CO₂ Sequestration in Australian Coal Seams: Feasibility and Plans for Pilot Study

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Introduction

Sequestration into coal seams is one option for geological storage of carbon dioxide. For some regions in Australia with large CO₂ sources and significant quantities of coal, and where other geological formations suitable for sequestration are not locally available [Bradshaw et al., 2001], the storage of CO₂ in coal seams is an option worthy of consideration.

Estimates of the sequestration capacity of coal in Australia range from 8960Mt of CO₂ [Bradshaw et al., 2001], which is approximately 50 years of current emissions from electricity generation, to 1280Mt [IEA, 1998]. If the Bradshaw et al. estimate is combined with the same efficiency factor of 30% as used in the IEA study, a storage potential of approximately 3000Mt is obtained [Carras et al. 2005].

The CO₂ storage mechanism in coal differs from that in other potential sequestration target formations; in coal the gas is stored in an adsorbed state. While the pore pressure is static the gas will remain adsorbed. The CO₂ injection can be planned to minimise free CO₂ at the end of the injection period by managing the injection pressure with respect to the hydrostatic equilibrium that will be re-established after sequestration activities. The potential for coal to store CO₂ over geologic timeframes is demonstrated by coals naturally rich in adsorbed CO₂ [Faiz et al., 2006].

Sequestration in coal will usually involve the associated capture of displaced methane, since coal seams are often naturally rich in adsorbed methane and this will be liberated with CO₂ injection. In fact, sequestration of CO₂ acts to enhance the recovery of in place methane over what would be produced using normal coalbed methane production methods. This enhanced recovery provides a financial return from the sequestration activity that will be a function of the value of additional methane recovered.

An important determinant in the economic feasibility of sequestration in coal will be the rate at which CO₂ can be injected and its reservoir behaviour, as this will determine the numbers of wells required and their spacing. A range of factors will determine the injection rate but a key parameter is the permeability. A complication with sequestration in coal is that gas adsorption leads to coal swelling (Levine, 1996). Under reservoir conditions much of this swelling will have to be taken up in the coal porosity. While the actual magnitude of the swelling is small, of the order of 1-2%, since coal porosity is also relatively small, typically of the same order, the coal porosity could be significantly reduced. A direct impact of this is a

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Abstract GHGT-8
reduction in permeability and ability to inject CO$_2$, and this has been observed in various sequestration in coal field trials (Pekot and Reeves, 2002).

Sequestration into coal would have to overcome a number of technical and economic challenges. In order to determine the feasibility of carbon dioxide sequestration in Australian coals, CSIRO Energy Technology and CSIRO Petroleum have, with funding from the CSIRO Energy Transformed Flagship Program, been conducting a comprehensive research program.

**Methodology and Results**

Estimating feasibility requires a sound understanding of the physical processes affecting CO$_2$ migration. However there is uncertainty with regard to key aspects of the reservoir behaviour of the sequestered CO$_2$. Therefore the program of work comprises two main facets; laboratory experimental activities to characterise the interactions of CO$_2$ and coal and simulation work to identify the economics and optimal sequestration arrangements of commercial scale activities. An important step in the work will be a pilot study and in this paper the design options for a pilot are presented.

**Adsorption Characterisation:** One aspect of the experimental work is to quantify the volume of CO$_2$ that can be stored at reservoir conditions. There has been considerable uncertainty in the experimental characterisation of this for supercritical CO$_2$ conditions, encountered at depths greater than approximately 700m (Goodman et al, 2004). In the program of work described in this paper a novel gravimetric adsorption apparatus has been developed to identify this high pressure behaviour. Measurements have shown that coal can adsorb larger volumes of CO$_2$ at these conditions compared to that predicted by extrapolating the results from subcritical gas pressures to higher pressures. This project is also undertaking studies to quantify the effect of coal rank and type on CO$_2$ adsorption at high pressure which may differ from their effect at sub-critical pressures.

The advantage of gravimetric systems is that they monitor the mass change in the sample on gas adsorption. By direct comparison with the mass gain of an empty chamber on pressurizing the gas, the problems associated with using equations of state of the gas, which are necessary for volumetric systems that measure sorption, are eliminated: gravimetric methods are thus suited to supercritical CO$_2$ applications. Figure 1 shows a range of excess sorption that is typically encountered in dry Australian bituminous coals. The sorption curves vary in their maximum extent and sorption at high pressure. Excess sorption decreases at high pressure, because the sorption on the surface of the coal takes up volume, which displaces gas. The difference in adsorbed phase density and gas density decreases with increasing pressure, and this variation must be corrected for (‘buoyancy correction’) in any model that tries to account for the sorption behaviour of coal (or any other material). For modeling purposes, it is often clearer to plot excess sorption versus gas density rather than pressure (Figure 2). On this scale a Langmuir sorption curve would show a rapid increase with increasing density, reaching a maximum and then decreasing linearly with increasing density to zero when the gas density reaches the adsorbed phase density (and gas and adsorbed material cannot be distinguished by their density).

In Figure 1, it is clear that the extent of sorption at high pressure is not directly related to sorption at lower pressure. Coal C has the least sorption capacity at 6MPa, but close to the greatest sorption capacity at higher pressure.

Figure 2 shows the best Langmuir fit and a modified Dubinin-Radushkevich fit to the sorption curve of an Australian coal. The sorption at high pressures is substantially underestimated.
indicating that coal can sorb more than predicted by extrapolation of low pressure sorption studies. This is a general phenomenon. The relationship between sorption behaviour and coal properties is being examined by extending this study to a range of coals from Australia and other countries. It is clear that this variation in excess sorption capacity must be explained if modeling of the sequestration capacity of a given coal is to be of useful accuracy.

Figure 1. Sorption behaviour of three dry Australian bituminous coals at 55 °C.

Figure 2. Best fits of Langmuir and modified Dubinin-Radushkevich equation to sorption data for an Australian coal (55°C)

Abstract GHGT-8
Coal permeability: Coal permeability is a key characteristic in determining the rate at which CO\textsubscript{2} can be injected. A number of studies have found that coal shrinks with gas desorption and swells with adsorption and that there is a gas specific effect in this; that is adsorption of carbon dioxide leads to greater swelling than methane adsorption. Since coal is under a degree of confinement due to the presence of overlying formations, the swelling and shrinkage leads to changes in permeability. In the RECPOL and San Juan Allison sequestration trials a reduction in coal permeability has been observed during the injection of CO\textsubscript{2} that may be a result of coal swelling due to CO\textsubscript{2} adsorption [Pekot and Reeves, 2002].

As a first step in describing the permeability impact of coal swelling, a model for swelling with adsorption was developed by the CSIRO project [Pan and Connell, 2006]. This model applies an energy balance approach, which assumes that the surface energy change caused by adsorption is equal to the elastic energy change of the coal solid. The elastic modulus of the coal, gas adsorption isotherm, and other measurable parameters, including coal density and porosity, are required in this model. Since the developed model combines the two processes affecting coal volumetric changes, namely swelling due to gas adsorption and matrix compression due to gas pressure, it is able to describe coal swelling behaviour for the whole pressure range. Importantly, it is able to describe the behaviour at high pressures where the swelling ratio may decrease after reaching a swelling maximum. In addition, it represents the differential swelling phenomena related to gas type; i.e. coal swells more with CO\textsubscript{2} adsorption than with CH\textsubscript{4}. Furthermore, the model describes the swelling behaviour caused by mixed gas adsorption. Figure 3 presents an example of the application of the swelling model to the swelling strain measurements of Levine [1996].

![Figure 3. Application of the Pan and Connell [2006] model for coal swelling to the Levine [1996] experimental measurements.](image)

*Abstract GHGT-8*
In order to investigate the influence of gas adsorption on permeability, laboratory measurements have been performed in a tri-axial permeability cell at the elevated pore pressures and temperatures encountered during injection into deeper coals. Figure 4 presents measurements of permeability and axial strain for CO$_2$ on a coal sample from the Bulli coal seam, New South Wales, Australia. These experiments were conducted at a constant effective stress of 1.0 MPa and the permeability was measured at a number of pore pressures after a period of equilibration during which adsorption of CO$_2$ took place. The permeability is seen to decrease with increased CO$_2$ pressure. At the same time the coal swells in response to CO$_2$ adsorption.

![Graph showing permeability and axial strain vs. pressure](image)

Figure 4. CO$_2$ Permeability and axial strain for Bulli coal sample under tri-axial stress conditions and an effective stress of 1 MPa.

The results from this experimental work have been incorporated into reservoir simulation and economic analyses to investigate the conditions under which sequestration could be feasible. A key question relates to the well technology used since coal tends to have a relatively low permeability and strategies often have to be used to enhance the rate of injection. One example is the use of horizontal wells which provide greater contact with the coal seam than vertical wells and allow lower injection pressures. However horizontal wells are more expensive to drill.

In addition to identifying the optimal strategies and conditions for economic feasibility for a commercial scale sequestration operation, this paper presents various design options and costings for a pilot project, the necessary next step forward in demonstrating this process.

**Conclusions**

This paper presents work investigating the feasibility of sequestration in coal with respect to Australian coals. Key uncertainties in the understanding of the interactions of CO$_2$ with coal are investigated through laboratory experimental studies. This improved characterisation is integrated into the reservoir simulation studies that are a central part of the economic analysis.
of feasibility leading to greater confidence in identifying the optimal sequestration strategies. A key step forward in this work is a pilot study which would provide an opportunity to characterise the in-situ reservoir behaviour and further refine our comprehension of the sequestration process.

References


*Abstract GHGT-8*