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Assessment of CO_2 storage performance of the Enhanced Coalbed Methane pilot site in Kaniow

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Abstract

A pilot site for CO_2 storage in coal seams was set-up in Poland, as has been reported on previous GHGT conferences. This site consisted of one injection and one production well. About 760 ton of CO_2 has been injected into the reservoir from August 2004 to June 2005. Breakthrough of the injected CO_2 was established, which resulted in the production of about 10% of the injected CO_2 by the production well in this period. A follow-up EC project, MOVECBM, aimed at determining the storage performance of the reservoir, i.e. whether the injected CO_2 was adsorbed onto the coal or whether it was still present as free gas in the pore space. The injection well was used for this purpose, because the production well had to be abandoned for permitting reasons. Several operational periods can be defined between the last injection in June 2005 and the abandonment of the well in October 2007. In the first period the well was shut-in to observe the pressure fall-off, followed by a decrease of pressure at the wellhead by releasing gas in a controlled way in the first months of 2006. The amount and composition of the gas were measured. As a result of the pressure reduction, the well flooded with water. A production pump was placed on the former injection well, enabling active production from the coal from March to September 2007. Results of these operations showed that whereas the gas production rates were as expected based on the experience with the production well, the water production was remarkably low. Further, 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. Although stabilization was not reached within the production period, the composition approached a 60% methane, 40% CO_2 ratio. This indicates that the exchange of these gases is more complex than often envisaged. After removal of the pump the well was filled with water, which ceased the gas release. This indicates that the pressure in the reservoir was back to its original, hydrostatic, state. As the total volume of CO_2 produced was only a fraction of the amount that was injected, it can be concluded that the CO_2 was taken up by the coal and is currently adsorbed. This gives confidence in the long-term stability of the injected CO_2. In conclusion, the field demonstration in Poland has been a successful experiment. Lessons learned in this demonstration indicate that the volumes that can be injected in low permeability coal seams (< 2mD) by a vertical well is likely to be less than 100 ton per day. The expected CBM production at these rates will be 1.5 to 2 times higher than by regular CBM operations 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.

Keywords: carbon dioxide ; swelling; production; injection

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1. Introduction

Storage of carbon dioxide (CO_2) in coal seams in the underground is considered to be one of the options to reduce the emissions of this greenhouse gas into the atmosphere. This technique has been tested in the field in the Upper Silesian Coal Basin in Poland. The results of the injection and production of this pilot site were reported extensively before [1]. In the follow-up period after the injection several activities were undertaken at the field site to assess the storage performance of the reservoir, i.e. whether the injected CO_2 was adsorbed onto the coal or whether it was still present as free gas in the pore space. Detailed descriptions of activities and results of this period have been reported recently by Van Bergen et al. [2]. This paper provides an overview of the activities and results of this period with emphasis on the conclusions drawn from this field demonstration. Further, the lessons learned that are relevant to other coal basins will be discussed.

2. Operations of the field pilot

The activities on the field site are summarized in this section, based on Van Bergen et al. [1] and [2]. 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 1. The Enhanced Coalbed Methane (ECBM) pilot site is located in the Upper Silesian Coal Basin (USCB) in Poland. The Carboniferous coal-bearing deposits in the USCB have a total thickness of at least 1000 m in the 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 upthrusted 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 uncomformably and disconcordantly 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 m^3/ton (dry ash free, i.e., corrected for moisture and mineral content of the coal), with CH_4 concentrations of usually 95 % or higher, with some percentages of N_2 (0.5-3 %) and CO_2 (1-3 %) and traces of other gases. Desorption tests, however, took several months and showed very slow diffusion out of the coal matrix.

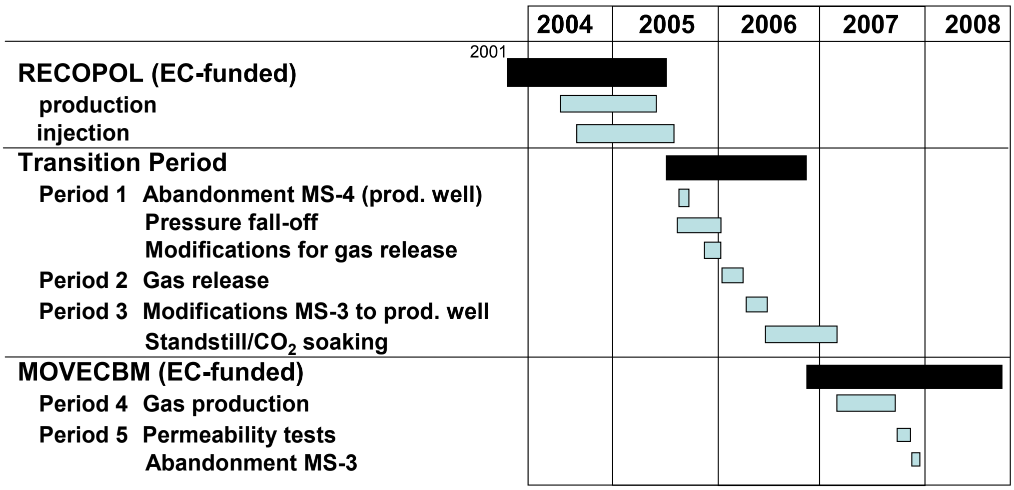

Figure 1 Overview of the main operational activities in the period of 2004-2008.

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 CO_2 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 CO_2 have been injected into the reservoir from August 2004 to June 2005. Breakthrough of the injected CO_2 was established, which resulted in the production of about 10% of the injected CO_2 by the production well in this period. As such, a total of 692 tons of CO_2 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 m^3 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% CH_4 and 60% CO_2. The CH_4 concentration appears to increase very slowly. During the gas release in this period 1322 m^3, or 2.5-3.0 tons CO_2 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).

Figure 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 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.

3. Results of the field pilot

The development of the field demonstration has been very worthwhile from an organizational point of view related to the future development of on-shore storage site in Europe. Many issues were solved in the course of the project, related to technology, regulations and public acceptance and perception.

From an operational side, an important lesson learned from this field experiment was that injection into these low permeability coal seams is not trivial. It was expected that a high injection pressure would overcome the low injectivity but this appeared not to be the case. Flexibility in the operational equipment and metering tools is highly recommended.

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 3). 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 CO_2 may have eventually sealed the coal matrix. This result gives confidence in the long-term stability of the injected CO_2.

CO_2 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/fixed in the reservoir:	682 [t]
• about 90% of injected CO_2	

Figure 3 Mass balance of the injected CO_2

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 CO_2 into the coal would be associated with release of more CH_4 than was currently observed from the production because of the higher affinity of coal for CO_2. 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% CO_2 and 60% CH_4 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 CO_2 is more probable [3]. The resulting composition of the gas after a 1 year soaking period, 60% CH_4 and 40% CO_2, could not be readily explained. These results suggest that while significant amounts of CO_2 are able to diffuse into the coal, there is hardly any diffusion of CH_4 out of the coal. The often reported exchange ratio of 2 molecules of CO_2 for 1 molecule of CH_4 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 CO_2. 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 CO_2 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 4).

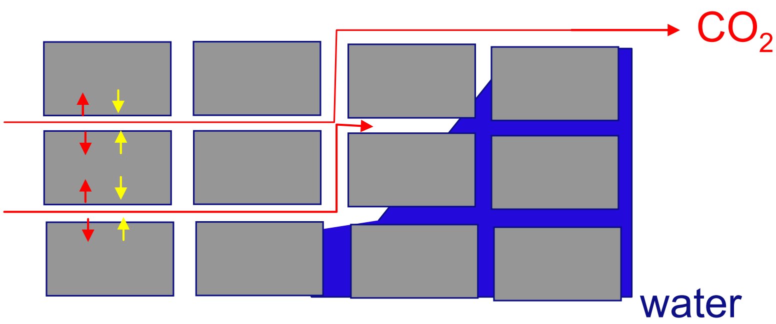

Figure 4 Schematic picture of part of the coal seam, representing a view on the face cleat surface. Because the transport time for the CO_2 in the cleats is much faster than the transport of the matrix, much of the CO_2 can already pass the matrix before the CBM can be released. Also, gravity override can occur if the cleats are still filled with water.

4. Lessons learned relevant to other coal deposits

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. Still, some general conclusions can be made that are relevant to other basins with similar low permeability coal.

Firstly, in planning an operational phase of any ECBM project it is vital to have a general idea about the in situ processes with regard to matrix diffusion and development of coal swelling. Secondly, 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 storage options. 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 are anticipated in storage projects in depleted gas fields or aquifers many vertical wells will be required which has to be taken into account in the spatial planning of the operation. Technological solutions (e.g. horizontal/multi-lateral wells) may increase the injection rates. Thirdly, it should be realized that although CO_2 enhances CH_4 production significantly (up to 2 times as much gas) this is probably not sufficient to change the CBM production of a non-commercial well into a commercial well. As such, ECBM seems to be most feasible when it can be applied in an area with existing, thus commercial, CBM production. In this case, major investments in wells and infrastructure are already made. ECBM would than be applied as a secondary production phase after regular CBM peak gas production (Figure 5). This has three other major advantages: the coal reservoir is already dewatered before CO_2 injection, it is depressurized and the quality of the gas is not affected by potential mixing with the injected CO_2 during the primary production phase. The disadvantage of this application is the long time it can take, possibly several years after the start of CBM production, before CO_2 injection starts. A tertiary phase in the operations can be envisaged during which CBM production ceases while CO_2 is still being injected, making this a pure storage operation in this phase. Fourthly, it is emphasized that both cleat and matrix transport properties should be taken into account. Low permeability of coal is likely to be related with a compaction stage during geological history. This will also have affected matrix compaction and therefore it can be expected that low cleat permeability is associated with slow matrix transport. Overcoming permeability problems (e.g. fracture stimulation) does not overcome matrix transport problems. Dedicated operational plans with optimized injection rates are required.

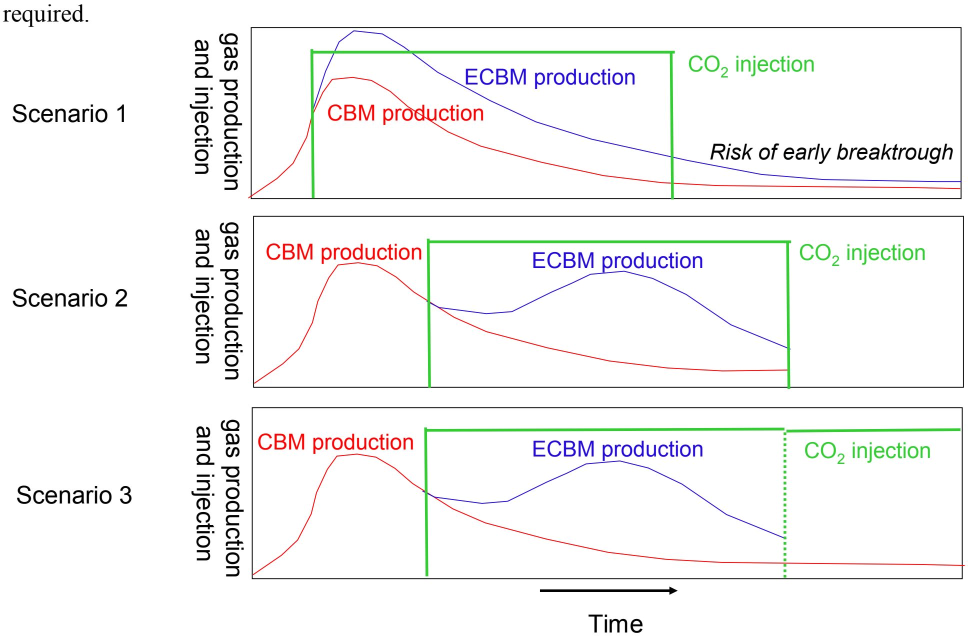

Figure 5 Different scenarios for future ECBM operations. Scenario 1 is often envisaged for storage in coal seams in unexplored coal basins, where it is wanted to inject CO_2 as early as possible to establish emission reductions. Associated with this scenario are the chance for an early breakthrough and the need for high injection pressures to overcome the hydrostatic pressure. These issues could be resolved in scenario 2, where the water and therefore the pressure in the coal are already depleted. Additionally, the mixing of CBM with CO_2 is postponed until after the peak production. Also, investments have been made during the primary phase which do not need to be earned back from the CO_2 operations. In scenario 3, there is a third phase with continued CO_2 injection. However, gas production is stopped because of uneconomical production due to a high CO_2 concentration after breakthrough.

In conclusion, coal holds an enormous volume of methane and provides a large potential storage medium for CO_2. 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 (Figure 6) and hardly any alternative options for CO_2 storage (Figure 7). The success of ECBM might become crucial in climate friendly energy production for those regions.

Figure 6 Distribution of coal in the world

ECBM projects can work if the boundary constraints are taken into account in the planning, with the most important being the injection volumes of CO_2 and the produced amounts of CBM, given the number of wells possible in the area. These volumes may be increased through technological developments, especially in drilling technology. Basic screening criteria for coal should be further developed related to transport properties, including the role of neighbouring strata and mineral matter.

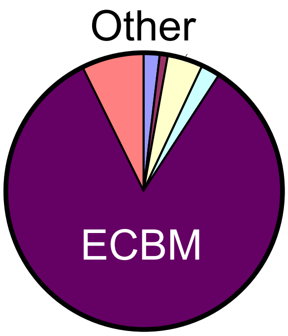

Figure 7 Relative portfolio of storage options (theoretical capacity) for China, based on an internal study.

5. Conclusion

- The field demonstration in Poland has been a successful experiment. A lot has been learned, especially considering the coal swelling under field conditions (see also Van Wageningen et al. [3]).
- 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 (< 2mD) 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.

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