Geological Sequestration of CO_2 in Coalseams: Reservoir Mechanisms Field Performance, and Economics

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ABSTRACT

Coalseams represent an attractive opportunity for near-term sequestration of large volumes of anthropogenic CO_2 at low net costs. There are several reasons for this:

- Coals have the ability to physically adsorb large volumes of gas.
- Coals are frequently located near large point sources of CO_2 emissions, specifically power generation plants (e.g., coal-fired plants).
- The injection of CO_2 into coalseams actually enhances the commercial methane recovery process.
- The recovery of CBM is enhanced when the injected gas contains nitrogen, the major constituent of power plant flue gas.

A joint U.S. Department of Energy and industry project to study the reservoir mechanisms, field performance and economics of CO_2 sequestration in coalseams has been initiated. The project involves laboratory and field-testing to define critical reservoir mechanisms, such as coal matrix expansion and permeability reduction with CO_2 injection, multi-component (CO_2-CH_4-N_2 ternary) sorption behavior, and geochemical reactions that could lead to permeability reduction. Two existing fields in the San Juan Basin, the most prolific CBM basin in the world, are currently under CO_2 and/or N_2 injection. These two fields, the Tiffany Unit – now under N_2 injection but with mixed CO_2/ N_2 injection planned, and the Allison Unit – under CO_2 injection since 1995, will be thoroughly studied as to CO_2 sequestration and enhanced CBM recovery performance, using both pure CO_2 and CO_2/ N_2 mixtures. This paper presents the fundamental reservoir mechanisms of CO_2 sequestration in coalseams, the field performances to date of the Tiffany and Allison Units, the advantages of mixed CO_2/N_2 injection, and some economic considerations for CO_2 sequestration in coalseams. It also summarizes the proposed DOE project.

INTRODUCTION AND BACKGROUND

The concentration of carbon dioxide (CO_2) in the atmosphere is rising and, due to growing concern about its effects, the U.S. and 164 other countries ratified the Rio Mandate in 1992, which calls for '…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.' Even modest stabilization will require enormous reductions in greenhouse gas (GHG) emissions resulting from fossil fuel use; the energy sector is responsible for roughly 90% of U.S. GHG emissions, and 85% of the current U.S. energy system is based on fossil fuels. Under virtually any stabilization and market scenario, fossil fuels will remain the mainstay of energy production for the foreseeable future. To achieve atmospheric stabilization that is deemed acceptable will require large-scale, low-cost sequestration of carbon, a need for which no cost-effective technology exists today. As a result, the U.S. Department of Energy (DOE) developed its Carbon Sequestration R&D Program Plan: FY1999-FY2000, which addresses the entire carbon sequestration 'life cycle' of capture, separation, transport, and storage or reuse.

As a first priority, the sequestration pathways being pursued by the program are those that offer large CO_2 storage capacity and comparatively lower costs. Geological sequestration, including the use of CO_2 for enhanced oil recovery (EOR) and enhanced coalbed methane (ECBM) recovery, and injection into depleted oil/gas or aquifer formations, possess these traits. Options for 'value-added' sequestration with multiple benefits, such as using CO_2 in EOR operations and in methane production from deep, unmineable coal seams, provide the greatest opportunity for near-term, low net-cost CO_2 sequestration, and hence are an immediate focus of R&D. This paper addresses one of these options—the geologic sequestration of CO_2 in deep, unmineable coalbeds.

Tests have shown that CO_2 is roughly twice as adsorbing on coal as methane, giving it the potential to displace methane and remain sequestered in the coal. The density of the adsorbed CO_2 is high, approaching that of a liquid, so it represents an opportunity for sequestration of CO_2 in a highly concentrated state. In addition, many of the large deposits of unmineable coal seams also happen to be near electricity-generation facilities that are large point sources of CO_2, reducing pipeline transport costs. Further, the injection of a mixed gas, nitrogen (N_2) and CO_2 in similar proportions as flue gas, actually enhances the methane recovery process, and would also reduce the costs of CO_2 separation and capture. Hence coalbeds represent a particularly unique opportunity for short-term, low net-cost and high impact CO_2 sequestration.

An industry project to investigate and advance this technology has recently been awarded by the U.S. DOE. The purpose of this integrated research project is to provide showcase field demonstrations of CO_2 sequestration in coal seams using ECBM. The field sites are in the San Juan Basin, the premier coalbed methane (CBM) basin in the U.S., if not the world. A rigorous program of science and reservoir engineering will provide a strong research foundation for understanding the performance of the field projects. This understanding will be used to assess the feasibility of CO_2 sequestration in a broad set of coal and CO_2 emissions environments across the U.S., and to develop screening models for project-specific technical and economic evaluations. This paper presents the fundamental reservoir mechanisms of CO_2 sequestration in coalseams, the field performances to date of the Tiffany and Allison Units, the advantages of mixed CO_2/N_2 injection, and some economic considerations for CO_2 sequestration in coalseams. It also highlights the technology gaps, which will be a focus of the proposed DOE project.

RESERVOIR MECHANISMS

Multi-Component Sorption Behavior

The mechanism by which CO_2 (or N_2) can enhance the coalbed methane recovery process, and CO_2 is sequestered, is a complex mix of physical and chemical interactions that must achieve equilibrium simultaneously in the sorbed state and in the gaseous state. Coal has the capacity to hold considerably more CO_2 than either methane (CH_4) or nitrogen in the adsorbed state (in an approximate ratio of 4:2:1). As a result, in the presence of multiple gases (e.g., CO_2, CH_4 and N_2), the amount of each in the adsorbed state would be in approximately these proportions. However, since any injected gas for ECBM is unlikely to be of exactly that composition, a partial-pressure disequilibrium will be created in the gaseous phase (i.e., in the coal cleat system). Adsorption/desorption of individual components will therefore occur until the gases in both the sorbed and gaseous states are each in equilibrium, and are in equilibrium with each other.

As an example, consider ECBM recovery via N_2 injection. Under certain conditions, the equilibrium ratio of CH_4 to N_2 in the adsorbed state is 2:1, but is 1:3 in the gaseous state. As N_2 is injected, it flushes the gaseous methane from the cleats, creating a near 100% N_2 saturation. The partial pressure of methane in the gaseous cleat-system phase is reduced to 'zero,' a disequilibrium condition in a system containing both methane and nitrogen. As a result, methane desorbs and is drawn (or 'pulled') into the gaseous phase to achieve partial-pressure equilibrium. This is why the N_2-ECBM recovery process is referred to as 'methane stripping'.

On the other hand, as CO_2 is injected, it becomes preferentially adsorbed onto the coal, displacing methane. However, there is no 'pull' on the methane into the cleat system, rather it is 'pushed' from the matrix by the CO_2. Previous modeling work indicates that the 'stripping' mechanism associated with N_2 injection is significantly more effective for ECBM recovery than displacement by CO_2. This behavior therefore has an important impact on an integrated ECBM recovery and CO_2 sequestration project; to achieve the low net-cost CO_2 sequestration desired, an injection gas consisting of both N_2 and CO_2, in optimized proportions, is the likely outcome. Obviously, this is attractive since power plant flue gas is comprised of these two components.

There is a growing body of laboratory and modeling work that has provided the basis for the above understanding of reservoir mechanics. However, experiments have been limited to measuring single-component isotherms to compute multi-component behavior, and only on a few coal types; more work is needed to understand and predict multi-component adsorption/desorption behavior (e.g., specifically with binary and ternary gas mixtures). Further, characterizing this behavior on a wider diversity of coal types is needed such that the potential for ECBM recovery and CO_2 sequestration in the broad range of coal types that occur across the U.S., particularly where large volumes of CO_2 are emitted, can be better understood. These are topics of the U.S. DOE project.

Permeability Reduction Mechanisms
There are two areas of reservoir engineering, both dealing with possible permeability reduction mechanisms, that are also important to consider:

- Matrix shrinkage occurs as methane gas desorbs from coal and is produced during primary production, causing separation of the cleats, a reduction in net stress, and an increase in bulk coal permeability. This permeability increase can be orders of magnitude in some cases, and can substantially improve the long-term performance of CBM wells. When CO_2 is injected into the coal, however, the opposite effect is surmised to occur; the matrix expands, stress increases, and permeability is reduced, exacerbated by high storage capacity of CO_2 on coal. While this effect was originally 'discovered' in the laboratory, proprietary industry studies have revealed that it is strongly affected by scale. Similar to the inability to effectively measure coal relative permeability in the laboratory due to the absence of macro-scale geological anomalies, matrix shrinkage/expansion effects are also affected by macro-scale features. Observing/understanding this phenomenon in the field (as opposed to in the laboratory) is therefore required.

- Geochemical reactions may also occur between injected CO_2 and coal formation water and may lead to solids precipitation and permeability reduction. Although the principal reaction pathways between CO_2 and sedimentary formation waters are relatively well understood, most of this work has focused on saline-rich waters that exist in oil and gas fields and storage aquifers. However, since coal formation water is bicarbonate-rich, significant solids precipitation is not expected (the in-situ water is already 'rich' in CO_2; the addition of more CO_2 would therefore have little impact on water geochemistry). Due to the extremely long reaction times associated with the kinetic processes (many years) they cannot be adequately studied in the short term. Geochemical (equilibrium) modeling studies are therefore needed to investigate these issues further.

Reservoir Modeling

Finally, and ultimately most important, the ability to replicate and predict these various reservoir phenomena, as well as ECBM recovery and CO_2 sequestration, on the desktop is needed. Specifically, reservoir models that can simulate the ECBM/sequestration process under a wide diversity of scenarios (e.g., coal types, injection gas compositions, etc.) will be required before industry begins to significantly invest in such projects. Fortunately, these reservoir mechanisms have already been incorporated into the state-of-the-art and publicly-available COMET2 model. However, due to the historical limited availability of field data on ECBM recovery and CO_2 sequestration in coalbeds, COMET2 (or any other model) has not been thoroughly tested and validated in a field setting. Doing so therefore represents an important scientific objective for CO_2 sequestration technology in coalbeds.

FIELD PERFORMANCE

There are two field sites where CO_2 and N_2 injection for ECBM purposes, is currently being performed. These sites represent a unique opportunity to gain insights into the practicalities of full-scale CO_2 sequestration and ECBM recovery.

Tiffany Unit

The first field site is the Tiffany Unit operated by BP Amoco in the northern San Juan basin (Fig. 1). BP Amoco began to investigate ECBM techniques in the late 1980's, primarily via laboratory experiments, which involved injecting a gas, or mixture of gases such as N_2, CO_2, or flue gas, to improve recovery. Building on the success of laboratory and pilot tests, BP Amoco moved forward with the first and largest full scale N_2-ECBM commercial pilot known as the Tiffany Unit. After nine years of primary production, nitrogen injection was commenced in January 1998, utilizing ten newly drilled nitrogen injection wells. Injection into two additional converted production wells commenced in December of 1998. Injection volumes have averaged 680-790 km^3/d (24-28 MMcf/d) into the 12 wells. Total Tiffany Unit production prior to injection of nitrogen averaged approximately 142 km^3/d (5.0 MMcf/d). As of March 1999, the Tiffany Unit was producing 820 km^3/d (29 MMcf/d) from the 34 production wells, representing a 5-fold increase in methane production (Fig. 2). Injection operations ceased in March 1999, because of limitations on pipeline capacity from the field. However, they resumed in late 1999 once system modifications were completed.

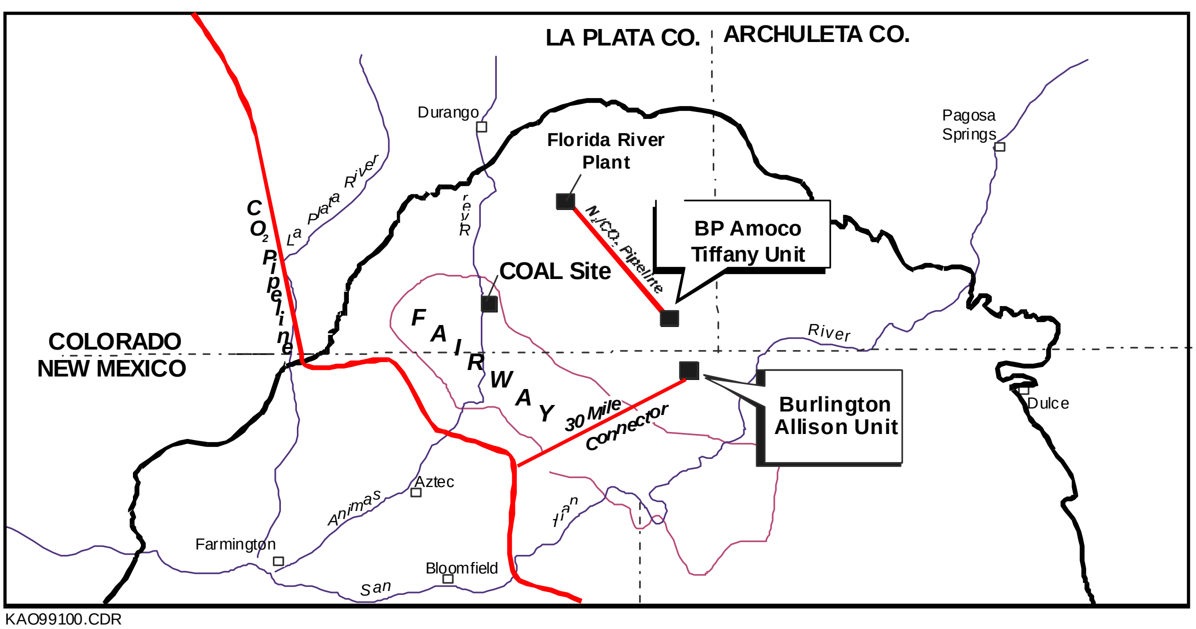

Fig. 1: Location of N_2/CO_2-ECBM Pilots, San Juan Basin

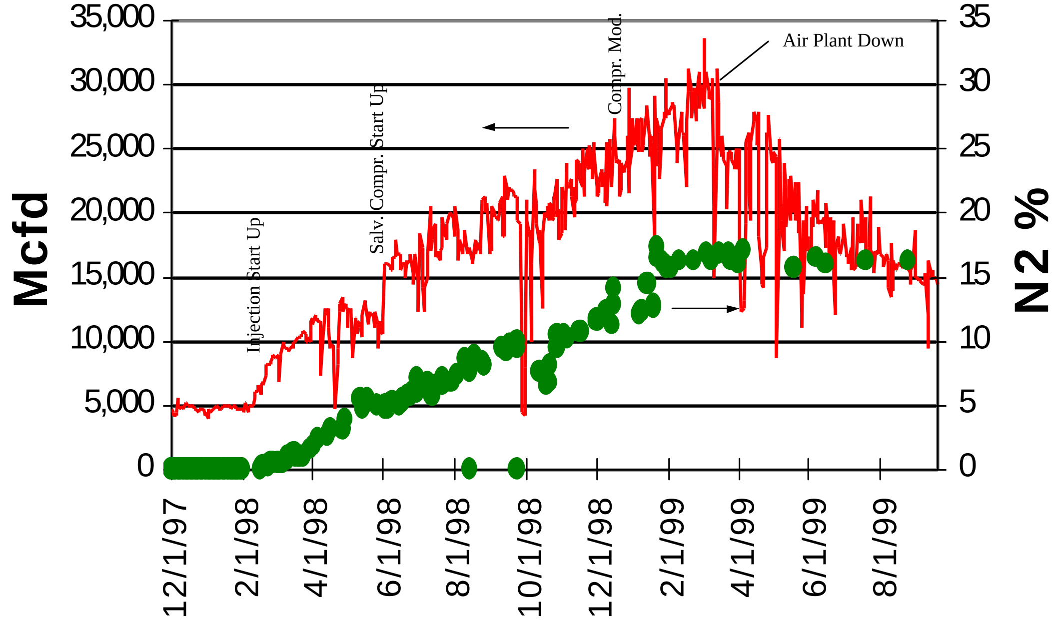

Fig. 2: Tiffany Unit N_2-ECBM Gas Production

Currently, 227 km^3/d (MMcf/d) of pure CO_2 is being vented from the amine regenerator at BP Amoco's Florida River gas processing plant, the site where the nitrogen generator that supplies the Tiffany Unit is also located. With relatively simple (but costly) facility upgrades (for CO_2 capture, compression and dehydration), this CO_2 can be injected at Tiffany through the existing pipeline system. Further, due to the availability of both nitrogen and CO_2 at the Florida River plant, mixtures of the two can be injected to study and optimize the N_2/CO_2-ECBM/sequestration process.

The Tiffany Unit provides a unique opportunity to examine the impact of N_2 on the economics of the process. Using their in-house model, BP Amoco simulated ECBM-recovery for a single well at Tiffany in a five-spot pattern under a variety of scenarios. After 10 years of primary production, the injection of nitrogen (at 790 km^3/d or 28 MMcf/d field equivalent) results in a rapid and significant increase in production; this is consistent with reservoir mechanics and actual field observations to date. With pure CO_2 injection (at 230 km^3/d or 8 MMcf/d field equivalent) a much slower response, with a lower peak production (albeit for a more sustained period of time) is predicted. By adding the N_2 and CO_2 together for a combined rate of 1,020 km^3/d (36 MMcf/d), the early production response is gained while simultaneously sequestering the same volume of CO_2. While cumulative incremental methane production for each case becomes equal after about 11 years of injection, one can easily appreciate the dramatic impact N_2 can have on project economics.

Allison Unit

The Allison Unit, operated by Burlington Resources, is the world's first experimental (pure) CO_2-ECBM recovery pilot, and is the second field demonstration site. The field is located within the northern portion of the San Juan basin (Fig. 1). The pilot comprises of four CO_2-injection wells and nine methane production wells. Formerly, these wells had been produced using conventional pressure-depletion methods for over five years. During 1995 Burlington drilled the four injection wells and initiated CO_2 injection at a rate of 85 km^3 (3 MMcf/d). (CO_2 is sourced from Kinder Morgan CO_2 Company's McElmo Dome natural CO_2 reservoir in Southwestern Colorado). Operations began with an initial 6-month period of CO_2 injection, during which time five of the production wells were temporarily shut in. The shut in time, as well as the subsequent production enhancement activities, such as recavitations, reductions in gathering system pressure, and water lift optimization, make it difficult to isolate and understand the role of CO_2 injection on methane recovery.

As a result, the production record at the Allison Unit is somewhat ambiguous (Fig. 3), and understanding the effectiveness of the ECBM recovery and CO_2 sequestration processes in any meaningful way at this site will require careful well-by-well analysis. However, breakthrough of CO_2 has been minimal during the life of the project; following three years of injection, current CO_2 concentrations at the production wells average 0.6%, which is only slightly above initial pre-injection levels of 0.4%. This suggests that the physical processes of CO_2 sequestration are indeed taking place.

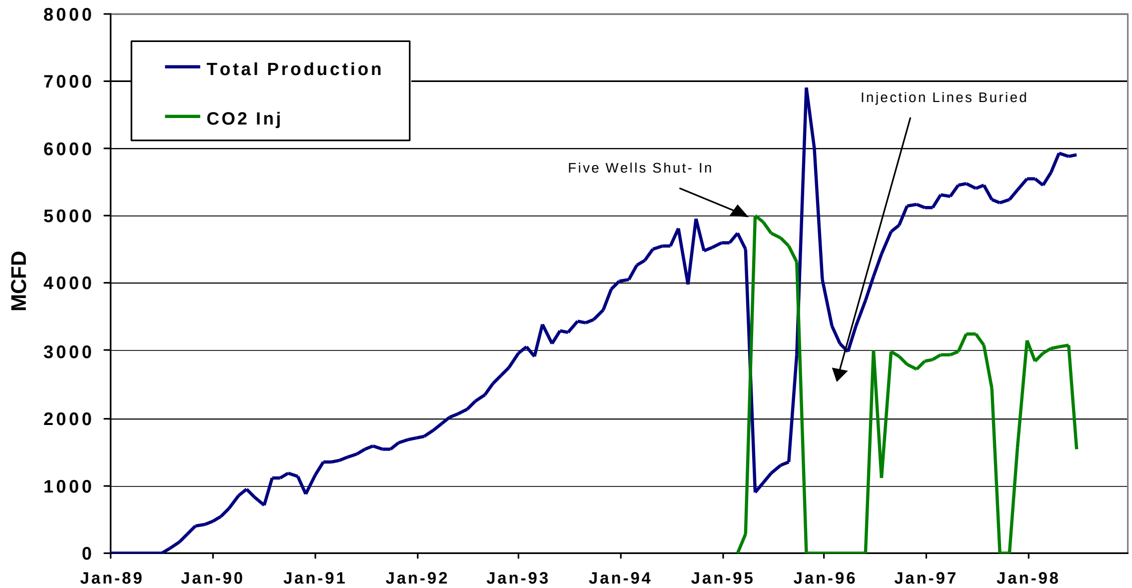

Fig.3: Allison Unit CO_2-ECBM Gas Production

ECONOMIC CONSIDERATIONS

Based on a worldwide study of coalbeds, the global CO_2 sequestration potential was estimated by unit cost, both for projects that face a modest $10/tonne ($0.50/Mcf) supply cost for CO_2, and a theoretical case where sequestration revenues from emission credits for accepting CO_2 cover collection and compression costs ("free" CO_2). In the best basins sequestration may actually be profitable, generating net profits estimated at $15/tonne of CO_2 for a small significant sequestration potential (5 to 15 Gt of CO_2). The San Juan Basin falls in this category. An additional 50 Gt may be sequestered at moderate costs of under $50/tonne, and 90 Gt of additional CO_2 at costs of less than $120/tonne. Advancements in ECBM technology, particularly integrated N_2/ CO_2-ECBM/sequestration, reduced costs, and higher natural gas prices all would shift this curve downward, improving the economics of sequestration in coal seams. Further work is needed to evaluate sequestration economics however.

CONCLUSIONS

CO_2 sequestration in coal represents an attractive new-term, high-impact and low net-cost option. Before it can be fully utilized on a commercial basis however, certain technical and demonstration hurdles must be overcome. These include a further understanding of key reservoir mechanisms, field demonstrations, and more thorough economic feasibility analysis. These needs are now being addressed via an integrated R&D project being jointly funded by the U.S. DOE and industry.