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Dossier

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

CO_2 Storage in Deep Unminable Coal Seams

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Résumé — Stockage du CO_2 dans des veines de charbon non exploitables — Le mécanisme de stockage du CO_2 dans les veines de charbon *(coalbeds)*, l'adsorption, est très différent de ceux intervenant dans les réservoirs d'hydrocarbures ou dans les aquifères, où le CO_2 occupe les pores en tant que phase distincte ou bien est dissous dans l'eau ou l'huile. Durant les 20 dernières années, le méthane issu des veines de charbon (*coalbed methane* ou CBM) est devenu une source importante (non conventionelle) de gaz naturel aux États-Unis. L'injection de CO_2 pour augmenter la récupération de CBM (CO_2-ECBM) est une technologie émergente qui pourrait permettre de stocker des volumes importants de CO_2 anthropique dans les veines de charbon, tout en augmentant l'efficacité de la production de méthane.

Abstract* — *CO_2 Storage in Deep Unminable Coal Seams — *The gas storage mechanism in coal seams, adsorption, is distinctively different from that in oil and gas reservoirs and aquifers, where injected CO_2 occupies the pore space as a separate phase or is dissolved in water or oil. Over the last two decades coalbed methane (CBM) has become an important source of (unconventional) natural gas supply in the United States. Carbon dioxide enhanced coalbed methane recovery (CO_2-ECBM) is an emerging technology, which has the potential to store large volumes of anthropogenic CO_2 in deep unminable coal formations (coalbeds), while improving the efficiency and potential profitability of coalbed methane recovery.*

INTRODUCTION

Adsorption is the main storage mechanism in coal seams at high pressure. Methane, which is one of the by-products (the others being water and CO_2) of the coalification process in coal seams, is primarily stored as a sorbate on the internal surface area of the microporous coal. Injection of CO_2 into deep seams initiates a displacement desorption process whereby adsorbed methane is displaced by the injected CO_2.

CO_2-ECBM in coalbed reservoirs is broadly analogous to CO_2 enhanced (oil) recovery. However, coalbeds are distinctively different from the conventional hydrocarbon reservoirs in production as well as gas storage mechanisms. Coalbeds are both a reservoir and source rock.

As well as some theoretical research in Europe, North America and Australia, a number of field trials, such as the Allison pilot in the San Juan Basin and the ARC micro-pilot in Alberta, are helping our understanding of the reservoir mechanisms that control the flow and retention of CO_2 in coal seams.

In order to move this technology towards wider acceptance, especially as a CO_2 storage measure, it is important that an adequate number of long-term "field demonstration laboratories" are set up and confirm practical considerations, such as stability, economics, performance and public acceptance.

1 STORAGE MECHANISM AND CAPACITY

Coalbeds may be characterised by two distinctive porosity systems: a well-defined and almost uniformly distributed network of natural fractures (generated by the shrinkage of the source plant material) and matrix blocks containing a highly heterogeneous porous structure between the cleats. The natural fractures (also known as cleats) can be subdivided into the face cleat, which is continuous throughout the reservoir, and the butt cleat, which is discontinuous and terminates at intersections with the face cleat *(Fig. 1)*. The cleat spacing is very uniform and ranges from the order of millimetres to centimetres.

The pore structure of coal is highly heterogeneous, with the pore size varying from a few Angstroms to frequently over a micrometer in size. According to the *International Union of Pure and Applied Chemistry (IUPAC)* classification (1994), pores may be divided into macropores (> 50 nm), transient or mesopores (between 2 and 50 nm) and micropores (< 2 nm). Determination of pore volumes and their distribution in coals is important to understand how gases such CH_4 and CO_2 are stored in the coalbeds. Gas and liquid adsorption are commonly used to study the pore structure of coal.

Many coals are found to exhibit a bidisperse (Gan *et al*., 1972; Thimons and Kissell, 1973; Smith and Williams, 1984) or even multi-modal (Clarkson and Bustin, 1999) pore structure. Gan *et al*. (1972) reported that significant fractions

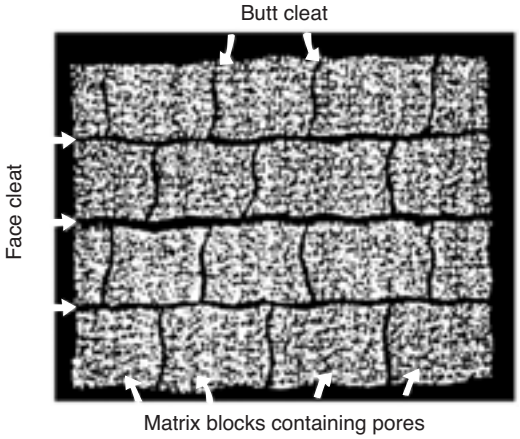

Figure 1

A schematic of coal structure.

of the total pore volume of the Eastern United States coals they studied were found to be in sizes greater than 30 nm and less than 1.2 nm.

Gases are stored in coal by three mechanisms:
- physically adsorbed compounds on the internal surfaces of coal;
- absorbed within the molecular structure;
- within pores and natural fractures.

Gas stored by sorption in the coal matrix accounts for approximately 95-98% of the gas in the coal seams. The shape of adsorption isotherms can provide information on the adsorption process, the porosity, and the surface area of the adsorbent. Methane and CO_2 adsorption on coal is usually described by a Langmuir-type isotherm, indicating that the adsorption is dominated by micropore-filling process.

Gas adsorption takes place primarily in the micropores of the coal matrix. A significant proportion of the total open pore volume is located in micropores (Sharkey and McCartney, 1981) and thus the potentially available sites for adsorption. The surface area of the coal on which the methane is adsorbed is very large (20-200 m^2/g) and, if saturated, coalbed methane reservoirs can have five times the volume of gas contained in a conventional gas reservoir of comparable size (Marsh, 1987).

Carbon dioxide is known to have a greater affinity to coal than methane. Early laboratory isotherm measurements for pure gases have demonstrated that coal can adsorb approximately twice as much CO_2 by volume as methane. Recent research on CO_2 sorption capacity of different ranks of United States coal has shown that this ratio may be as high as 10:1 in some low rank coals (Stanton *et al*., 2001). Therefore, potentially large volumes of CO_2 could be stored in deep unminable coal seams worldwide.

A NOVEM report estimated that about 8 Gt of CO_2 could be stored in Dutch coals (Hamelinck *et al*., 2000). The CO_2 storage capacity of deep coals in Alberta, Canada has been

estimated to be about 20 Gt (Gunter *et al*, 1997). An update to an earlier study by Advanced Resources International (ARI, 1998; Stevens, 2002) shows that deep coals have 220 Gt of CO_2 (60 GtC) storage capacity worldwide. This evaluation is based upon the simple assumption that two molecules of CO_2 can be stored for every CH_4 molecule in place and therefore has considerable uncertainty. In a more recent study (Reeves, 2003), it was estimated that the CO_2 storage capacity of United States coalbeds is about 90 Gt. It is further estimated that between 25 and 30 Gt of CO_2 can be stored at a profit, and 80-85 Gt can be stored at costs of less than US$5/t (excluding any costs associated with CO_2 capture and transportation).

It is considered that injected CO_2 in coal seams will be trapped by combination of sorption on the coal surface and by physical trapping in the cleats within coal. Therefore, providing that coal is never mined, the CO_2 stored should, in theory, remain permanently within the coal deposits forever. Conservatively, the retention time for CO_2 injection in deep unmined coal seams are on the order of 10^5-10^6 years (Gunter *et al*., 1998).

2 METHANE AND CO_2 TRANSPORT IN COALBEDS

Virgin seams are often saturated with water. During primary recovery by pressure depletion, methane production is facilitated by dewatering the target seams to allow desorption of the adsorbed methane, which then migrates through the coal matrix into the cleats. In the early stages of dewatering, mainly water will be produced. As more and more gas desorbs and becomes available for production, a two-phase flow regime will develop. Eventually the water production will tail off and become insignificant and the coalbeds behave almost as a dry gas reservoir. It is generally assumed that flow of gas (and water) through the cleats is laminar and obeys Darcy's law. On the other hand, gas transport through the porous coal matrix is controlled by diffusion.

2.1 Gas Diffusion in Coal

Three mechanisms have been identified for diffusion of an adsorbing gas in the macropores. They are molecular diffusion (molecule-molecule collisions dominate), Knudsen diffusion (molecule-wall collisions dominate) and surface diffusion (transport through physically adsorbed layer). The effective macropore diffusivity is thus a complex quantity which often includes contributions from more than one mechanism. As a rule of thumb, molecular diffusion prevails when the pore diameter is greater than ten times the mean free path; Knudsen diffusion may be assumed when the mean free path is greater than ten times the pore diameter (Yang, 1997). In the intermediate regime both wall collisions and intermolecular collisions contribute to the diffusional resistance and the effective diffusivity depends on both the Knudsen and molecular diffusivities. Because of the dependence of mean free path on pressure, for any given adsorbent and adsorbate, there will be a transition from Knudsen flow at low pressures to molecular diffusion at high pressures (Smith and Williams, 1984).

It has been estimated that the mean free path of the methane molecule at room temperature and atmospheric pressure (0.1 MPa) is about 50 nm (Thimons and Kissell, 1973). In deep coal seams, the reservoir pressure will be much higher (> 5 MPa) and thus the mean free path would be substantially lower than 50 nm. This implies that molecular and transitional diffusion, rather than Knudsen diffusion, would prevail in the macropores of deep coal seams.

Due to their extremely small pore sizes, gas diffusion in micropores (< 2 nm) is controlled by a distinctively different mechanism. In fine micropores (< 1 nm), the diffusing molecules never escape the potential field of the adsorbing surface, and their transport occurs by an activated process involving jumps between adsorption "sites". Thus, the process is more similar to surface diffusion than to ordinary pore (or macropore) diffusion, except that the domain through which diffusing molecules migrate is not a two-dimensional surface but rather a three-dimensional space (Ruthven, 1984). Studies on transient diffusion of several gases in eastern United States coals (Nandi and Walker, 1964; 1970; Nelson and Walker, 1961) have shown that diffusion of CO_2, N_2 and CH_4 from ultra-fine pores is activated.

2.2 Counter-Diffusion and Competitive Desorption

During a CO_2 storage/enhanced methane recovery operation, flow of CO_2 gas in the cleats would initiate a counter-diffusion between CH_4 and CO_2 in the coal matrix, whereby adsorbed methane molecules are displaced by incoming CO_2 molecules, which has a higher adsorption capacity in coal. Although diffusion of methane and other gases in coal has been extensively investigated in the past, research on CO_2-CH_4 counter-diffusion and competitive adsorption/desorption in coal has been very limited.

CO_2 has a greater adsorption capacity, ranging from 2 to 10 times depending upon coal rank, than methane under normal reservoir pressures. Therefore one might conclude that CO_2 component in a CO_2-CH_4 binary mixture would preferentially adsorb in coal, whereas the CH_4 component would preferentially desorb. However, this has turned out to be an over-simplified statement, as demonstrated by recent laboratory studies. Busch *et al*. (2003b) reported CH_4 preferential adsorption in the low-pressure range for a number of coals tested. Ceglarska-Stefanska and Zarebsks (2002) concluded that coal properties, such as capillary structure or maceral composition, could act to reverses the usual trend and result in preferential desorption of CO_2. Further research in this field should aim at eliminating any uncertainty in our understanding of this phenomenon.

Kroose *et al*. (2002) carried out high-pressure CH_4 and CO_2 adsorption tests on dry and moisture-equilibrated coals. They refer to the phenomenon of "negative excess sorption capacities", which was observed for CO_2 in the sorption pressure range 80 to 120 bar, to volumetric effects, *i.e*. coal swelling. The results indicate that swelling started at a pressure of about 80 bar, reaching a maximum at around 105 bar, and then declined with increase in the gas pressure.

There is laboratory evidence that CO_2 injection could also have a detrimental impact on the micropore diffusivities. "Adsorption swelling may narrow some micropore entrances and enhance the diffusion energy barrier of adsorbate in micropores, consequently reducing the diffusivities" (Cui *et al*. 2003). Shi and Durucan (2003a) applied a bidisperse pore-diffusion model that accounts for both macropore and micropore diffusion in the coal matrix to analyse the performance of a laboratory core flush test and found that a variable apparent micropore diffusivity, which declines with increasing total sorbate concentration in the coal sample, was required to yield a close match to the test data.

Given that the pore structure of coal matrix is highly heterogeneous and gas adsorption takes place primarily in the micropores (< 2 nm), the relative adsorbate molecule size and pore structure may be expected to play an important role in selective gas adsorption and diffusion in coal. In a recent study (Cui *et al*, 2003) the apparent micropore diffusivity of the three gases (CH_4, CO_2 and N_2) were measured on a high volatile, moisture-equilibrium bituminous coal for sorption pressures of up to 5 MPa. The apparent micropore diffusivities of the three gases tested was found to correlate strongly with their gas kinetic diameter. For example, CO_2 has the largest apparent micropore diffusivity among the three gases, in contrast to the theoretical self-diffusivities of the three gases in open space, due to its relatively small kinetic diameter (0.33 nm as compared to 0.38 nm for CH_4 and 0.364 nm for N_2). This suggests that coal has an interconnected pore network highly constricted by ultra micropores (< 0.6 nm). Busch *et al*. (2003a) also observed that CO_2 tends to desorb faster from crushed coal particles than CH_4 does under similar test conditions.

It needs to be pointed out that the above studies on selective gas transport in coal matrix were performed under the sub-CO_2 critical pressure. Furthermore, it is not clear that to which degree the observed selectivity for the three gases would be mirrored for a mixture of the two or three gas components? Therefore, further investigations on selective transport in the super-CO_2 critical pressure ranges, with a mixed gas, are imperative to achieve a better understanding of the selective transport phenomenon during CO_2 storage and enhanced CBM recovery in deep coal seems.

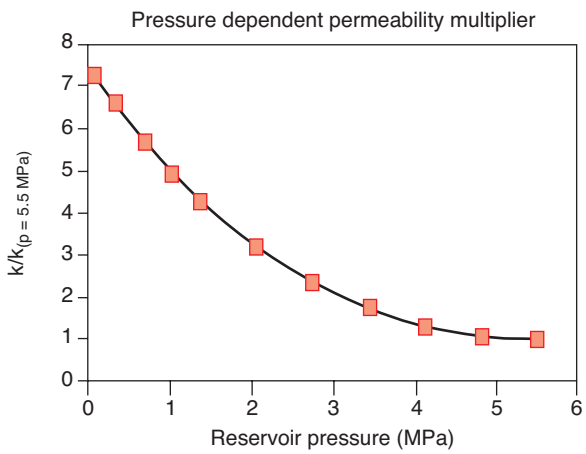

Figure 2

San Juan Basin coalbed permeability data (after McGovern, 2004).

2.3 The Response of Coalbed Permeability to Methane Production and CO_2 Injection

An important feature of coalbed reservoirs is that coal matrix shrinks (expands) on desorption (adsorption) of gases. Matrix shrinkage associated with methane desorption is generally regarded to be responsible for preventing the collapse of coalbed permeability caused by increasing compaction with reservoir pressure depletion during primary methane production. Both experimental measurements (*e.g*. Somerton *et al*., 1975; Durucan and Edwards, 1986) and theoretical studies (McKee *et al*., 1987 and Seidle *et al*., 1992) show that permeability of coal decreases exponentially with increasing effective stress. However, United States field experience has shown no noticeable reduction in the absolute permeability of coal during primary recovery. On the contrary, the absolute permeability appears to have increased with continuing pressure depletion in the San Juan Basin.

Figure 2 presents perhaps the most comprehensive set of data on the response of the absolute coalbed permeability to reservoir pressure depletion in the San Juan Basin at below 5.5 MPa when the reservoirs are largely dewatered (McGovern, 2004). The figure shows that the absolute permeability of the San Juan Basin coalbeds has increased by up to a factor of 7 as the reservoir pressure is reduced from 5.5 to 0.07 MPa. At higher reservoir pressures, estimation of changes in the absolute permeability becomes problematic due to the relative permeability effects.

During enhanced recovery/CO_2 storage in coal, the permeability behaviour is expected to be further complicated by adsorption of the injected gas(es) in coal. For example, the adsorption of CO_2 would cause matrix swelling which, in

contrast to matrix shrinkage, could result in a reduction in coalbed permeability.

CO_2 sorption on coal causes the matrix to swell, decreasing cleat width and, consequently, reducing permeability (Seidle, 2000). Early research has suggested that matrix shrinkage/swelling is proportional to the volume of gas desorbed/adsorbed, rather than change in sorption pressure (Harpalani and Chen, 1995; Seidle and Huitt, 1995). Recent laboratory studies on the impact of matrix swelling on coal permeability have confirmed these results. Reduction in permeability was observed in two studies (Durucan *et al*., 2003; Xue and Ohsumi, 2003). However, it must be noted that laboratory tests are normally performed under applied stress/gas pressure conditions and therefore do not conform to the field reservoir conditions where the coalbeds ate laterally bounded.

Field evidence concerning the impact of CO_2 injection on coalbed permeability is limited and not conclusive. Dramatic reduction (by up to 40%) in CO_2 injection rates is reported at the Allison pilot in the San Juan Basin at the early stages of CO_2 injection (Reeves, 2002). This reduction has been attributed to a two-order reduction in the coalbed permeability, as a result of CO_2 induced coal matrix swelling (Pekot and Reeves, 2003). Loss of injectivity is also observed at the CO_2 micro-pilot in the Qinshui Basin of Shanxi province, China (Law, 2004).

On the other hand, Mavor and Gunter (2004) found that CO_2 injection actually increased absolute and effective permeability to a level easily allowing injection into a low permeability (few mD) seam at the ARI micro-pilot (Fenn Big Valley, Canada). They also observed that CO_2 injectivity was greater than that for weakly adsorbing N_2, and contributed this to the use of alternating injection and shut-in consequences and perhaps as the result of coal weakening. Clearly, further field studies are required to elucidate the effect CO_2 injection on coalbed permeability and injectivity.

Other factors that could affect the CO_2 injectivity in CBM reservoir are:

- **Thermal effect of CO_2 injection:** Temperature of the injected CO_2 could be different from the temperature of the reservoir; therefore, the non-isothermal effects of gas flow may affect injectivity in the reservoir. Further development of the simulators to account for this effect is required.
- **Wellbore effects:** Drilling, production and/or injection of fluids affect the stress regime around the wellbore (Shi *et al*, 1997). As well as being affected by the pore pressure effects, the permeability regime around the borehole may be mechanically altered, affecting injectivity.
- **Precipitate formation**: An understanding of potential geochemical reactions between injected CO_2, the reservoir rock, and coal formation water is needed through laboratory and theoretical studies in order to evaluate the potential for precipitate formation. If these reactions do occur, there will be important implications for coalbed permeability, thus affecting CO_2 injectivity and storage/ECBM economics (Smith and Revees, 2002). Detailed water geochemical analyses as well as rock mineralogy, wellbore and reservoir temperature, and pressure information is needed to be investigated.

In order to alleviate the impact of CO_2 matrix swelling on well injectivity, the following techniques have been identified: injection of flue gas instead of pure CO_2; using multilateral horizontal boreholes to improve connectivity to the reservoir. Horizontal boreholes have the potential to tap into the anisotropic permeability of coal by cutting cross face cleats. Although hydraulic fracturing could also improve well injectivity, it is not advisable for CO_2 injection wells in order to avoid CO_2 leakage into the surrounding strata.

2.4 CBM/ECBM Permeability Models and their Validation

Permeability models (Pekot and Reeves, 2003; Shi and Durucan, 2003b; Mavor *et al*., 2004) have been developed to account for the effects of matrix swelling/shrinkage as well as pore pressure on permeability. The model developed by Shi and Durucan will be described in some detail, as it has been successfully used in history matching the Allison CO_2-ECBM pilot (Shi and Durucan, 2004).

The absolute permeability of coalbed varies exponentially with changes in effective horizontal stress:

$$k = k_0 e^{-3c_f(\sigma-\sigma_0)} \tag{1}$$

where c_f is referred to as the cleat volume compressibility with respect to changes in the effective horizontal stress normal to the cleats and k_0 is the initial coalbed permeability. The cleat volume compressibility is analogous to the pore volume compressibility for a conventional sedimentary porous rock. Cleat volume compressibility (with respect to the net/equivalent hydrostatic stress) for six San Juan Basin coal samples has been determined to range from 0.06206 to 0.5133 MPa^{-1} (Seidle *et al*., 1992).

Changes in the effective stress is given by:

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E}{3(1-\nu)}\sum_{j=1}^{n}\alpha_{Sj}(V_j - V_{j0}) \tag{2}$$

where α_{Sj} is the shrinkage/swelling coefficient, and V_j and V_{j0} are the specific adsorbed gas volume for component j at current and initial reservoir conditions (gas composition as well as pressure), respectively. Measurements by Levine (1995) and more recently by Chui (2004) indicate that matrix swelling is adsorbate specific. Specifically, gases with higher affinity to coal would result stronger swelling. This has a direct bearing on understanding and modelling the effects of CO_2 adsorption on coal permeability.

Using the extended Langmuir isotherm and assuming instant sorption equilibrium, the adsorbed gas volume for component j is given by:

$$V_j \approx V_{Ej} = \frac{V_{Lj} p_j b_j}{1 + \sum_{j=1}^{n} b_j p_j} = \frac{V_{Lj} p Y_j b_j}{1 + p \sum_{j=1}^{n} b_j Y_j} \quad (3)$$

where V_{Lj} and b_j are Langmuir parameters for gas component j and p_j is the partial free gas pressure, $\Sigma p_j = p$ and $Y_j = p_j/p$.

Equations (1), (2) and (3) may be used to estimate the impact of CO_2 injection on coalbed permeability. As shown in Figure 3a, magnitude of permeability reduction caused by CO_2 matrix swelling is strongly affected by the swelling coefficient ratio $\alpha_{CO_2}/\alpha_{CH_4}$. It was found that a close match to the field injection bottomhole pressures could be achieved by using $\alpha_{CO_2}/\alpha_{CH_4} = 1.276$, which would result in a drop of over two orders of magnitude in the permeability around the injection well ($Y_{CO_2} = 1$). The history matching results for injection well 141 at the Allison Unit CO_2-ECBM Pilot are presented in Figure 3b (Shi and Durucan, 2004).

3 CO_2 STORAGE IN COALBEDS WITH ENHANCED CBM RECOVERY

Current commercial CBM production is almost exclusively through reservoir pressure depletion (primary recovery), which causes incremental desorption of methane in a manner determined by the sorption isotherm. This production technique is simple but has long been recognised to be rather inefficient, given that the sorption isotherm is nonlinear and skewed towards the low-pressure end, which means that a large potion of the methane-in-place is only available to production at low reservoir pressures.

In the early 90's, enhanced coalbed methane recovery (ECBM), involving injection of N_2 or CO_2, was proposed as a more efficient means for the recovery of a larger fraction of methane in place without excessively lowering the reservoir pressure. The two principal variants of ECBM, namely N_2 and CO_2 injection, employ two distinct mechanisms to enhance methane desorption and production. The mechanism employed in nitrogen injection is somewhat similar to inert gas stripping since nitrogen is less adsorbing than methane. Injection of nitrogen reduces the partial pressure of methane in the reservoir, thus promotes methane desorption without lowering the total reservoir pressure.

On the other hand, carbon dioxide injection works on a different mechanism, namely competitive sorption, since it has a greater adsorption capacity, up to ten times depending on coal rank, than methane under normal reservoir pressures. CO_2-ECBM thus has an added benefit that a potentially large volume of greenhouse gas can be stored in deep coal seams globally.

Geological factors play a key role on coalbed methane reservoir capacity for CO_2 storage and potential methane production as ECBM:

– **Pressure, temperature, moisture content and rank:** In general, the gas content increases with coal rank, depth of the coalbed, and reservoir pressure. Moisture content may affect significantly the adsorption capacity, adsorption phase-density, and mixture adsorption behaviour. Temperature-pressure conditions have a strong influence on the CO_2 storage on coalbed methane reservoirs, as CO_2 becomes a supercritical above a temperature of 31.1°C

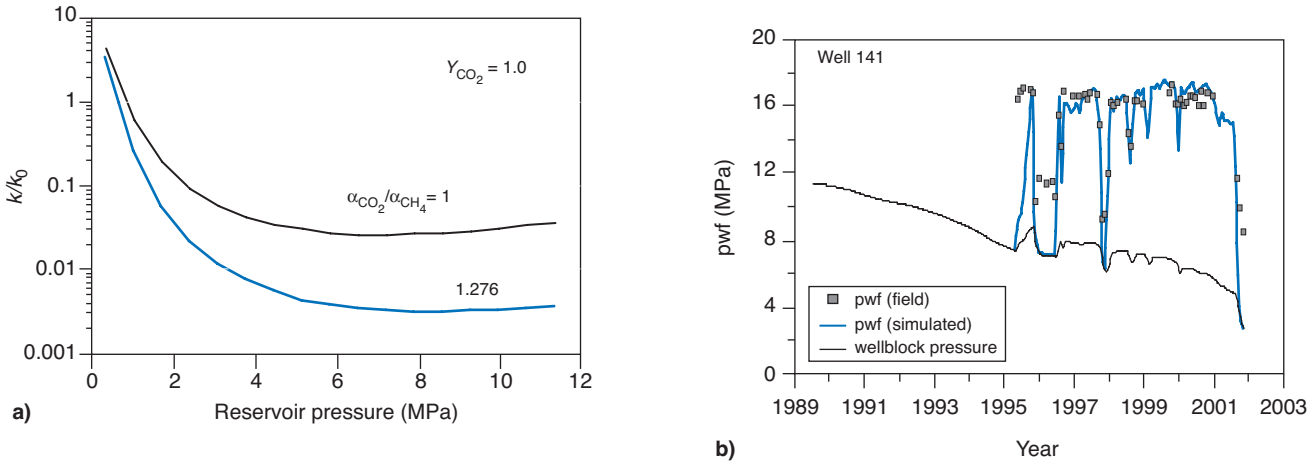

Figure 3

a) Model prediction of CO_2 injection on coalbed permeability; b) history match of the injection bottomhole pressure for well 141, at the Allison Unit CO_2-ECBM Pilot (After Shi and Durucan, 2004).

and a pressure of 7.4 MPa . Under supercritical conditions, coal can hold more gas than predicted by the Langmuir isotherm theory, yet the mobility and reactivity of supercritical fluids in coal-bearing strata are poorly understood (Pashin and McIntyre, 2003).

– **Local hydrology:** Often, the coalbed methane reservoirs are undersaturated with gas and need significant dewatering before coming on production. Hydrologoical constraint should be considered as one of the main factors for the effective CO_2 storage.
– **Inherent permeability**: Permeability of coal is considered as the main factor that control coalbed methane production during primary and enhanced coalbed methane recovery through CO_2 injection. US experience suggests that an absolute permeability of 10^{-15} m^2 (1 mD) is generally required to achieve commercial production rates. Theoretical and experimental studies investigating the effects of stress on coal permeability have been reported in the literature and indicate that coal permeability declines exponentially with depth. Shallow reservoirs tend to be low in reservoir pressure and gas content, whereas deep reservoirs suffer from diminished permeability. Seams deeper than 1500 m are generally considered not suitable for CBM extraction due to the excessive overburden weight.
– **Structural setting:** Favourable areas for successful CO_2-ECBM application would have coal seams that are laterally continuous and vertically isolated from the surrounding strata (Stevens *et al*, 1998). This will ensure containment of injectant within the reservoir as well as efficient lateral sweep through the reservoir. Furthermore, the reservoir should be minimally faulted and folded to avoid CO_2 channeling.
– **Natural analogues:** Natural CO_2 fields may be viewed as unique "natural analogues" that can be used to assess crucial aspects of geologic storage. These assessments would include: integrity of storage, candidate site screening and selection, and operational safety and efficiency. Thus, these CO_2 deposits offer considerable potential for understanding and publicising geologic storage and can serve to build public confidence in this CO_2 management technique.

3.1 CO_2-ECBM Field Projects

The Allison unit pilot, which is located in the Northern New Mexico sector of the San Juan Basin, represents the world's first field trial on CO_2-ECBM (Stevens *et al*., 1998). The San Juan Basin hosts the most prolific CBM developments in the world. In 1998 it was responsible for 75% of total worldwide CBM production. The field is well studied and characterised. The pilot area consists of four CO_2 injecting wells and nine producing wells, drilled on a 320-acre spacing. CO_2 injection started in April 1995, after approximately six years of primary production, and was suspended in August 2001. A total of 4.7 Bcf CO_2 was injected into the four wells, with only limited CO_2 breakthrough. Reservoir simulation and history matching studies indicate that enhanced CBM recovery and simultaneous CO_2 storage has occurred (Reeves *et al*., 2003; McGovern, 2004). It is estimated that injection reported to date will yield 1.6 Bcf of incremental gas reserves.

The Alberta Research Council is performing a project entitled "Sustainable Development of Coalbed methane; A Life-Cycle Approach to Production of Fossil Energy" (Gunter, 2000). The project consists of five phases: I) Proof of concept for Alberta (1997); II) Single well CO_2 micro-pilot (1998); IIIA) Single well flue gas micro-pilot (1999-2001); IV) Matching CBM resource with CO_2 sources (2002-2005); IIIB) Multi-well CO_2-pilot (2002-2005); and V) Methanogesis of coals (2002-2010). Phases I, II and IIIA have been completed. ECBM micro-pilot tests at two wells in the Fenn Big Valley using CO_2, N_2 and, for the first time, flue gas injection were successfully carried out. One of the main conclusions of the field study is that "low permeability coal seams that may not be commercial under primary production could still be CO_2 storage sites with the added benefit of improving the possibility for commercial productivity" (Mavor and Gunter, 2004b).

The success of the CO_2-pilot test in Alberta has led to the launch of a new pilot initiative in late 2001 "CO_2 Sequestration and Enhanced Coalbed Methane Production (CSEMP)" by a consortium led by *Suncor Energy Inc.* (Melnic, 2004). The objective of this pilot is to test coal seam response to CO_2 injection, determination of CO_2 storage parameters, to evaluate the ECBM production potential and establish storage, monitoring and verification parameters. The project area is located at the Pembina field in west-central Alberta. The zone of interest is the Ardley coal at depths of greater than 400 m.

A demonstration pilot was planned at the Dawson River Site, Southern Bowen Basin in Australia where major coalbeds and CO_2 sources are located (Bradshaw *et al*., 2001). The pilot is planned to run in three phases spanning 4.3 years:

– micro-pilot testing;
– five-spot pilot testing;
– nine-pattern field-testing (16 injection and 25 production wells).

The main objective of the demonstration pilot is to collect sufficient data to evaluate the technical and economic performance of the coalbed reservoir and feasibility for installation of a commercial CO_2-ECBM and storage operation.

The RECOPOL (Reduction of CO_2 emissions by means of CO_2 storage in the Silesian Coal basin of Poland) project is a European Commission funded field demonstration project looking into the technical and economic feasibility of

ECBM and CO_2 storage in a European setting (Pagnier and Van Bergen, 2002). The project site in the Silesian basin was chosen for its favourable reservoir properties (depth, permeability, gas content etc), and an existing infrastructure (surface facilities and two existing production wells). The projected started in November 2001. A new injection well has been drilled and completed. CO_2 injection is currently under way.

An ARC led joint Sino-Canadian ECBM project "The development of China's Coalbed Methane Technology and Carbon Dioxide Storage Project" started in March 2002 (Law, 2004). The 3.5 years project has a joint budget of 10 M Canadian dollars. The micro-pilot test site is located at the Qinshui Basin in the Shanxi province. The high rank (semi-anthracite and anthracite) target coal seam is less than 500 m deep and has a net thickness of just over 6 m. The progress to date includes the successful completion of a single well CO_2 micro-pilot tests and coal characterisation. The results indicate that CO_2 storage in low permeability coal seams (few mD) is feasible.

In Japan, a CO_2 storage project entitled "Technology Development for Carbon Dioxide Sequestration in Coal Seams" commenced in 2002 (Yamaguchi *et al*., 2004). This project involves fundamental research into CH_4-CO_2-coal interaction, CO_2 monitoring technologies, cost reduction of CO_2 capture from flue gases, and economics of storage. One important component of the project is a micro-pilot test. After preliminary screening the Ishikari Coal Field in Hokkaido was selected as the micro pilot test site. In 2003, the first well (Shuparo IW-1) was drilled. Field studies are currently being undertaken.

Consol Energy is exploring the effectiveness of horizontal wells for CO_2-ECBM on a 200-acre undeveloped block in north-western Virginia in the Appalachian Basin (Cairns, 2003). The project includes one mineable and one unminable seam. Deviated slant wells with multi-laterals from the surface are being used. After primary production from the two seams monitored CO_2-ECBM recovery is planned to run for two years in the unminable seam only. The project is expected to run for 5-7 years.

3.2 Numerical Modelling Tools

The use of numerical models is essential in the development of ECBM and CO_2 storage technology. However many researchers still believe that CO_2 injection in coalbeds is extremely complex and not fully understood. A better understanding of all the mechanisms involved in the CO_2 storage/ECBM recovery processes is necessary in order to establish full confidence in the numerical models used in assessing the performance of this process.

A study led by Albert Research Council (Law *et al*, 2002a) initiated a simulator comparison study for the current numerical simulators used for CO_2-ECBM. Six numerical simulators have participated in the comparison study: METSIM2 (*Imperial College*, United Kingdom), GEM (*CMG*, Canada), ECLIPSE (*GeoQuest*, United Kingdom), COMET2 (*ARI,* USA), SIMED II (*TNO&CSIRO,* the Netherlands/ Australia) and GCOMP (*BP-Amoco*, United States). The findings of this comparison study have been progressively reported by Law *et al* (2000; 2002a; 2002b; 2003). It was recommended that an ECBM simulator should have all the basic capabilities that a commercial coalbed methane simulator for primary CBM recovery has, as well as the capability to handle:

- multi-component gas mixtures;
- matrix swelling effects due to CO_2 adsorption on coal;
- mixed gas adsorption;
- mixed gas diffusion;
- non-isothermal effect for gas injection.

The *Imperial College* permeability model (Shi and Durucan, 2004) is implemented in METSIM 2. Different models are featured in GEM and COMET2. The extended Langmuir model is almost exclusive used in all the simulators, even though there is laboratory evidence that other isotherm models, such as the two-dimensional equation-of-state and ideal adsorbed solution (IAS) models are more accurate than the extended Langmuir model in describing binary gas sorption in coal (Hall *et al*., 1994).

The Allison CO_2-ECBM pilot, augmented by a detailed reservoir characterization work carried out in a recently completed DOE sponsored research project (Reeves *et al*., 2003), provides a unique benchmark test case for reservoir simulation of ECBM recovery and associated CO_2 storage. In a recent history matching study (Shi and Durucan, 2004), the validity of Imperial College model in describing permeability changes in coalbeds under CO_2-ECBM conditions has been confirmed. In addition, the extended Langmuir sorption equations have also been proved to be adequate, at least within the context of this simulation effort, in modelling competitive desorption of methane in coalbeds.

3.3 Environmental and Safety Issues

3.3.1 Health, Safety and Risk Assessment

The potential leakage paths for CO_2 storage in coalbed reservoirs are;

- natural pathways such as faults and/or fractures;
- poorly cemented wellbores;
- wellbore and/or caprock failure;
- dissolved CO_2 in groundwater.

During CO_2 storage, there is the possibility that free or dissolved CO_2 will diffuse into the caprock. This might trigger geochemical reactions between dissolved CO_2 and the minerals present in the cap rock and affect the sealing

capacity. This process may take a long time, however, an understanding of the caprock mineralogy and its geochemical behaviour is essential.

With regards to geological disposal of CO_2, coordinated research efforts are underway in North America, Europe and Australia to study naturally occurring carbon dioxide deposits (NASCENT, NACS and GEODISC projects), with a view to understand and explain the CO_2 storage process in natural reservoirs (Czernichowski-Lauriol *et al*., 1996; Pearce *et al*., 1996). As a first step in the CO_2 Capture Project (CCP) (Lewis, 2002), a HSE risk assessment literature search has been conducted (Benson *et al*., 2002) and TNO has investigated a safety assessment methodology using FEPs (Features, Events and Processes) principle for two European scenarios. This work was based on qualitative risk assessment in the first instance (Lewis, 2002; Wildenborg, 2001).

The assessment of the risks associated with the storage of CO_2 in deep coal seams requires the identification of the potential subsurface leakage processes, the likelihood of an actual leakage, the leak rate over time and long-term implications for safe storage. The truly quantitative assessment of uncertainty and risk associated with this process can only be achieved if the reservoir parameters and physical process involved are used to quantify these risks. As part of the CO_2 capture project, researchers at the INEEL have conducted a probabilistic risk assessment study of CO_2 storage in coalbeds utilizing the BP's in house reservoir simulator GCOMP (Liang, 2001). The risk quantification is carried out by randomly selecting input parameters from distributions, conducting the model runs, analysing the output and assigning risk value and finally compiling statistics for the risk profile (Lewis, 2002). However, the Monte Carlo analysis approach is based on the assumption that the reservoir field data are random and independent of each other. Further research, which considers the:

– data uncertainty and variability,
– model parameter uncertainties,
– risk scenario uncertainties

is currently being carried out at *Imperial College*.

3.3.2 Produced Water

In general, coalbed methane wells initially produce large volumes of water. Formation water often contain dissolved salts and they can cause undesirable effects on aquatic organisms and sweet water resources. Consequently, the treatment of produced water should be considered as a priority, whether to inject them back to the formations or to treat them at the surface. Re-injection of formation water would be favourable for the high permeability seams, whereas surface discharge is a good cost-effective option for low permeability seams.

3.3.3 Monitoring

Research is needed to develop a comprehensive monitoring capability which:

– helps to ensure that geological storage of CO_2 is safe;
– enables the assessment of the volumes of stored CO_2 in order to satisfy regulators and local government officials.

Many tools exist or are being developed for monitoring geologic storage of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and bore hole seismic. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection (Klara *et al*, 2003). Therefore, further monitoring needs include:

– high resolution mapping techniques for tracking migration of stored CO_2;
– deformation and microseismicity monitoring;
– remote sensing for CO_2 leaks and land surface deformation.

4 RECOMMENDATIONS FOR FUTURE RESEARCH

The technology of CO_2 storage in deep unminable coal seams is still in its development phase. Basic, fundamental and applied research programs, as well as field demonstration projects, are required to address the existing knowledge gaps. Further research is required on:

– Mobility and reactivity of supercritical fluids in coal-bearing strata.
– Pore pressure and adsorbate gas species effects on matrix swelling and permeability.
– Relative permeability of coal matrix and cleat.
– Selective transport of gases in the super-CO_2 critical pressure ranges.
– Preferential sorption and desorption of CO_2, CH_4 and other gas mixtures.
– Geochemical reactions between injected CO_2, coal as well as impurities, and formation water.
– Numerical modelling tools incorporating:
  • pore pressure effects;
  • wellbore mechanical behaviour;
  • mixed gas adsorption;
  • mixed gas diffusion;
  • geochemical reactions;
  • non-isothermal effect of gas injection.
– Caprock mineralogy, its geochemical and mechanical behaviour.
– Subsurface and surface uncertainty modelling and risk assessment,
– Data and risk scenario uncertainty modelling and risk assessment.
– Reservoir screening criteria for CO_2 storage in coals within Europe. The primary objective is to develop a

screening model that is widely applicable, that could quantify CO_2 storage, and apply screening modelling to identify favourable demonstration sites for CO_2 storage in Europe.
- Selection and implementation of a multi-well CO_2-ECBM demonstration project within a thoroughly studied coal basin in Europe. Controlled field experiments of injection and production well technology could be conducted to optimise CO_2-ECBM operating procedures.
- The economic potential and role of ECBM in future energy supply.
- The role of policy instruments that could stimulate ECBM development.

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