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USING COAL SEAMS FOR CO_2 SEQUESTRATION

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(2 figures and 2 tables)

ABSTRACT. Injection of carbon dioxide, an important anthropogenic greenhouse gas, into deep unminable coal seams can enhance methane recovery, whilst simultaneously locking up the carbon dioxide in the coal measure. The process is known as CO_2 enhanced coal bed methane production (CO_2-ECBM). Providing the coal is never mined, the carbon dioxide would be sequestered for many years and thereby help to avoid climate change. The worldwide potential for CO_2 sequestration in deep unminable coal seams has been estimated at 148 Gt CO_2. Analysis of representative CO_2-ECBM projects indicates that 5 to 15 Gt of carbon dioxide could conceivably be sequestered at a net profit, while about 60 Gt of sequestration capacity may be available at moderate costs of under \$50/t CO_2, not including the cost of capture. Currently, CO_2-ECBM technology is at an early stage of technical development. However, new demonstration projects currently under development should provide valuable information on the technology that should allow a decision to made within a few years on whether the technology can be regarded as a safe and environmentally acceptable mitigation technology.

Keywords: Climate Change, CO_2, CO_2 Sequestration, CO_2-Enhanced Coal Bed Methane.

1. Introduction

Climate change is now widely recognised as a long-term threat. It is thought that the climate is being changed by the increasing emissions of greenhouse gases, especially CO_2, arising from human activities. Useful reductions in CO_2 emissions can be achieved by fuel switching and improving energy efficiency. However, such actions will not be sufficient to reduce global emissions to the extent that some expect to be needed (Houghton et al, 1996). To make deep reductions in emissions, widespread application of other options, such as renewable energy or nuclear power, may be required. However, it is generally recognised that fossil fuels will continue to meet a significant share of the world's energy demand for the foreseeable future. So, it will be important to have options available that will enable deep reductions in CO_2 emissions from fossil-fuel fired power generation and other energy intensive industry to be achieved. This can be achieved by capturing the CO_2 from the flue gas streams of such plant using established acid-gas scrubbing technology. To combat climate change, it would be necessary then to store the CO_2, away from the atmosphere, for hundreds of years.

There are a number of potential geological reservoirs that can be used to store captured CO_2 (Freund, 1999). These geological reservoirs include depleted and disused oil and gas fields, deep saline aquifers and deep unminable coal seams. The global storage capacity for these geological storage reservoirs has been estimated and is compared with the projected total emissions between 2000 and 2050 according to IPCC's "business as usual" scenario in Table 1 (Davison et al, 2001). The capacity estimates for these reservoirs show that geological storage of CO_2 can make a substantial impact on CO_2 emissions reduction. Depleted oil and gas fields also have a significant storage potential, capable of accepting 45% of the CO_2 that needs to be stored. However, the capacity figures suggest that, from a global perspective, storage of CO_2 in deep unminable coals seams will not have a significant impact. However, we should not discount CO_2 storage in deep coal seams because there may well be some regional niche opportunities where its potential could be more significant.

Storage Option	**Global Capacity Gt CO2**	**% of emissions to 2050**
Depleted oil and gas fields	920	45
Deep saline aquifers	400 - 10 000	20 - 500
Unminable coal seams	20	<2

Table 1. Estimates of storage capacities for different geological reservoirs.

Geological storage of CO_2 is not a new technology. Currently there are some 74 enhanced oil production projects throughout the world that are injecting and sequestering CO_2 (Stevens & Gale, 2000). In addition there is a major project in the North Sea which has been injecting CO_2 into a deep saline aquifer at 1 Million t/y since 1996 (Torp & Gale, 2002). This paper describes a technique for CO_2 sequestration in deep coal seams, which also can enhance the recovery of coal bed methane.

2. CO_2-Enhanced Coal Bed Methane

Recently, new technologies have been proposed for enhancing coal bed methane (ECBM) production (Murray, 1994 and Wong et al, 1999). The two principal variants are: inert gas stripping using nitrogen injection and displacement desorption employing carbon dioxide (CO_2) injection. In the CO_2 injection process (Figure 1), injected CO_2 is preferentially adsorbed at the expense of the coal bed methane, which is simultaneously desorbed and can then be recovered as free gas. The CO_2 remains stored within the seam, providing the seam is never disturbed. Laboratory isotherm measurements demonstrate that coal can adsorb roughly twice as much CO_2 by volume as methane - the working assumption is that the ECBM process stores 2 moles of CO_2 for every 1 mole of CH_4 desorbed. However, the physical chemistry of this process has not yet been fully defined and there remains the possibility that there are other physical processes active within the reservoir, which could alter this ratio. Early indications from actual applications suggest this ratio might be higher (5 or more) depending on channelling of CO_2 through faults and other high-permeability pathways. The depth “window” for CO_2-ECBM is expected to be the same as that for CBM production (300 to 1500m). CO_2-ECBM is likely to be less attractive in areas of high coal permeability from a CBM production prospective, although CO_2 sequestration alone would be effective. It is felt that ECBM might work more effectively than pressure depletion in areas with low to medium porosity.

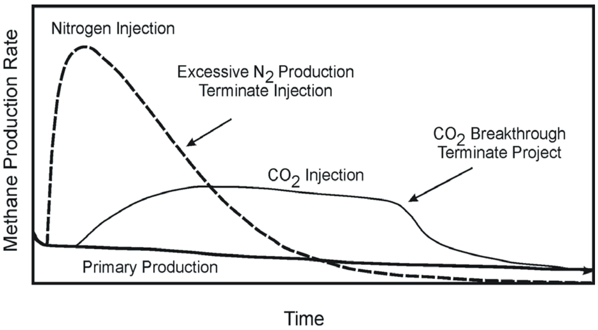

Figure 1. Indicative methane production profiles with N_2 and CO_2 injection.

CO_2-ECBM, therefore, is potentially capable of providing storage for anthropogenic CO_2 as well as improving the production of coal bed methane. If the coal is never mined, it is likely that the CO_2 would be sequestered for geological time-scales. However, if the coal were disturbed, this would void any potential for CO_2 storage so the fate of the coal seam is a key determinant of its suitability for sequestration.

3. The worldwide potential for CO_2-ECBM

The IEA Greenhouse Gas R&D Programme has undertaken a study to examine the potential for the application of CO_2-ECBM recovery and CO_2 sequestration in worldwide coal basins. The study was based on the results of the only large scale CO_2-ECBM injection project, the Allison unit, operated by Burlington Resources in the USA. Since 1996 Burlington Resources has conducted a commercial pilot application of CO_2 injection. While intended to test enhanced coal bed methane recovery, the pilot also sequesters CO_2 as part of its routine operation (Stevens et al, 1999). The pilot project is located within the Allison production unit of the northern San Juan basin, in north-central New Mexico. The San Juan basin is by far the most successful CBM development in the world, with per-well gas production averaging over 23,000 m^3/day of methane.

The results showed that the potential for this process is significant, both from the point of view of enhanced methane recovery and CO_2 sequestration potential. Initially the study focused on geologically favorable basin settings where CO_2-ECBM recovery could be profitably developed. A CO_2 supply cost of \$0.014/m^3 (\$0.5/Mcf) was assumed. For these areas the analysis indicated a sequestration potential worldwide of up to 7.1 Gt of CO_2. Far more CO_2, perhaps 20 to 50 times as much, could ultimately be sequestered in less favorable coal settings, but under sub-economic conditions as a net storage/disposal cost rather than a profitable venture (Stevens, 1999).

The initial focus of this study was on coal basins where reservoir and market conditions appear to be most favourable for ECBM. In these areas, ECBM and CO_2 sequestration operations have a reasonable chance of being economically viable on a stand-alone basis based on the current state of technology development as demonstrated by the Allison Unit. However, such unusually favourable settings probably represent only about 2 to 5% of the worldwide coal resource base.

For each basin considered, the minimum economic gas price was calculated using cash flow analysis and then compared with the market gas price. The difference between these two prices was used to determine net CO_2 sequestration costs. If market gas prices are higher than the minimum economic gas price then the project is likely to be profitable. Cost estimates indicate that, within the USA, CO_2-ECBM projects would be economic at a current wellhead gas price of \$0.07/m^3 (assuming the CO_2 is provided at no cost to the operator). Outside the USA, projects would require gas prices of \$0.11/m^3 or more depending on such considerations as infrastructure development and existence of oil and gas service industries.

Preliminary analysis of the CO_2 sequestration potential for enhanced coal bed methane (ECBM) recovery projects indicates that approximately 148 Gt of CO_2 could be sequestered in worldwide coal basins at total capital and operating costs of less than \$110/tCO_2. The global distribution for CO_2 sequestration in deep unminable coal seams is given in Table 2. An estimated 60 Gt of CO_2 could be sequestered at costs of under \$50/tCO_2. These costs do not include the cost of separating the CO_2 from the flue gas stream, which will be significant. In the most favourable coal basins, it is estimated that between 5 and 15 Gt of CO_2 may be sequestered within profitable ECBM operations, generating revenue up to \$20/t of sequestered CO_2. The economics of worldwide CO_2 sequestration using ECBM are summarised in Figure 2 for a number of coalfields, arranged in order of increasing cost. Figure 2 provides 2 sets of data which show cost of ECBM assuming CO_2 is available at no-cost, or at typical cost of CO_2 supplies used for EOR. The former curve allows the cost of CO_2 separation to be incorporated later, as this depends on the particular source of CO_2 considered.

Country (GtCO2)	**Sequestration potential**
USA	35
Australia	30
Indonesia	24
Russia., Ukraine	19
China	13
Canada	12
Zimbabwe	5.1
India	5.0
France/Germany	1.9
South Africa	1.7
Poland/Czech	1.6
Total	**148.3**

Table 2. Global Sequestration Potential for CO_2-ECBM in Geologically High-Grade Coal Basins.

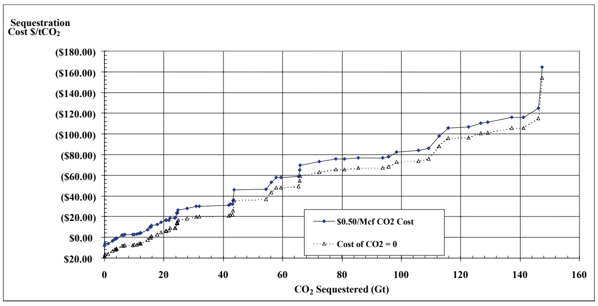

Figure 2. CO_2 sequestration using enhanced coal bed methane recovery in major coal basins worldwide.

4. Technology implementation

In order to move this technology towards wider acceptance, especially as a CO_2 sequestration measure, it is important there should be successful demonstrations. To facilitate demonstrations outside North America, the IEA Greenhouse Gas R&D Programme undertook a detailed geological assessment of coal basins in Australia, China, India and Poland was undertaken. Two potential sites, one in Australia and one in China were selected for further detailed evaluation as potential demonstrations of CO_2-ECBM technology. The cost to undertake a CO_2-ECBM demonstration test at these sites was determined based on a staged project development scenario. The project was assumed to involve three stages. First a single injection well pilot test would be completed, and then a 5 spot pilot test and finally a 41-well commercial demonstration, which would inject 400 tonnes, CO_2 per day or 120,000 tonnes CO_2 per year. The cost of such a phased development project has been estimated at US \$ 42 million at the Australian site and US \$ 47.5 million at the Chinese site (Wong et al, 2001).

The demonstration projects were shown to be economically viable at each demonstration site. At gas prices of \$ US 2/GJ and a zero cost for the CO_2, project payback times (before tax) of 4-5 years could be realised, which could be attractive to commercial operators. The projects' economic viabilities are obviously strongly dependent on; the natural gas price - higher prices will result in more favourable break-even periods. Conversely, lower natural gas prices will make the project less economically attractive and the cost of CO_2 delivered to the site. It is noted that under CO_2 trading regimes the CO_2 might achieve a net value (up to \$15/tonne or more) which would have a positive benefit on the project economics. Over the lifetime of each potential demonstration project, which is estimated at 20 years, some 28.6 Mt CO_2 would be sequestered in the coal seams at both the Australian and the Chinese demonstration sites, if they were to proceed. This equates to a cost of sequestration of between US \$ -4 and -5/t CO_2 at these sites. These sequestration costs are consistent with previous work which has indicated that, in favourable basins, CO_2 sequestration could generate a small net income when part of a CO_2-ECBM scheme (Wong et al, 2001).

5. Technical status of technology

As indicated earlier, to date there has only been one significant technology demonstration of CO_2-ECBM in the northern San Juan basin, in north central New Mexico. The San Juan basin is one of the most successful coal be methane developments in the world, with per-well gas production averaging over 23,000 m^3/day of methane. The coal in the basin varies from sub-bituminous in the southern San Juan to medium volatile bituminous in the north central area, known as the "Fairway". The coal is extremely well cleated and faulting is minimal. Permeability ranges from 1 to 100 milliDarcy, averaging 20 milliDarcy. Coal seam thickness averages 20m at a depth of about 1000 m. The "Fairway" section is the most productive CBM section of the basin. The Allison Unit pilot injects some 85,000 m^3/day of naturally occurring CO_2 produced in South-western Colorado. The Allison Unit pilot comprises four CO_2 injection wells and nine CH_4 production wells. Production took place using conventional pressure-depletion methods for a period of about five years prior to injection of CO_2. The production/injection history for the field has been studied as part of a US DOE sponsored research project (Reeves, 2002). Evaluation of the field data was complicated because for a period following the commencement of CO_2 injection operations, other production enhancement activities were also performed, such as recavitations, well reconfigurations and the installation of dewatering pumps, line pressure reductions, and the implementation of on-site compression. To understand the field results, particularly with the operational complexity that exists, the field was simulated and matched with a three-layer reservoir model. Individual well matches were achieved for gas rate, gas composition, water rate, producing pressures, and reservoir pressures (where available). Using the calibrated model, an analysis of incremental methane recovery due to CO_2 injection was performed. The results indicated that approximately 56 Mm^3 of incremental methane was recovered as a result of injecting 174 Mm^3 of CO_2. This yields a CO_2/CH_4 ratio of 3.2; this ratio is consistent with the CO_2/CH_4 sorptive capacity ratio based on the isotherms at the abandonment pressure of about 3.5 Bar (Reeves, 2002).

Also the results have indicated that CO_2 injection has caused swelling of the coal matrix to occur, resulting in reduced permeability around the well area (10). Analysis of pressure transient data from several producing wells in the field in the vicinity of the four injector wells suggested that in-situ coal permeability for the area was in the 100 – 130 milliDarcy range. However later when the four injector wells were temporarily shut-in, bottom hole pressure data was collected which indicated coal permeability's in the >1 milliDarcy range, two orders of magnitude less than the implied initial values, or a reduction of 99%. These data provide our first insight into the potential magnitude of coal permeability reduction with CO_2 injection on a field-level basis (Reeves, 2002). It must be restated that the coal in the San Juan basin has a very high permeability (up to 40 milliDarcy) and seams are thick (10 m). In essence, they represent a restricted band of coal type that is not typical of the coals available for CO_2-ECBM throughout the rest of the world. Most coal seams will be thinner (0.5 to 5 m) and have much lower permeability (1-5 milliDarcy) and will also be highly faulted. If swelling occurs in such seams and such substantive reductions in permeability are observed as seen in the San Juan Basin then injectivity into these coals seams might be severely restricted. Also, stresses might be induced on the overlying and underlying rock strata that could cause faulting and possible migration pathways out of the coal seam. Equally, if repeated hydraulic fracturing is necessary to maintain connectivity between the well bore and the permeable areas of the coal seam this in turn could result in over/under burden fracturing. A new project in Poland, called RECOPOL (Pagnier & van Bergen, 2002), will begin injection into a more typical coal seam in mid 2003, until we have results from this and a similar project planned in Canada (a development of the Alberta Research Councils existing project) we will have to keep an open mind about the safety of deep coal seam CO_2 injection.

6. Conclusions

Injecting CO_2 into deep coal seams combined with enhanced production of coal bed methane has some technical merits, provided that the coal seams are never mined. This technology has the potential to sequester up to 148 Gt of CO_2 worldwide. Whilst other CO_2 sequestration options have significantly higher potentials, CO_2-ECBM must not be ignored because it will likely have niche opportunities in regions of the world.

If we consider the costs of CO_2 sequestration in CO_2-ECBM operations, then an estimated 60 Gt of CO_2 could be sequestered at costs of under \$50/tCO_2. These costs do not include the cost of separating the CO_2 from the flue gas stream, which will be significant. In the most favourable coal basins, it is estimated that between 5 and 15 Gt of CO_2 may be sequestered within profitable ECBM operations. Such projects can generate revenues of up to \$20/t of sequestered CO_2. These profitable options are significant because they represent early opportunity projects for the implementation of CO_2 sequestration technology. Development of such early opportunities or "low hanging fruit" should mean that more demonstration projects for CO_2 capture and storage will occur. Through extensive demonstration of CO_2 capture and storage it is hoped that the technology will become widely accepted as a safe and effective abatement option.

Currently CO_2-ECBM technology is at a much early stage of technical development than the other main CO_2 sequestration technologies. Only one substantive CO_2 injection trial to date has been undertaken in the San Juan Basin in the USA. Results from this study have indicated that incremental production of CH_4 following CO_2 injection has occurred, although the results are somewhat subjective. In addition, a significant reduction in in-situ coal seam permeability around the injection wells was observed. The San Juan Basin is an extremely favourable situation for coal bed methane production, in may well be unique in the world. Further injection projects are needed outside the USA to demonstrate that CO_2-ECBM technology is a practical prospect outside the USA. Several new demonstration projects are currently under development in Canada, China and Poland which should provide valuable information on the technology. This information should allow a decision to be made within a few years on whether the technology can be regarded as a safe and environmentally acceptable mitigation technology.

7. Acknowledgement

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