming planning with social participation (and also jointly decision making).

Adequate forms of carrying out social consultations concern geological storage of CO₂ are first of all consultation meetings with local governments, representatives of ecological organizations and independent experts, also public informational meetings and public hearing, and public debate. Applying such kind of forms of conducting social consultations are not easy. It should cover appropriate preparations, organisation and including the planning of applying specific technological solutions. Necessary is also taking into consideration the recommendations submitted by local community. Above-mentioned forms of conducting social consultations assuming direct (face-to-face) contact with residents and guarantee their participation in decision process.

1.4.7 Guidelines for site certification

From the European perspective it should be taken into consideration the need of making amendments and elaboration of an unambiguous interpretation to the requirements of the EU directives. This in the area of underground CO₂ storage, (e.g. in injected into coal seams). In the climate change context CO₂ is most often classified as an important greenhouse gas, an emission, or—in some countries—a waste. In the Polish law the classification of CO₂ is also not clear. During granting for storage permits, the definition stating that if a waste is used for useful purposes, than it is not classified as a waste. In case of the previous RECOPOL project, the injection of CO₂ was performed to enhance methane production. According to the requirements of the Geological and Mining Law Regulation, storage of waste in the underground formations is permitted after receiving a concession.

Based on the results of risk assessment, undertaken safety precautions as well as based on the real case of “Kaniow Operational site” the existing mining and geological law regulations shall be verified and following amendments are proposed:

Changes in the being currently in force directives shall go in the same direction. It is proposed to classify greenhouse gas intended to be stored underground, in the frame of EU regulation - not as a waste.

1.5 WP 5 Results and verification

1.5.1 Objectives

The activities that are undertaken in the scope of Task 5.2 of the MOVECBM project aimed at cooperation with partners from China on the subject of ECBM. The main goal of this cooperation was the establishment of a long term relationship between European and Chinese partners in order to prepare a pilot ECBM site in China in the near future. For this reason, a selection of potential areas was undertaken within the project. These could than be compared to prospective locations in Poland.

The work that is reported here is the result of combined efforts and contributions of the MOVECBM consortium, in particular by PetroChina, CUCBM, State Key Lab of Coal Conversion, CMI, Schlumberger, Shell and TNO. TNO has acted as Work Package leader and has prepared the report. The information on ECBM potential of Poland was provided by CMI, while the information on China was the result of three workshops (two in Beijing, one in Rijswijk).



Figure 5.1 Pictures of the workshop meeting in Beijing, March 2007



Figure 5.2 The workshop was finalized with a field visit to CBM fields in the Shanxi and Shaanxi provinces. Picture of the delegation at a CUCBM gas gathering station near Jincheng, Shanxi province.

1.5.2 Selection of potential ECBM sites in China and Poland

Both China and Poland have large resources for CBM (20-415 billion m³ for Poland and over 14,000 billion m³ for China up to 2,000 m) and for CO₂ storage in coal seams (470 Mt in the Upper Silesian Coal Basin in Poland and 87 Gton in China). These are theoretical figures and a further site selection was made for prospective areas. Five sites in China and two sites in Poland were further evaluated.

During the workshop held in March 2007 in Beijing a total of 5 sites have been proposed. CUCBM suggested the Jincheng/Shizhuangbei (Qinshui Basin) and Hancheng sites (figure 5.3), which were visited by the workshop participants. RIPED pre-selected the Jinshi 1 Block (Qinshui Basin), Southern Ningwu and Yangquan-shouyang sites (figure 5.4). In Poland, two sites have been selected: Warsowice and Miedzyrzecze (Figure 5.).



Figure 5.3 Location of pre-selected sites for development of an ECBM project in China.

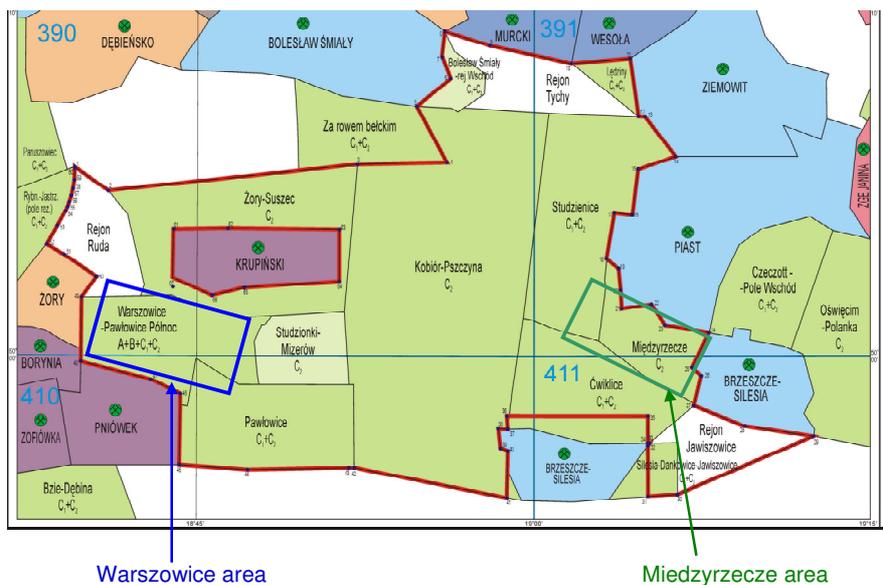


Figure 5.4 Location of the Warsowice and Miedzyrzecze areas in the Upper Silesian Basin in Poland

Based on this first evaluation it was concluded that two areas in particular could be attractive for ECBM: the Jinshi1 block in the Quinshui Basin and the Hancheng area in the Ordos Basin (both in China). Very important criterion was the development of production CBM in the area and the planned CBM activities.

The Jinshi 1 block was selected for further investigations through geological modeling and reservoir simulation.

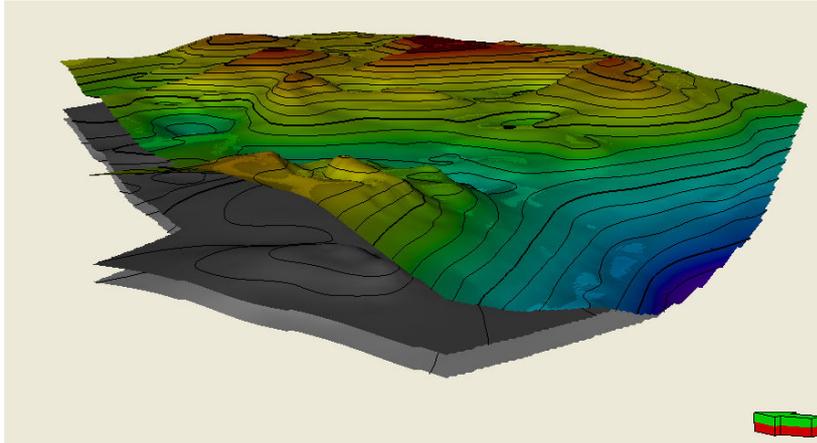


Figure 5.5 3D visualization of the Jincheng area geological model. View from southwestern direction. Light grey layer represents Base Taiyuan Fm., dark grey layer represents top No. 3 coal seam, colored layer represents surface elevation. Vertical scale is amplified with a factor 4.

1.5.3 Discussion

The results showed that ECBM can be successful but requires the correct conditions. Currently, there are a lot of uncertainties in these conditions. Further research should address the reduction of these uncertainties and more detailed evaluations.

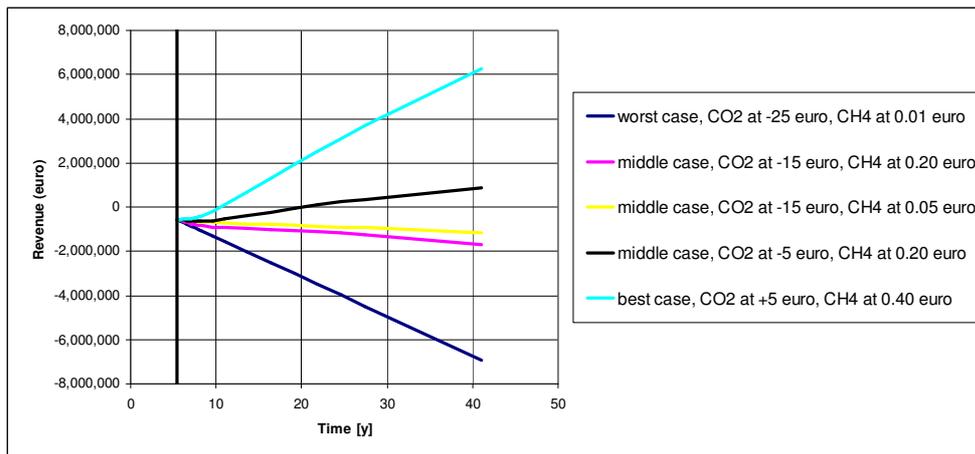


Figure 5.6 Calculated revenues on the basis of the additional gas produced in scenario P4-I1_frac compared to scenario P4-S1_frac. The CO₂ price is considered the net cost before injection, thus the difference between the CO₂ credit and the supply cost. The price for CH₄ is the price at which it is sold to the consumer, thus after processing.

1.5.4 Conclusions

In conclusion, China has huge resources of coal that are not attractive for mining in the next decades, and probably longer. These coal seams can be targeted for CBM production. Many of these coal basins show low production rates and low recovery factors. Current developments in drilling technology should be followed and applied to improve these performance parameters. However, injection of CO₂ may provide a further enhancement of the production (therefore ECBM production). Because the CO₂ is adsorbed on the coal it is stored in the reservoir and, if obtained from an anthropogenic source, thereby reduces the CO₂ emissions to the atmosphere. Subsurface coal in China is likely to hold the largest theoretical storage capacity for CO₂ compared to other underground storage options. Although these are theoretical figures, and the actual matched capacity could be several orders less than the theoretical capacity, ECBM could become a vital part of the CCS strategy in China.

ECBM projects can work in China if the economic, infrastructural, and geological constraints are taken into account in the planning. It should be anticipated in the development stage of an ECBM project that the injection rates per well are, due to a limited permeability, lower than in other types of underground CO₂ storage options (EOR, depleted gas fields, aquifers). For vertical wells in low permeability coal seams (< 2mD) the rate is likely to be less than 100 ton per day (depending on well completion, cumulative coal thickness, etc.), or about 30,000 ton per well per year. To reach similar injection volumes as anticipated for storage projects in depleted gas fields or aquifers many vertical wells (or multilateral/horizontal wells) will be required which has to be taken into account in the spatial planning of the operation. It is recommended to perform ECBM operations as a secondary production phase after an initial CBM production phase. This way, the CO₂ can be injected in dewatered coal seams. Additionally, CO₂ injection takes place in an area with existing, thus commercial, CBM production. This will reduce the investment cost for the wells and infrastructure. This cost reduction will be required to make ECBM economically feasible under the envisaged conditions.

Two of the selected areas (Hancheng and Jinshi1) could meet the requirements as outlined above. Especially, the planned CBM production in these areas in the next years makes them attractive. More detailed study should be undertaken to check these criteria and to make a development plan to test the application of ECBM in these areas.

The selected sites in Poland currently lack planned CBM production in the next years, which makes them less attractive for ECBM before 2012.

2 Dissemination and use

2.1 Exploitable knowledge and its use

Overview table

Exploitable Knowledge (description)	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Other Partner(s) involved
Numerical modelling techniques for the modelling of cap rock integrity	Numerical modelling technique	1. Energy 2. Environmental	-	-	CSIRO
New data for permeability of coal under the given condition	Modeling (Shell)	1. Energetics 2. Coal-mining	Not defined (still in progress)	-	ERICo ⁱ
Better understanding interaction CO ₂ with coal	Improved reservoir simulation model	Reservoir Engineering, CCS and (E)CBM	2009	No patent, but proprietary computer code	Shell ⁱⁱ
New method to monitor CO ₂ corrosion in-situ (EIS and/or LPR)	Permanent sensor or wireline/slickline-conveyed tool	Corrosion monitoring of wells exposed to CO ₂	2010	Under review	TNO ⁱⁱⁱ
Sorption / swelling behaviour of coal matrix and effects of water	Data	(E)CBM research & feasibility assessment	2008	Paper in press	UU + TNO ^{iv}
Effect of stress on sorption capacity of coal matrix	Data	ECBM research & feasibility assessment	2009	Future journal publication	UU ^v
CO ₂ penetration and transport properties of coal matrix	Data	ECBM research & feasibility assessment	2009	Future journal publication	UU + TNO ^{vi}
ECBM concepts for China	-	Energy	> 3 years	NA	TNO and WP5 partners

ⁱ ERICo's part of the research was a small piece of whole understanding of the adsorption kinetics and diffusivity of gases into the coal / matrix. The goal of this experiment was to acquire data about the permeability of coal seam for CO₂ in Velenje Coalmine and acquire missing data from RECOPOOL project. It represents a link between laboratory testing on permeability of coal for CO₂ and the test experiments on CO₂ storage and on extraction of CH₄ with ECBM, which are being conducted into the coals seam from the surface.

ⁱⁱ Shell's proprietary reservoir simulator MoReS is extended with new models that were partly based on the MOVECBM experience. The model was tested on the MOVECBM field data and proved to be successful in simulating both field tests. Results are published at the GHGT-9 conference in Washington. The new model enables us to better predict CBM and ECBM plays. There is also some spin-off to other CSS schemes such as aquifer storage. The improved models lead to more accurate forecasts and as a consequence reduced uncertainty in (economic) decision making

ⁱⁱⁱ The result is a method for monitoring steel corrosion in-situ during underground CO₂ storage conditions. The two methods mentioned above, which can be used separately or in conjunction, are Electrochemical Impedance Spectroscopy (EIS) and Linear Polarization Resistance (LPR).

Their suitability to monitor CO₂ corrosion was proven by TNO. They could be deployed either as a logging tool or as permanent sensors for monitoring.

Additional work required will be packaging to allow deploying in injection or monitoring wells and partnering with companies that could offer the service.

^{iv} The data obtained on this topic by UU and TNO provide a basis for understanding and crudely modelling how water extraction from coal seams influences in-situ stress-strain development, permeability evolution and CO₂ sorption capacity. The results are in press (Van Bergen, F., Spiers, C.J., Floor, G and Bots, P. (2008). Strain development in unconfined coals

exposed to CO₂, CH₄ and Ar: Effect of moisture. *Int. J. Coal. Geol.*, doi:10.1016/j.coal.2008.10.003). The measurements need to be extended to specific coals to achieve site-specific predictions of the effects of dewatering on (E)CBM production rates. The observed shrinkage of coal due to drying suggests that an alternative injection-production scheme can possibly be developed in poorly productive CBM fields, whereby the field is dewatered as much as possible before CO₂ injection. This could prevent gravity override in the reservoir, which has been identified as an operational problem. In such a scheme, a phased injection of scCO₂ might be considered whereby the first phase of injection may serve to bring about additional drying of the coal. If sufficient water is removed, this may result in coal matrix shrinkage and permeability increase. Once the coal seam reaches maximum permeability it can be used to store CO₂.

^v Data obtained by UU on the effects of applied stress on laterally confined, granular coal provide the first data showing how stress reduces the CO₂ sorption capacity of coal matrix material at fixed CO₂ pressure. This is key input for modelling how coal matrix swelling during CO₂ injection into coal seams influences the effective CO₂ sorption capacity and the in-situ stress-strain-permeability evolution. The measurements need to be extended to specific coals and to intact matrix blocks to achieve site-specific predictions.

^{vi} The results obtained by UU and TNO on the permeability and diffusive transport properties of coal matrix blocks, with respect to CO₂, show that cleat or other fracture systems must be maintained open for successful ECBM operations. The problem is most severe for bituminous coals but must also be considered in the case of lignites. The data can be used in (commercial) numerical modelling assessments of (E)CBM field behaviour.

2.2 Dissemination of knowledge

Overview table

Planned/ actual dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible/ involved
November 22-23, 2006	Conference/ Workshop	Coal & (E)CBM Research	Belgium, Netherlands, Germany, France, United Kingdom	25	Shell
January 2007- recent	Project web-site	Various	all	Internet community	TNO
March 28- 29, 2007	Conference/ Workshop	Coal & (E)CBM Research	Belgium, Netherlands, Germany, France, United Kingdom	25	Shell
October 15- 17, 2007	Oral presentation at SPE ATW Wellbore Integrity	Research & Industry	International	50-80	TNO, CMI, EPS
2007, 2008	Publications*	Research, industry	Serbia and Montenegro, Austria, Slovenia	-	ERICo
2007	Conference*	Research, industry	Slovenia	100	ERICo
November 1, 2007	Conference/workshop	Research	Netherlands	25	UU
November 2007	Conference: CO2NETLisbon	Research + Industry	Portugal + International	50-100	CMI
November 2007	ConferenceVU Amsterdam	Research	Netherlands	20-40	UU
December 13, 2007	Conference/ Workshop	Coal & (E)CBM Research	Belgium, Netherlands, Germany, France, United Kingdom	25	Aachen
January 2008	Publication: First Break	Research	International	1000- 10000	TNO
January 2008	Conference for COACH project	Research	International	20-40	TNO
March 2008	Conference: IEA GHG wellbore integrity network meeting	Research & Industry	France + International	30-60	TNO, CMI, EPS
April 13-18, 2008	EGU General Assembly	Researcher	Austria		SKLCC, RWTH, Shell
April 2008	Conference: Coal-seq V, Houston	Research + Industry	USA + International	50	ARI
April 2008	Conference: CO2NETWarsaw	Research + Industry	Poland + International	50-100	TNO
May 19-22, 2008	SPE Conference, presentation	Research, Industry (CCS)	International	250	Shell

Planned/ actual dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible/ involved
May 23, 2008	ECBM Workshop at TU-Delft	Research, Industry (CCS)	Netherlands, Germany, Belgium, France, UK	25	Shell
June 25-28, 2008	The 7th China-Korea workshop	Researcher	China		SKLCC, Shell
September 22 - 24, 2008	APCBM	Researcher	Australia		SKLCC, Shell
22 - 24 September 2008	APCBM	Researcher	Australia		SKLCC, RWTH, Shell
September 24-26, 2008	CBM Conference, Jing gangshan, Jiangxi, China	Research	China	98	RIPED
September 2008	Conference	Research	International	~ 100	RWTH
September 2008	Oral presentation and paper (conference ESREL 2008)	Research, and industry	International	> 2000	Oxand / SLB
September 2008	Oral presentation (conference EUROCORR 2008)	Research and industry in corrosion	International		TNO
September 2008	Oral presentation (conference ISE)	Research and industry in corrosion	International		TNO
September 2008	Publication: Int. J. Coal Geol.	research	International	1000- 10000	TNO
September 2008	Italian local TV	Regional broad audience	Italy	>25,000	TNO
September 2008	Conference: 2 nd CCS conference Brazil	Research + Industry	Brazil	350	TNO
September 2008	Open workshop	Local/regional/natio nal stakeholders in an area (Sardinia, Italy) currently under evaluation for ECBM	Italy	20	IEA GHG
September 2008	Publications	Coal & (E)CBM Research	International	1000	UU / TNO
September 2008	CBM Conference	Research	China	80~120	RIPED
November 11, 2008	Workshop with RWTH-Aachen, U- Utrecht, Monash University and Shell	University, Industry (CSS)	Netherlands, Germany, Australia	10	Shell, RWTH, UU
November 17-20, 2008	Conference, Poster, Publication	Research, Industry (CCS)	International	1000	Shell
November 2008	Conference	Research	International	> 100	RWTH
November 2008	Poster presentation and paper (conference GHGT-9, 2008)	Research, and industry in CCS business	International	≈ 1300	Oxand / SLB

Planned/ actual dates	Type	Type of audience	Countries addressed	Size of audience	Partner responsible/ involved
November 2008	Poster presentation and paper (conference GHGT-9, 2008)	Research, and industry in CCS business	International	≈ 1300	SLB/Oxand /TNO
November 2008	Oral presentation and paper (conference GHGT-9, 2008)	Research and Industry	International	1500	TNO
November 2008	Poster presentation and paper (conference GHGT-9, 2008)	Research and Industry	International	1500	TNO
November 2008	Publication: Int. J. Coal Geol.	Research	all	1000- 10000	TNO
December 2008	Newsletter article	IEA GHG membership, international scientific community	International readership, covering 113 countries	Approx 7100	IEA GHG
January 2009	Newsletter article	IEA GHG membership, international scientific community	International readership, covering 113 countries	Approx 7100	IEA GHG
2009	Publications	Researchers and anyone who is interested.	Non-specific	Unknown	CSIRO
2009	Paper (Journal of Fuel Chemistry and Technology)		China		SKLCC, Shell
In prep.	Publications	Higher education	International	1000- 10,000	RWTH

2.3 Publishable results

IPR protection of exploitable results is still under evaluation.