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CO₂ Storage in Deep Unminable Coal Seams

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Résumé — Stockage du CO₂ dans des veines de charbon non exploitables — Le mécanisme de stockage du CO₂ 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 CO₂ 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 conventionnelle) de gaz naturel aux États-Unis. L'injection de CO₂ pour augmenter la récupération de CBM (CO₂-ECBM) est une technologie émergente qui pourrait permettre de stocker des volumes importants de CO₂ anthropique dans les veines de charbon, tout en augmentant l'efficacité de la production de méthane.

Abstract — CO₂ 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 CO₂ 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 (CO₂-ECBM) is an emerging technology, which has the potential to store large volumes of anthropogenic CO₂ 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 CO₂) of the coalification process in coal seams, is primarily stored as a sorbate on the internal surface area of the microporous coal. Injection of CO₂ into deep seams initiates a displacement desorption process whereby adsorbed methane is displaced by the injected CO₂.

CO₂-ECBM in coalbed reservoirs is broadly analogous to CO₂ 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 CO₂ in coal seams.

In order to move this technology towards wider acceptance, especially as a CO₂ 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 as CH₄ and CO₂ 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

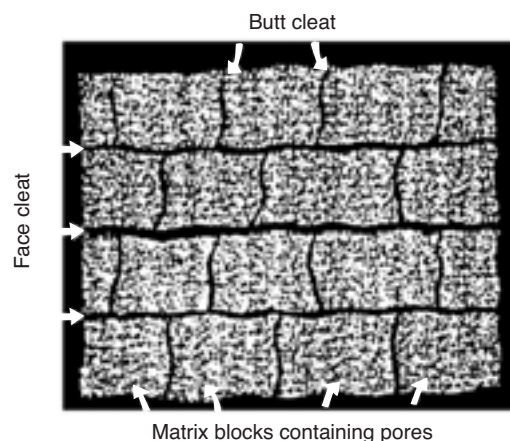


Figure 1
A schematic of coal structure.

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 CO₂ 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 m²/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 CO₂ by volume as methane. Recent research on CO₂ 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 CO₂ could be stored in deep unminable coal seams worldwide.

A NOVEM report estimated that about 8 Gt of CO₂ could be stored in Dutch coals (Hamelinck *et al.*, 2000). The CO₂ 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 CO₂ (60 GtC) storage capacity worldwide. This evaluation is based upon the simple assumption that two molecules of CO₂ can be stored for every CH₄ molecule in place and therefore has considerable uncertainty. In a more recent study (Reeves, 2003), it was estimated that the CO₂ storage capacity of United States coalbeds is about 90 Gt. It is further estimated that between 25 and 30 Gt of CO₂ 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 CO₂ capture and transportation).

It is considered that injected CO₂ 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 CO₂ stored should, in theory, remain permanently within the coal deposits forever. Conservatively, the retention time for CO₂ injection in deep unmined coal seams are on the order of 10⁵-10⁶ years (Gunter *et al.*, 1998).

2 METHANE AND CO₂ 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 CO₂, N₂ and CH₄ from ultra-fine pores is activated.

2.2 Counter-Diffusion and Competitive Desorption

During a CO₂ storage/enhanced methane recovery operation, flow of CO₂ gas in the cleats would initiate a counter-diffusion between CH₄ and CO₂ in the coal matrix, whereby adsorbed methane molecules are displaced by incoming CO₂ 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 CO₂-CH₄ counter-diffusion and competitive adsorption/desorption in coal has been very limited.

CO₂ 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 CO₂ component in a CO₂-CH₄ binary mixture would preferentially adsorb in coal, whereas the CH₄ 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 CH₄ 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 reverse the usual trend and result in preferential desorption of CO₂. 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 CH₄ and CO₂ adsorption tests on dry and moisture-equilibrated coals. They refer to the phenomenon of “negative excess sorption capacities”, which was observed for CO₂ 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 CO₂ 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 (CH₄, CO₂ and N₂) 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, CO₂ 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 CH₄ and 0.364 nm for N₂). This suggests that coal has an interconnected pore network highly constricted by ultra micropores (< 0.6 nm). Busch *et al.* (2003a) also observed that CO₂ tends to desorb faster from crushed coal particles than CH₄ 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-CO₂ 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-CO₂ critical pressure ranges, with a mixed gas, are imperative to achieve a better understanding of the selective transport phenomenon during CO₂ storage and enhanced CBM recovery in deep coal seams.

2.3 The Response of Coalbed Permeability to Methane Production and CO₂ 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/CO₂ 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 CO₂ would cause matrix swelling which, in

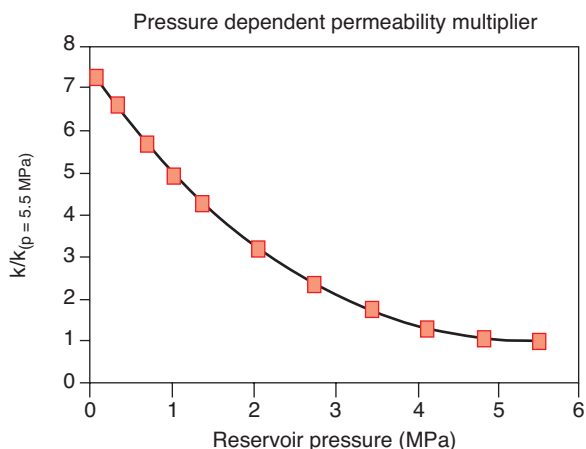


Figure 2

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

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

CO₂ 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 are laterally bounded.

Field evidence concerning the impact of CO₂ injection on coalbed permeability is limited and not conclusive. Dramatic reduction (by up to 40%) in CO₂ injection rates is reported at the Allison pilot in the San Juan Basin at the early stages of CO₂ injection (Reeves, 2002). This reduction has been attributed to a two-order reduction in the coalbed permeability, as a result of CO₂ induced coal matrix swelling (Pekot and Reeves, 2003). Loss of injectivity is also observed at the CO₂ micro-pilot in the Qinshui Basin of Shanxi province, China (Law, 2004).

On the other hand, Mavor and Gunter (2004) found that CO₂ 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 CO₂ injectivity was greater than that for weakly adsorbing N₂, 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 CO₂ injection on coalbed permeability and injectivity.

Other factors that could affect the CO₂ injectivity in CBM reservoir are:

- **Thermal effect of CO₂ injection:** Temperature of the injected CO₂ 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 CO₂, 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 CO₂ injectivity and storage/ECBM economics (Smith and Reeves, 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 CO₂ matrix swelling on well injectivity, the following techniques have been identified: injection of flue gas instead of pure CO₂; 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 CO₂ injection wells in order to avoid CO₂ 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 CO₂-ECBM pilot (Shi and Durucan, 2004).

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

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

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:

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

where α_{s_j} 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 CO₂ adsorption on coal permeability.

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

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

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

Equations (1), (2) and (3) may be used to estimate the impact of CO₂ injection on coalbed permeability. As shown in Figure 3a, magnitude of permeability reduction caused by CO₂ matrix swelling is strongly affected by the swelling coefficient ratio $\alpha_{\text{CO}_2}/\alpha_{\text{CH}_4}$. It was found that a close match to the field injection bottomhole pressures could be achieved by using $\alpha_{\text{CO}_2}/\alpha_{\text{CH}_4} = 1.276$, which would result in a drop of over two orders of magnitude in the permeability around the injection well ($Y_{\text{CO}_2} = 1$). The history matching results for injection well 141 at the Allison Unit CO₂-ECBM Pilot are presented in Figure 3b (Shi and Durucan, 2004).

3 CO₂ 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 portion 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 N₂ or CO₂, 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 N₂ and CO₂ 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. CO₂-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 CO₂ 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 CO₂ storage on coalbed methane reservoirs, as CO₂ becomes a supercritical above a temperature of 31.1°C

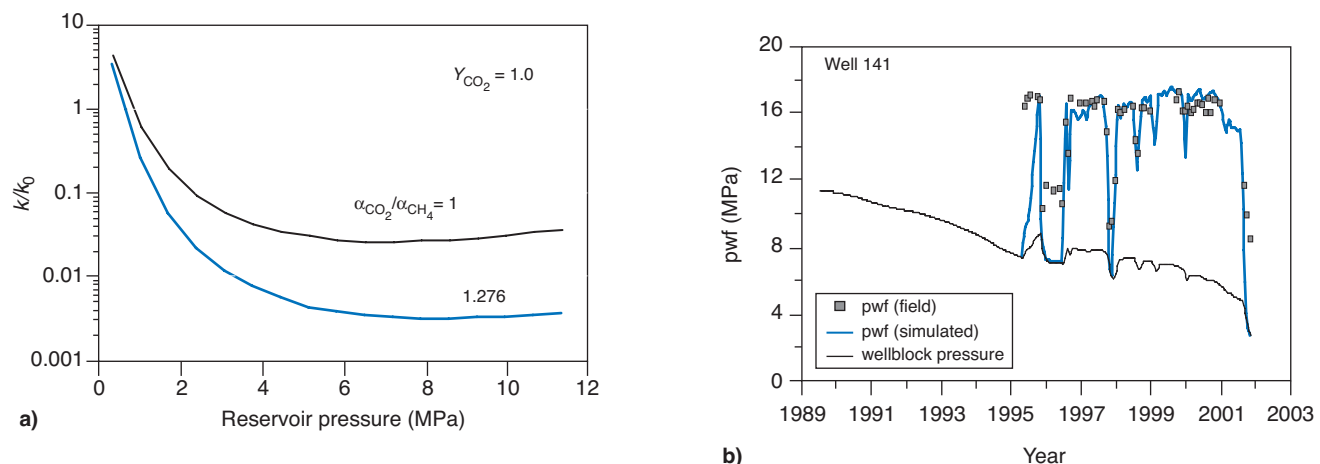


Figure 3

a) Model prediction of CO₂ injection on coalbed permeability; b) history match of the injection bottomhole pressure for well 141, at the Allison Unit CO₂-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. Hydrogeological constraint should be considered as one of the main factors for the effective CO₂ 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 CO₂ injection. US experience suggests that an absolute permeability of 10⁻¹⁵ m² (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 CO₂-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 CO₂ channeling.
- **Natural analogues:** Natural CO₂ 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 CO₂ deposits offer considerable potential for understanding and publicising geologic storage and can serve to build public confidence in this CO₂ management technique.

3.1 CO₂-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 CO₂-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 CO₂ injecting wells and nine producing wells, drilled on a 320-acre spacing. CO₂ injection

started in April 1995, after approximately six years of primary production, and was suspended in August 2001. A total of 4.7 Bcf CO₂ was injected into the four wells, with only limited CO₂ breakthrough. Reservoir simulation and history matching studies indicate that enhanced CBM recovery and simultaneous CO₂ 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 CO₂ micro-pilot (1998); IIIA) Single well flue gas micro-pilot (1999-2001); IV) Matching CBM resource with CO₂ sources (2002-2005); IIIB) Multi-well CO₂-pilot (2002-2005); and V) Methanogenesis 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 CO₂, N₂ 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 CO₂ storage sites with the added benefit of improving the possibility for commercial productivity” (Mavor and Gunter, 2004b).

The success of the CO₂-pilot test in Alberta has led to the launch of a new pilot initiative in late 2001 “CO₂ 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 CO₂ injection, determination of CO₂ 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 CO₂ 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 CO₂-ECBM and storage operation.

The RECOPL (Reduction of CO₂ emissions by means of CO₂ 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 CO₂ 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 project started in November 2001. A new injection well has been drilled and completed. CO₂ 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 CO₂ micro-pilot tests and coal characterisation. The results indicate that CO₂ storage in low permeability coal seams (few mD) is feasible.

In Japan, a CO₂ 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 CH₄-CO₂-coal interaction, CO₂ monitoring technologies, cost reduction of CO₂ 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 CO₂-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 CO₂-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 CO₂ storage technology. However many researchers still believe that CO₂ injection in coalbeds is extremely complex and not fully understood. A better understanding of all the mechanisms involved in the CO₂ 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 CO₂-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 CO₂ 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 exclusively 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 CO₂-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 CO₂ storage. In a recent history matching study (Shi and Durucan, 2004), the validity of Imperial College model in describing permeability changes in coalbeds under CO₂-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 CO₂ storage in coalbed reservoirs are;

- natural pathways such as faults and/or fractures;
- poorly cemented wellbores;
- wellbore and/or caprock failure;
- dissolved CO₂ in groundwater.

During CO₂ storage, there is the possibility that free or dissolved CO₂ will diffuse into the caprock. This might trigger geochemical reactions between dissolved CO₂ 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 CO₂, 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 CO₂ storage process in natural reservoirs (Czernichowski-Lauriol *et al.*, 1996; Pearce *et al.*, 1996). As a first step in the CO₂ 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 CO₂ 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 CO₂ capture project, researchers at the INEEL have conducted a probabilistic risk assessment study of CO₂ 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 CO₂ is safe;
- enables the assessment of the volumes of stored CO₂ in order to satisfy regulators and local government officials.

Many tools exist or are being developed for monitoring geologic storage of CO₂, 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 CO₂;
- deformation and microseismicity monitoring;
- remote sensing for CO₂ leaks and land surface deformation.

4 RECOMMENDATIONS FOR FUTURE RESEARCH

The technology of CO₂ 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-CO₂ critical pressure ranges.
- Preferential sorption and desorption of CO₂, CH₄ and other gas mixtures.
- Geochemical reactions between injected CO₂, 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 CO₂ storage in coals within Europe. The primary objective is to develop a

screening model that is widely applicable, that could quantify CO₂ storage, and apply screening modelling to identify favourable demonstration sites for CO₂ storage in Europe.

- Selection and implementation of a multi-well CO₂-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 CO₂-ECBM operating procedures.
- The economic potential and role of ECBM in future energy supply.
- The role of policy instruments that could stimulate ECBM development.

REFERENCES

- Advance Resources International (1998) Enhanced Coalbed Methane Recovery with CO₂ Sequestration, *Report No PH/3/3*, IEA Greenhouse Gas R&D Programme.
- Benson, S. et al. (2002) Health, Safety and Environmental Risk Assessment For Geologic Storage of Carbon Dioxide: Lessons Learned From Industrial and Natural Analogues, *GHGT-6*, Kyoto, Japan.
- Bradshaw, B.E., Simon, G., Bradshaw, J., and Mackie, V. (2001) GEODISC Research: Carbon Dioxide Sequestration Potential of Australia's Coal Basins, *Proc. 18th Annual International Pittsburgh Coal Conference*, Newcastle, NSW, Australia, December 3-7.
- Busch, A., Gensterblum Y., Siemons, N., Krooss B.M., van Bergen, F., Pagnier, H.J.M. and David, P. (2003) Investigation of Preferential Sorption Behaviour of CO₂ and CH₄ on Coals by High-Pressure Adsorption/Desorption Experiments with gas Mixtures. *Proc. 2003 International CBM Symposium*, 5-9 May, Tuscaloosa, Alabama.
- Busch, A., Gensterblum Y., and Krooss B.M. (2003) High-pressure Thermodynamic and Kinetic Gas Sorption Experiments with Single- and Mixed Gases on Coal: the RECOPOL Project, presented at the *2nd International Workshop on Research Relevant to CO₂ Sequestration in coal Seam*, Tokyo, 25 October, 39-55.
- Cairns, G. (2003) Enhanced Coal Bed Methane (CBM) Recovery and CO₂ sequestration in an Unmineable Coal Seam, Presented at the *2nd International Forum on Geologic Sequestration of CO₂ in Deep, Unminable Coalseams (Coal-Seq II)* Washington DC, March 6-7. http://www.coal-seq.com/Forum_II.htm.
- Ceglarska-Stefanska, G. and Zarebsks, K. (2002) The Competitive Sorption of CO₂ and CH₄ with regard to the release of Methane from Coal, *Fuel Processing Technology*, **77-78**: 423-429.
- Clarkson, C.R., Bustin, R.M. (199) The Effect of Pore Structure and Gas Pressure upon the Transport Properties of Coal: a Laboratory and Modelling Study. 1. Isotherms and Pore Volume Distributions, *Fuel*, **78**, 1333.
- Cui, X., Bustin, R.M. and Dipple, G. (2003) Selective Transport of CO₂, CH₄, and N₂ in Coals: insights from Modelling of Experimental Gas Adsorption Data, *Fuel*, **83**, 293-303.
- Cui, X. (2004) Sequestration by sorption on organic matter, Presented at the *third International Forum on Geologic Sequestration of CO₂ in Deep, Unminable Coalseams (Coal-Seq III)* Baltimore MD, March 25-26. http://www.coal-seq.com/Forum_III.htm.
- Durucan, S, Shi, J.Q. and Syahrial, E. (2003) An Investigation into the Effects of Matrix Swelling on Coal Permeability for ECBM and CO₂ Sequestration Assessment, *Final report on EPSRC Grant No GR/N24148/01*.
- Gan H, Nandi S.P., Walker Jr P.L. (1972) Nature of the Porosity in American Coals, *Fuel*, **51**, 272.
- Gale, J. (2002) Geological Storage of CO₂: What's Known, Where are the Gaps and What more Needs to be Done, presented and published in *Proc. 6th International Conference on Greenhouse Gas Control Technologies (GHGT-6)*, Kyoto, Japan, 2002.
- Grimston, M.C., Karakoussis, V., Fouquest, R., van der Vorst, R., Pearson, P., and Leach, M. (2001) The European and global potential of carbon dioxide sequestration in tackling climate change, *Climate Policy I*, 155-171.
- Gunter, W.D., Gentzis, T., Rottenfusser, B.A., and Richardson, R.J.H. (1997) Deep coalbed methane in Alberta, Canada: a fuel source with the potential of zero greenhouse gas emissions, *Energy Convers. Mgmt.* **38**, (Supplement 1, S217-S222).
- Gunter, W.D., Wong, S., Cheel, D.B., Sjostrom, G. (1998) Large carbon dioxide sinks: their role in the mitigation of greenhouse gases from an international, national (Canada) and provincial (Alberta) perspective, *Appl. Energy* **61**, 209-227.
- Gunter, W. (2000) CO₂ Sequestration in Deep Unmineable Coal Seams, *Proceedings of CAPP/CERI Industry Best Practices Conference*, Calgary, Canada, April 18-19.
- Hall, F.E., Chunhe Z., Gasem, K.A.M. and Robinson Jr., R.L. (1994) Adsorption of Pure Methane, Nitrogen, and Carbon Dioxide and their Binary Mixtures on Wet Fruitland Coal, paper *SPE 29294* presented at *1994 Eastern Regional Conference & Exhibition*, Charleston, WV (8-10 November).
- Harpalani, S. and G. Chen (1995) Estimation of Changes in Fracture Porosity of Coal with Gas Emission, *Fuel*, **74**:1491-1498.
- Hamelinck, C.N., Faaij, A.P., Ruijg, G.J., Jansen, D., Pagnier, H.J.M., van Bergen, F., Wolf, K.-H. A.A., Barzandji, O.H., Bruining, H., and Schreurs, H. (2000) *Potential for CO₂ Sequestration and Enhanced Coalbed Methane Production in the Netherlands*, NOVEM BV (Netherlands Agency for energy and the Environment) <http://www.chem.uu.nl/nws/www/publica/e2001-07.pdf>.
- International Union of Pure and Applied Chemistry (1999) *Pure Appl Chem*, **66**, 1739.
- Klara, S.M., Srivastasa, R.D., and McIlvried, H.G. (2003) Integrated collaborative technology development program for CO₂ sequestration in geologic formations – United States Department of Energy R&D, *Energy Conversion & Management*, **44**, (17), 2699-2712.
- Kroose, B.M., van Bergen, Gensterblum Y., Siemons, N., Pagnier, H.J.M. and David, P. (2002) High-Pressure Methane and Carbon Dioxide Adsorption on Dry and Moisture-Equilibrated Pennsylvanian Coals, *International Journal of Coal Geology*, **51**, 69-92.
- Law, D., van der Meer, B., Mavor, M., and Gunter, B. (2000) Modelling of Carbon Dioxide Sequestration in Coalbeds: A Numerical Challenge, presented and published in *Proc. 5th International Conference on Greenhouse Gas Control Technologies (GHGT-5)*, Cairns, Australia, August 13-16, 2000.
- Law, D.H.-S., van der Meer, L.G.H and Gunter, W.D. (2002a) Numerical Simulator Comparison Study for Enhanced Coalbed Methane Recovery Processes, Part I: Pure Carbon Dioxide Injection, Paper SPE 75669 presented at the *SPE Gas Technology Symposium*, Calgary, Alberta, Canada, April 30-May 2.
- Law, D.H.-S, L.H.G. van der Meer, and W.D. Gunter (2002) Comparison of numerical simulators for greenhouse gas storage

- in coalbeds, Part II: Flue gas injection, Paper presented at the *Sixth International Conference on Greenhouse Gas Technologies (GHGT-6)*, Kyoto, Japan, October 1-4, 2002
- Law, D.H.-S, L.H.G. van der Meer, and W.D. Gunter (2003) Comparison of numerical simulators for greenhouse gas storage in coalbeds, Part III: More Complex Problems, Paper presented at the *2nd annual conference on carbon sequestration*, Alexandria, VA, May 5-8, 2003.
- Law, D.H.-S (2004) Enhanced Coalbed Methane Recovery & CO₂ Sequestration Projects in Canada and China: Single Well Micro-Pilot Tests, presented at the *SPE ATW Enhanced CBM Recovery and CO₂ Sequestration*, Denver, CO, 28-29 October 2004
- Levine, J.R. (1996) Model Study of the Influence of Matrix Shrinkage on Absolute Permeability Coal Bed Reservoirs, Coalbed Methane and Coal Geology, R. Gayer and I. Harris (eds.), *Geological Society Special Publication*, 109, 197.
- Lewis, C. (2002) CO₂ Capture and Geologic Storage, IOGCC and the U.S., *Department of Energy (DOE) held a meeting presentations*, Alta, Utah.
- Liang, J.-T. (2001) Methodology for conducting probabilistic risk assessment, of CO₂ storage in coal beds, CO₂ Capture Project (CCP), *SMV Workshop*, GeoForschungsZentrum, Potsdam, Germany.
- Marsh, H. (1987) *Carbon*, **25**, 49-58.
- Mavor, M, Gunter, W.D. and Robinson, J.R. (2004) Alberta Multiwell Micro-Pilot Testing for CBM properties, Enhanced Recovery and CO₂ Storage Potential, paper *SPE 90256* presented at the *SPE Annual Conference and exhibition*, Houston, Texas, 26-29 September.
- Mavor, M, and Gunter, W.D. (2004) Second Porosity and Permeability of Coal vs. Gas Composition and Pressure, paper *SPE 90255* presented at the *SPE Annual Conference and exhibition*, Houston, Texas, 26-29 September.
- McGovern, M. (2004) Allison Unit CO₂ Flood, presented at the *SPE ATW Enhanced CBM Recovery and CO₂ Sequestration*, Denver, CO, 28-29 October 2004
- Melnic, M. (2004) CSEMP Pilot, presented at the *SPE ATW Enhanced CBM Recovery and CO₂ Sequestration*, Denver, CO, 28-29 October 2004
- Nandi SL, Walker Jr PL. (1964), *Fuel*, **43**, 385.
- Nandi SL, Walker Jr PL. (1970) Activated diffusion of methane in coal, *Fuel*, **49**, 309.
- Nelson ET, Walker Jr PL. (1961) *J. Appl. Chem.*, **11**, 358.
- Pagnier, H. and Van Bergen, F. (2002) CO₂ Storage in Coal: the RECOPOOL Project, presented at the *1st International Forum on Geologic Sequestration in Deep, Unmineable Coal Seams (Coal-Seq I)*, Houston, TX, March 14-15.
- Pashin, J.C. and McIntyre, M.R. (2003) Temperature-pressure conditions in coalbed methane reservoirs of the Black Warrior basin: implications for carbon sequestration and enhanced coalbed methane recovery, *International Journal of Coal Geology*, **54**:167-183.
- Pearce, J. et al. (1996) Natural occurrences as analogues for the geological disposal of carbon dioxide, *Energy Conversion and Management*, **37**, 1123-1128.
- Pekot, L.J. and Reeves, S.R. (2003) Modelling the Effects of Matrix Shrinkage and Differential Swelling on Coalbed Methane Recovery and Carbon Sequestration, *Paper 0328* presented at *2003 International Coalbed Methane Symposium*, Tuscaloosa, Alabama (5-9 May).
- Reeves, S. (2002) The Coal-Seq Project: Field studies of ECBM and CO₂ sequestration in coal, *Coal Seq Forum*, March 14-15, Houston, Texas.
- Reeves, S, A. Taillefert, L. Pekot and C. Clarkson. (2003) The Allison Unit CO₂ – ECBM Pilot: A Reservoir Modeling Study, *Topical Report*, U.S. Department of Energy, DE-FC26-0NT40924 (February).
- Reeves, S. (2003) Assessment of CO₂ Sequestration and ECBM Potential of U.S. Coalbeds, *Topical Report*, U.S. Department of Energy, DE-FC26-0NT40924 (February).
- Ruthven D.M. (1984) *Principles of Adsorption & Adsorption Processes*. New York, John Eiley & Sons.
- Seidle, J.P., D.J. Jeansonne, and D.J.Erickson (1992) Application of matchstick geometry to stress dependent permeability in coals, *Paper SPE 24361* presented at the *1992 SPE Rocky Mountain Regional Meeting*, Casper, Wyoming (18-21 May).
- Seidle, J.P. and L.G., Huitt (1995) Experimental Measurement of Coal Matrix Shrinkage Due to Gas Desorption and Implications for Cleat Permeability Increases, *Paper SPE 30010* presented at *1995 SPE International Meeting on Petroleum Engineering*, Beijing, China, 14-17 November.
- Seidle, J.P. (2000) Reservoir Engineering Aspects of CO₂ Sequestration in Coals, *SPE 59788*, presented at the *2000 SPE/CERI Gas Technology Symposium*, Calgary, Alberta Canada, 3-5 April 2000.
- Sharkey, A.G., Jr. and McCartney, J.T. (1981) *Chemistry of Coal Utilization, Second Supplementary Volume*, Elliott, M.A. Ed. John Willey & Sons Inc., 159-283.
- Shi, J.Q., Durucan, s., Sinka, I.C. and Daltaban, T.S. (1997) A Numerical Investigation into the Laboratory and Field Behaviour of cavitated Coalbed Methane Wells, *Proc. 1st Southern African Rock Engineering Symposium (SARES'97)*, Johannesburg, 15-17 September, 131-142.
- Shi, J.Q. and Durucan, S. (2003a) A Bidisperse Pore Diffusion Model for Methane Displacement Desorption in Coal by CO₂ Injection, *Fuel*, **82**:1219.
- Shi, J.Q. and S. Durucan (2003b) Modelling of Enhanced Methane Recovery and CO₂ Sequestration in Deep Coal Seams: The Impact of Coal Matrix Shrinkage/Swelling on Cleat Permeability, *Proc. 2003 Coalbed Methane Symposium*, Alabama, May 5-9, Paper no. 0343.
- Shi, J.Q. and Durucan, S. (2004) A Numerical Simulation Study of the Allison Unit CO₂-ECBM Pilot: the Impact of Matrix Shrinkage and Swelling on ECBM Production and CO₂ Injectivity, In, E.S.Rubin, D.W.Keith and C.F.Gilboy (Eds.), *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. 1*, Peer-Reviewed Papers and Plenary Presentations, IEA Greenhouse Gas Programme, Cheltenham, UK.
- Smith, D.M., Williams, F.L. (1984) Diffusional Effects in the Recovery of Methane From Coalbeds, *SPEJ*, **24**,529.
- Smith, L.K. and Reeves, S.R.(2002) Scoping Equilibrium Geochemical Modeling to Evaluate the Potential for Precipitate Formation when Sequestering CO₂ in San Juan Basin Coals, *DOE Topical Report* (October).
- Stanton, R., Flores, R., Warwick, P.D., Gluskoter, H. and G.D., S. (2001) Coalbed Sequestration of Carbon Dioxide, *1st National Conference on Carbon Sequestration*, Washington, USA.
- Stevens, S.H., Spector, D., and Riemer, P.(1998) Enhanced Coalbed Methane Recovery Using CO₂ Injection: Worldwide Resource and CO₂ Sequestration Potential, *SPE 48881*, presented at the *1998 SPE International Conference and Exhibition in China* held in Beijing, China, 2-6 November.

Stevens, S.H. (2002) CO₂-ECBM: Insights from USA and International CBM Pilots, *Coal Seq I Forum*, Houston, Texas.

Thimons, E.D. and Kissell, F.N. (1973) Diffusion of Methane Through Coal, *Fuel*, **52**, 274.

Wildenborg, T. (2001) Safety assessment methodology for carbon dioxide sequestration (SAMCARDS), *CO₂ Capture Project (CCP) SMV Workshop*, GeoForschungsZentrum, Potsdam, Germany.

Xue, Z. and Ohsumi, T. (2003) Laboratory Measurements on Swelling in Coals Caused by Adsorption of Carbon Dioxide and Its Impact on Permeability, presented at the *2nd International Workshop on Research Relevant to CO₂ Sequestration in coal Seam*, Tokyo, 25 October, 57-68.

Yamaguchi, S., Ohga, K., Fujioka, M., and Muto, S. (2004) Prospect of CO₂ Sequestration in the Ishikari Coal field, Japan, In, E.S.Rubin, D.W.Keith and C.F.Gilboy (Eds.), *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. 1*, Peer-Reviewed Papers and Plenary Presentations, IEA Greenhouse Gas Programme, Cheltenham, UK, 2004)

Yang R.T.(1997) *Gas Separation by Adsorption Processes* (Chapter 4), London: Imperial College Press.

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