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Abstract

Injection of carbon dioxide into deep coal seams has the potential to enhance coalbed methane recovery, while simultaneously sequestering a greenhouse gas. Analysis of production operations from the world's first carbon dioxide-enhanced coalbed methane (CO₂-ECBM) pilot, a 4-injector/7-producer pattern in the San Juan Basin, indicates that the process is technically and economically feasible. To date, over 2 Bcf of CO₂ has been sequestered with negligible breakthrough. Enhancement of gas production can be as high as 150% over conventional pressure-depletion methods. Dewatering of the reservoir is also improved. ECBM development may be profitable in the San Juan basin at wellhead gas prices above $1.75/Mcf, adding as much as 13 Tcf of additional methane resource potential within this mature basin.

The key reservoir screening criteria for successful application of CO₂-ECBM include laterally continuous and permeable coal seams, concentrated seam geometry, and minimal faulting and reservoir compartmentalization. Operational practices for CO₂-ECBM recovery are still being refined. Injection wells should be completed unstimulated, while production wells can be caviated or hydraulically stimulated. CO₂ injection should be continuous and concurrent with methane production to prevent lateral water encroachment. Apart from the San Juan basin, many other coal basins have significant CO₂-ECBM potential. In the U.S., the Uinta and Raton basins are geologically most favorable, while additional potential exists in the Greater Green River, Appalachian and other coal basins. Coal basins in Australia, Russia, China, India, Indonesia and other countries also have large CO₂-ECBM potential. When viewed from a commercial project viewpoint, the total worldwide potential for CO₂-ECBM is estimated at approximately 68 Tcf, with about 7.1 billion metric tons of associated CO₂ sequestration potential. If viewed purely as a non-commercial CO₂ sequestration technology, the worldwide sequestration potential of deep coal seams may be 20 to 50 times greater.

Introduction

Coalbed methane (CBM) has become a significant component of U.S. natural gas supplies. CBM production grew to 2.9 Bcf/d of gas supply during 1997, accounting for about 6% of total U.S. natural gas production. Essentially all CBM operations still employ primary recovery methods, generally by pumping off large volumes of formation water to lower reservoir pressure and elicit methane desorption from the coal. Primary production of coalbed methane recovers only 20% to 60% of original gas-in-place, depending on coal seam permeability, gas saturation, and other reservoir properties. Well spacing and other operational practices also will affect recovery efficiency. Primary recovery thus bypasses a sizeable gas resource. For example, we estimate that primary production in developed areas of the San Juan basin alone may leave behind as much as 10 Tcf of natural gas in areas with completed coal seams.

New technologies have been proposed for enhanced coalbed methane recovery (ECBM) to recover a larger fraction of gas in place. The two principle variants of ECBM are 1) inert gas stripping using nitrogen injection and 2) displacement desorption employing carbon dioxide injection. Simulation and early demonstration projects indicate that N₂-ECBM is capable of recovering 90% or more of gas in place, at an average incremental capital and operating cost of about $1.00/Mcf. The CO₂-ECBM process is less well documented but likewise shows significant promise for enhanced coalbed methane recovery. For the past three years, Burlington Resources, the world's largest producer of coalbed methane, has been operating an 11-well CO₂-ECBM pilot in the San Juan basin. Initial results show improvement in methane recovery in some wells with minimal breakthrough of CO₂. However, due to the complex operational history of this pilot, this

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conclusion remains preliminary. The design, operation, and results of this pilot are presented here for the first time in print. They serve as a benchmark for our larger study of worldwide CO2-ECBM potential.

A secondary benefit associated with the CO2-ECBM process is that it sequesters large volumes of carbon dioxide, a suspected greenhouse gas. Should global restrictions on CO2 emissions be promulgated, CO2-ECBM could be one of the very few profitable technologies for sequestering CO2. (The broadly analogous CO2-EOR process both recycles and sequesters CO2.) Tradeable credits for CO2 sequestration could dramatically improve CO2-ECBM economics over current performance levels. This paper, abstracted from our larger study, presents initial results of research into the technical and economic feasibility of CO2-ECBM application in worldwide coal basins.3

The CO2-ECBM Process
At least four patents have been issued during the past two decades relating to the process of injecting carbon dioxide into methane-bearing coal seams.4-6 Each of these patents is based on the principle that CO2 adsorbs more readily onto the coal matrix than methane. Injected CO2 is preferentially adsorbed (and remains sequestered within the seam) at the expense of the coalbed methane, which is simultaneously desorbed and thus can be recovered as free gas. (Nitrogen injection EBM works using a different physical process by lowering the partial pressure of methane to elicitation desorption). Because laboratory isotherm measurements demonstrate that coal can adsorb roughly twice as much CO2 by volume as methane, our working assumption is that the ECBM process stores 2 Mcf of CO2 for every 1 Mcf of CH4 desorbed and produced. 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.

Allison Unit CO2-ECBM Pilot
Burlington’s Allison Unit field contains the world’s first (and to date only) experimental CO2-ECBM recovery pilot. The Allison Unit is located within the northern portion of the San Juan basin, in northern New Mexico close to the Colorado border (Fig. 1). The San Juan basin is by far the most prolific coalbed methane development, currently accounting for over 75% of total worldwide CBM production. It is also the most thoroughly studied from a reservoir standpoint. Prior to CO2 injection, the Allison Unit had been considered a sub-average performer, with gas production rates less than half that of San Juan Basin Fairway wells (which average about 3 MMcf/d/well), but it was still economically viable. Another reason for selecting the pilot location was its proximity to a major carbon dioxide pipeline that crosses the basin.

The Allison Unit pilot comprises four CO2-injection wells and seven methane production wells in T32N-R6,7W (Fig. 2). The production wells were drilled on 320-acre spacing. Formerly, these wells had been produced using conventional pressure-depletion methods over a period of five years prior to injection of CO2. During mid-1995, Burlington drilled the four injection wells in a diamond-shaped pattern also on 320-acre spacing and initiated CO2 injection. Detailed well completion data are presented in Table 1.

Injection wells for CO2-ECBM are similar to those used in enhanced oil recovery operations, such as the Permian oil fields of West Texas. Stainless steel or fiberglass tubulars, which are corrosion-resistant, are not needed provided that the injected CO2 has been dehydrated. In the Allison Unit, all four injection wells were completed in essentially identical fashion (Fig. 3). After setting 8-5/8 inch surface casing to a depth of about 350 feet, Burlington Resources drilled through the Fruitland coal formation using a 7-7/8 inch bit to total depth of about 3,300 feet. Production casing (5-1/2 inch) was then cemented across the Fruitland coal zones and perforated. Acidization and hydraulic stimulation were avoided in order to reduce the risk of connecting to natural conduits that could channel injected CO2 outside of the targeted coal reservoir.

The production wells at the Allison Unit field were drilled during the late 1980’s, prior to any plans for ECBM application. The nine producing wells were completed using two dissimilar techniques -- natural completion or cavitating; none of the wells were hydraulically stimulated. In addition, several of the production wells were re-cavitated after CO2 injection began. A further complication is that production has been discontinuous over the pilot life. This diversity in operation style and history hinders analysis of the efficacy of the CO2-ECBM process at the Allison Unit. To resolve this, the authors plan to integrate initial results from the Allison Unit into a field-wide reservoir simulation study using AR1’s COMET2 coalbed methane simulator, which is capable of accurately modeling enhanced recovery using CO2.

As shown in Figure 4, the Allison Unit production wells typically were spudded using a 12-1/4 inch bit and drilled to a depth of about 250 feet. Surface casing (9-5/8 inch) was then cemented in place. An 8-3/4 inch hole was drilled to just above the Fruitland coal (3,000 feet), and 7-inch intermediate casing was set-top and cemented in place. Finally, a 6-1/4 inch hole was drilled through the Fruitland coal to a total depth of about 3,200 feet. The well was either completed open-hole or pre-drilled 5-1/2 inch liner was positioned across the coal seams. Five of the wells were cavitated or re-cavitated, while the remaining four wells were completed without stimulation.

Operation at the Allison Unit pilot began with an initial 6-month period of CO2 injection, during which time the production wells were temporarily shut in. Although initially intended to allow pressure buildup within the reservoir, in order to promote substitution of CO2 for methane, shutting in the wells may have been detrimental to gas production. Injection rates were maintained at a relatively constant rate of 600 to 750 Mcf/d/injection well. Breakthrough of CO2 has been minimal
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During the life of the project: following 3 years of injection current CO₂ concentrations at the production wells average 0.4%, which is only slightly above initial pre-injection levels of 0.3%. This suggests that the physical processes of CO₂ sequestration and CH₄ release indeed are taking place.

Unfortunately, the production record at the Allison Unit pilot is somewhat ambiguous. Some wells exhibit strong production enhancement, whereas others actually declined (Fig. 5). Below, we examine in detail the response of two of the wells to CO₂ injection. First, gas production from the #113 well (which was shut in) suffered, probably due to water encroachment. In contrast, the production record of the second well (#115, which was not shut in) is more favorable, exhibiting a dramatic (150%) improvement in gas production rate. We conclude that the difference in performance is largely due to operational procedures, rather than reservoir variation, and that future CO₂-ECBM pilots can achieve significant enhanced recovery as "best practices" operational procedures are developed.

Following commencement of CO₂ injection at the Allison Unit, CBM production frequently was lower than pre-injection levels. For example, the #113 well had exhibited typical inclining gas production during its initial five years of operation, improving to a plateau of about 2 MMcfd during late 1994, just prior to CO₂ injection (Fig. 6). However, after the well was shut in and then returned to production during mid-1996, the gas production rate had fallen to only one-half of pre-injection levels. Gas production then improved gradually, but only to about 1.3 MMcfd by early 1997. During the same period, the water production rate rose dramatically to 100 BWPD following injection; pre-injection water production levels had been reduced to essentially zero. The reason for this initial poor performance is likely due to:

1) Water Encroachment: Shutting the well for two years allowed encroachment of water into the reservoir surrounding the wellbore. Higher reservoir pressure slowed the desorption of methane from the coal reservoir. More seriously, higher water saturation resulted in much less favorable relative permeability to gas and thus lower gas production.

2) Improved Contact with Bypassed Reservoir Area: Simultaneously, the injection of CO₂ at high pressure swept free water from the coal pore and fracture systems within the reservoir. This effect was particularly strong in regions of the reservoir that may have been isolated under normal pressure depletion operations.

...Continued operation of the pilot is starting to overcome the deleterious effects of water encroachment/sweep, resulting in normal declining water and inclining gas production. In a sense, the effective dewatering is a positive indication, demonstrating that the CO₂ process is efficient and that long-term gas recovery is likely to be enhanced.

In contrast, the Allison Unit #115 well exhibits a very different (and much more positive) production history (Fig. 7). The #115 well was completed without stimulation (natural), with 5-1/2 inch pre-drilled liner set across the Fruitland coal interval. Prior to CO₂ injection, the #115 well had been a relatively lackluster producer. Although effectively dewatered (<5 BWPD), the well had attained a modest gas rate of just 500 Mcf/d by early 1995. However, following CO₂ injection, the gas rate increased dramatically to about 1.3 MMcfd. Water production also jumped markedly, but then declined steadily to 50 BWPD. The level of gas production rate improvement (750 Mcf/d) is comparable to the CO₂ injection rate for one injection well. The positive performance of the #115 well is probably due to the fact that it was operated continuously without shut-in throughout the life of the pilot, precluding or limiting water encroachment.

We view the enhanced production achieved in the #115 well as illustrative of "best practices" CO₂-ECBM, at least during the current preliminary development of this technology. Future R&D and operational experience may be expected to lead to further improvements in recovery.

CO₂ Sources

A variety of CO₂ sources, both natural and anthropogenic, may be used within CO₂-ECBM recovery operations. Naturally occurring, high-pressure CO₂ from underground reservoirs is likely to be the lowest cost source, provided that the transport distance to the CBM field is not excessive. The Burlington pilot utilizes approximately 3 MMcfd of naturally occurring CO₂ produced at McElmo Dome field in southwestern Colorado. Shell CO₂ Co. operates an existing pipeline that transports about 900 MMcfd of CO₂ from McElmo Dome across the San Juan basin to the Permain basin of West Texas, where it is injected for enhanced oil recovery operations. A short (30-mile) connector links the Allison Unit to this CO₂ pipeline. Line pressure of the main Cortez pipeline is approximately 2,000 psi, which is then reduced to 1,500 psi in the connector. The CO₂ is injected at bottom-hole pressures of about 1,100 psi, safely below the formation fracture gradient. Injected CO₂ is of high purity (99%) and essentially dry. Thus, the availability of high-quality, high-pressure CO₂ in this portion of the San Juan basin is particularly favorable. Delivered supply costs are approximately $0.50/Mcf of CO₂.

A second option for sourcing CO₂ is to utilize anthropogenic sources that currently are being vented to the atmosphere. In the San Juan Fairway, the natural CO₂ concentration of produced coal seam gas is 6 to 12%. Over 150 MMcfd of CO₂ is currently separated from produced CBM and vented in the San Juan basin to enable the gas to meet pipeline specifications. However, because this waste CO₂ stream is vented at atmospheric pressure, significant compression would be required to boost line pressure to injection levels. For a small pilot of limited duration, the higher capital costs of compression make McElmo Dome CO₂ more attractive than separated CO₂, although this may not be true for...
commercial operations.

Finally, and of particular relevance to the control of potential greenhouse gas emissions, industrial CO₂ may also be used as injectant in ECBM operations. Potential industrial CO₂ sources include primarily coal- or gas-fired power plants and other large industrial plants. Industrial CO₂ is not widely available in the San Juan basin, but could be a viable source in other coalbed methane basins (particularly the Appalachian basins). Unlike relatively pure natural formation CO₂ sources, however, industrial emissions require considerable processing to remove water, SOₓ, and other undesirable constituents. Industrial CO₂ also requires compression. These considerations probably make industrial CO₂ less economic as a source of injectant than natural deposits or processed natural gas streams. Nevertheless, potential future restrictions on emissions could make industrial CO₂ more cost effective. For example, an industrial emitter may find it economically attractive to pay a CBM operator to sequester CO₂. Under this scenario, handling and disposing of CO₂ injectant could actually become a revenue stream for a CBM operation, rather just than a cost.

**Reservoir Screening Criteria**

Reservoir screening criteria are essential for locating favorable areas for successful application of CO₂-ECBM; these criteria have not yet been fully defined. Some of these criteria are likely to be similar to those established for similar injection-based processes, such as waterflood and steamflood operations. We have expanded and refined these criteria, based on the results of scoping reservoir simulation, to develop a preliminary list of first-order reservoir characteristics that are important for CO₂-ECBM application. The key criteria are likely to be:

1) **Homogeneous Reservoir**: The coal seam reservoir(s) should be laterally continuous and vertically isolated from surrounding strata. This ensures containment of injectant within the reservoir as well as efficient lateral sweep through the reservoir.

2) **Simple Structure**: The reservoir should be minimally faulted and folded. Closely spaced faults can compartmentalize the reservoir into isolated blocks, inhibiting effective sweep. The faults themselves may divert injectant away from the reservoir, reducing the efficiency of enhanced recovery and sequestration. In addition, structurally complex areas frequently have damaged coal cleat systems and low permeability.

3) **Adequate Permeability**: Although no minimum permeability criterion can be specified, our preliminary simulation indicates that at least moderate permeability is necessary for effective ECBM (1 to 5 mD). Because many coal basins throughout the world have much lower permeability, locating adequate permeability is a primary exploration challenge.

4) **Optimal Depth Window**: Just as for conventional CBM, ECBM recovery is likely to be most successful within a depth window, which varies by basin. This is because shallow reservoirs tend to be low in reservoir pressure and gas content, whereas deep reservoirs suffer from diminished permeability. For deep settings, CO₂ injection may actually improve permeability by maintaining pore pressure.

5) **Coal Geometry**: Concentrated coal deposits (few, thick seams) are generally favored over stratigraphically dispersed (multiple, thin seams) settings. Likewise, thick "completable" coals are preferred over thin coals that cannot be efficiently targeted.

6) **Gas Saturated Conditions**: Coal reservoirs that are saturated with respect to methane are preferred from an economic viewpoint, since methane production is not seriously delayed. Undersaturated areas can experience delay in methane production, although CO₂ injection could reduce delays by increasing saturation. From a sequestration viewpoint, undersaturated coal seams are still effective CO₂ disposal zones.

Other secondary reservoir criteria likely to affect ECBM recovery include coal rank, coal maceral composition, ash content, gas composition, as well as numerous other factors. These characteristics are shared in common with conventional CBM requirements, but for the most part they are expected to only marginally affect ECBM economics.

**Worldwide Potential for CO₂-ECBM**

Finally, we examined the potential for application of CO₂-ECBM recovery in worldwide coal basins. This analysis was based on a) the performance of the Allison Unit pilot as a preliminary benchmark; b) the reservoir and basin screening criteria outlined above; and c) ARI’s proprietary data base of CBM reservoir properties in international coal basins. We conclude that the potential for this process is indeed significant, both from the point of view of enhanced methane recovery and CO₂ sequestration potential. We focused on geologically favorable basin settings where CO₂-ECBM recovery could be profitably developed. A CO₂ supply cost of $0.50/Mcf was assumed. For these areas our analysis indicates an ultimate, enhanced-recovery methane resource of approximately 68 Tcf worldwide. Up to 7.1 million tonnes of CO₂ could be sequestered within these favorable settings. Far more CO₂, perhaps 20 to 50 times as much, ultimately could be sequestered in less favorable coal settings, but under sub-economic conditions as a net disposal cost rather than a profitable venture.

Coal basins were ranked based on a number of diverse criteria that influence project success. Criteria included both technical measures (reservoir quality/quantity) and project development criteria (development costs/gas market/CO₂ availability). The individual criteria that influence overall rank can be grouped into three general categories:
1. **CBM Resources**: Separately ranked criteria included coal seam complete thickness (feet); gas content and saturation; total prospective gas in place (Tcf); technically recoverable resources (Tcf); and resource concentration (Bcf/mi²).

2. **Costs/Markets**: Capital and operating costs ($/Mcf); current and future natural gas markets (subjective).

3. **CO₂-ECBM Potential**: Availability of CO₂ (subjective); recovery enhancement factor (related to permeability and structural setting).

The results of our assessment of worldwide applicability of CO₂-ECBM technology is summarized below for the high-potential countries and basins (Table 2).

**United States.** The U.S. has by far the brightest outlook for successful near-term commercial application of CO₂-ECBM recovery technology. This is because: a) CBM resources in several basins appear to be geologically suitable for enhanced recovery technology; b) large CO₂ resources are accessible via established pipeline systems, and anthropogenic CO₂ sources also are available for injectant; c) the U.S. natural gas pipeline infrastructure and end-use markets are well developed; d) U.S. production companies have expertise and confidence in investing in CBM technology and field development; and e) service companies and equipment manufacturers compete in an efficient supply market, minimizing development costs. Three U.S. basins (San Juan, Uinta, Raton) appear to have particular potential for CO₂-ECBM recovery. Other basins (Appalachian, Warrior, etc.) have lower permeability and are not discussed here, but these areas also may be suitable for enhanced recovery.

**San Juan Basin.** This mature CBM basin averaged 2.5 Bcfd of gas production from nearly 4,000 producing wells during 1997. Over 14 Tcf of CBM reserves have been booked to date. The San Juan ranked highest using our ranking scheme for CO₂-ECBM feasibility (29 out of a possible score of 30). It is also the site of the first commercial pilot. We anticipate that operators could apply CO₂-ECBM on a large scale in this basin during the next decade. The Fruitland Fm. coal seams are thick, concentrated, laterally consistent, and permeable. Structural faulting and reservoir compartmentalization are minor. Reservoir data control and characterization are excellent. A CO₂ pipeline carries nearly 1 Bcfd across the center of the basin, while additional waste CO₂ from gas processing is available. Development and operating costs for CBM are low. Natural gas pipelines are abundant, although wellhead prices are not high. We estimate that widespread application of CO₂-ECBM could add up to 13 Tcf of reserves in the San Juan basin, while sequestering about 1.4 billion tonnes of CO₂.

**Uinta and Raton Basins.** CBM development in these emerging basins is not as mature as in the San Juan, although several hundred CBM wells are currently on line and 0.6 Tcf of CBM reserves have been added. The Ferron and Vermejo reservoirs in these respective basins resemble the Fruitland coal of the San Juan, except that coal seams are somewhat thinner and have lower gas content. We estimate an additional 2.2 Tcf of potential for the Uinta basin (ranked 24/30) and 0.8 Tcf for the Raton basin (23/30). CO₂ sequestration potential in commercially viable projects is estimated to be 230 and 85 million tonnes, respectively.

**Australia.** After the U.S., Australia is likely to become the next country to experience widespread commercial development of CBM. Five large basins in eastern Australia have CBM resource potential assessed at over 500 Tcf in place: Bowen, Sydney, Gunnedah, Galilee, and Clarence-Moreton. Conoco's 20-well project in the Bowen basin currently produces about 6 MMcfd, and is the first significant (albeit still modest) CBM project outside the U.S. However, the producibility of Permian coal seams in Australia has not been as favorable as in the western U.S., due primarily to high stress and low permeability. Industry development costs are significantly higher than in the U.S. Despite this, two basins have particular potential for CO₂-ECBM application:

**Bowen Basin.** This large basin (ranked 24/30) in east-central Queensland contains over 100 Tcf of targetable CBM resources in the Moranbah and Rangal Formations. The better portions of the basin contain thick, concentrated coal seams with high gas content and moderate permeability. However, long-term development costs are likely to be 25% higher than the San Juan. Pipeline infrastructure also is limited and wellhead gas prices currently are below US$2.00/Mcf. Industrial CO₂ emissions from coal-fired power plants constitute a potential source of injectant, as is 130 MMcfd of CO₂ currently vented from gas fields in the Cooper basin (although a CO₂ pipeline would need to be constructed). We estimate that widespread application of CO₂-ECBM recovery could add 8.3 Tcf in the Bowen basin, while sequestering about 870 million tonnes of CO₂.

**Sydney Basin.** The Sydney basin (22/30) is particularly well located to gas markets and industrial CO₂ sources. Wellhead gas prices are high, while coal-fired power plants could provide a ready source of CO₂ injectant. However, initial testing has encountered limited permeability in the Illawarra and equivalent coal measures, due to high stress and local mineralization. While exploration activity has slowed recently, the prospective resource of over 70 Tcf in place has been only partly tested. CO₂-ECBM development in just a few percent of the Sydney basin could add about 1.4 Tcf of natural gas reserves and sequester 150 million tonnes of CO₂.

**Russia.** Numerous coal basins exist in Russia, but no commercial CBM development has taken place (apart from in-mine methane recovery). However, the 30,000-km² Kuznetsk basin in...
south-central Russia appears to have significant potential (24/30). Gas in place is estimated at 400 Tcf, with an attractive average resource concentration of 35 Bcf/mi². Structure is favorably simple, with indications of moderately high permeability. Coal-fired power plants and other industrial CO₂ sources are abundant within the Kuznetsk basin. We estimate about 10 Tcf of enhanced recovery potential. Approximately 1 billion tonnes of CO₂ could be sequestered.

India. Two significant CBM areas exist in India.⁹ The Damodar coal fields (19/30) in eastern India are better known, but are small and structurally complex. Deliverability from the poorly cleated Permian Gondwana coals is limited by low permeability. The Cambay basin located in heavily industrialized Gujarat state may be a more favorable area (23/30). The Cambay contains thick, low-rank coal deposits within the Tertiary Kadi and Kalol Formations. Initial testing indicates low-moderate gas content and limited permeability, but the unusually thick coal provides k. The Cambay is a petroleum producing basin with good infrastructure and services, including some gas pipelines; data control also is good. Wellhead natural gas prices are considered to be favorable (US$3.00/Mcf). We speculate that 0.7 Tcf of methane (out of about 35 Tcf in place) may be recovered using CO₂-ECBM in commercial projects. About 74 million tonnes of CO₂ may be sequestered.

China. Initial CBM testing in China has confirmed large resource potential (500 to 1,000 Tcf in place),¹⁰ but most areas appear to have low permeability. Two very different settings exist in east-central China for potential CO₂-ECBM within the Permo-Carboniferous coal deposits.

NE China. The Northeast China coal region (19/30) comprises a number of small- to medium-sized, discontinuous coal fields that stretch from Anhui Province in the south to Liaoning in the north. NE China is a heavily industrialized region with rapidly growing urban gas demand and numerous coal-fired power plants for CO₂ injectant. Natural CO₂ sources also are abundant in petroleum fields of eastern China.¹¹ However, there is no existing gas pipeline infrastructure, apart from local town gas distribution systems. Despite attractive resource concentration and gas content, permeability in two dozen CBM test coreholes drilled to date has been low (<1 mD). Potential reservoirs are fragmented by intense faulting. Due to poor producibility, we estimate only about 0.2 Tcf of technically recoverable methane resources in commercial CO₂-ECBM projects, with about 21 million tonnes of CO₂ sequestration potential.

Ordos Basin. This large coal basin in north-central China has superior reservoir quality compared with NE China, but less favorable market and CO₂ supply outlooks (thus an identical 19/30 score). The key geologic distinction is that the Ordos basin is structurally simple, with minimal faulting and gentle dip. Preliminary testing indicates that permeability is an order of magnitude higher than in NE China. A small CBM production pilot has produced at rates of up to 250 Mcfd/well. Amoco, Phillips, and ARCO have CBM exploration programs in the Ordos. Unfortunately, no significant natural CO₂ sources exist and anthropogenic sources are also limited. Two new natural gas pipelines entered operation during 1997, crossing the CBM areas and improving market access. We estimate that commercial CO₂-ECBM application could add 6.4 Tcf of gas potential, while sequestering about 660 million tonnes of CO₂.

Canada. Technically recoverable CBM resources in Canada are substantial, estimated at 135-261 Tcf within the Cretaceous Mannville and Scollard Formations in the Western Canada sedimentary basin in Alberta.¹² Other smaller basins exist in British Columbia and eastern Canada but appear to be less favorable. However, despite an estimated $40 million investment in E&P, development in western Canada has not occurred due to poor test results and low wellhead gas prices.¹³ Undersaturation and low permeability appear to be widespread reservoir problems. However, the gas pipeline infrastructure is well developed and development costs are low. We estimate that the potential for CO₂-ECBM application in commercial projects is about 1.6 Tcf of enhanced methane production, along with perhaps 170 million tonnes of carbon sequestration. Non-commercial projects could sequester far more CO₂.

Other Countries. Significant additional potential also exists within other coal basins for CO₂-ECBM application, although these areas appear to be less favorable for a variety of geologic and market reasons. The Donets basin in Ukraine is structurally complex and probably not suitable for injection of CO₂. The South and Central Sumatra basins in Indonesia may have favorable reservoir, gas market and CO₂ availability conditions but no testing has yet taken place. Western and Eastern European coal fields have abundant industrial CO₂, but suffer from complex structure, undersaturated reservoirs, and high costs. The Zambezi and Main Karoo coal fields in Southern Africa may have potential but testing has been limited.

Conclusions/Future R&D
Technology development and application for CO₂-ECBM recovery is still at a nascent stage. The potential for simultaneous enhanced methane recovery and carbon dioxide sequestration using this process appears to be favorable. Based on early project performance and preliminary resource assessments, about 68 Tcf of enhanced recovery potential is estimated for favorable (potentially commercial) settings. If successfully applied, an estimated 7.1 billion tons of CO₂ may be permanently sequestered in deep, unminable coal seams. A far larger volume of CO₂ could be sequestered in deep coal seams, but at a net operating cost. Additional R&D is needed to confirm the potential of this technology, including:

1) Field-wide reservoir simulation study of the Allison Unit CO₂-ECBM pilot in the San Juan basin to establish the performance of ECDM.
2) Refinement and upgrades to coalbed methane reservoir simulators to validate existing models and optimize field development.

3) Selection and implementation of a multi-well CO₂-ECBM demonstration project within a thoroughly studied coal basin, such as the San Juan. Controlled field experiments of injection and production well technology could be conducted to optimize CO₂-ECBM operating procedures (much as the COAL site in the San Juan basin demonstrated coalbed methane technology).

4) Improved matching of reservoir, gas market, and CO₂ availability within international coal basins to more rigorously establish the worldwide potential of CO₂-ECBM and to target medium-term pilot projects.

Acknowledgments
The authors wish to thank the IEA Greenhouse Gas R&D Programme for their generous support of this study. We also thank Craig McCracken of Burlington Resources and Dan Yee of Amoco for valuable discussions of the ECBM process. Finally, we wish to recognize the contributions of Vello Kuuskraa and Jonathan O'Donnell of ARI.

References


### Table 1
Well Completion Summary, Burlington Resources Allison Unit CO₂-ECBM Pilot, San Juan Basin

#### Allison Unit Wells, Producers

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#### Allison Unit Wells, CO₂ Injectors

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Table 2
Ranking of World’s Most Prospective Coal Deposits for CO₂-ECBM Recovery

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*Estimated reserves additional to pressure-depleted recovery
Scale: 1 (lowest) to 5 (highest)

Total High-Potential Basins 48.5 5,070
Figure 1: Location of Burlington Resources' CO₂-ECBM Pilot, San Juan Basin, USA

Figure 2: Location of Production and Injection Wells, Allison Unit CO₂-ECBM Pilot, San Juan Basin
Figure 3: Completion Schematic for CO₂ Injection Wells, Allison Unit Pilot, San Juan Basin

ALLISON UNIT #140
BASIN FRUITLAND COAL
SEC. 19, T32N,R6W, SAN JUAN COUNTY,NM

CEMENT

2-7/8" TBG SET @3376'

DV TOOL SET @3376'
PACKER SET @3059'
PERFORATED INTERVALS @3109-3376

4-1/2" CSG SET @ 3436'
CMT CIRC. TO SURFACE
Figure 4: Cross-Sectional Diagram Through Allison Unit CO₂-ECBM Pilot San Juan Basin, USA

Note: Depths, elevations, thicknesses expressed in feet

Figure 5: Gas Production Testing for Allison Unit CO₂-ECBM Pilot, Showing Diverse Production Response to CO₂ Injection
Figure 6: Production History of Allison Unit #113 Well, Showing Effects of Water Encroachment

Figure 7: Production History for the Allison Unit #115 Well Showing 150% Production Enhancement, Typical CO₂ Injection Rate for One Injection Well Is Also Shown.