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Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

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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 CO_2 in a highly concentrated state.
- Coals are frequently located near large point sources of CO_2 emissions, specifically power generation plants.
- The injection of CO_2 into coalseams actually enhances the commercial methane recovery process.
- The recovery of coalbed methane is enhanced when the injected gas contains nitrogen, a major constituent of power plant flue gas.

A joint U.S. Department of Energy and industry project to study the reservoir mechanisms and field performance of CO_2 sequestration in coalseams has recently been initiated. The project involves laboratory and field-testing to define critical reservoir mechanisms, including multi-component (CO_2-CH_4-N_2 ternary) sorption behavior. Two existing fields in the San Juan Basin, the most prolific coalbed methane basin in the world, are currently under CO_2 and/or N_2 injection. These two fields, the Tiffany Unit (operated by BP) – now under N_2 injection (but with mixed CO_2/N_2 injection being studied), and the Allison Unit (operated by Burlington Resources) – under CO_2 injection since 1995 will be thoroughly studied via reservoir simulation to understand CO_2 sequestration and enhanced coalbed methane recovery performance, using both pure CO_2 and N_2, as well as CO_2/N_2 mixtures. This paper presents the fundamental reservoir mechanisms of CO_2 sequestration and enhanced recovery of methane from coalseams, and the field performances to date of the Tiffany and Allison Units.

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 over 160 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". Since under virtually any stabilization or market scenario fossil fuels will remain the mainstay of energy production for the foreseeable future even modest stabilization will require enormous reductions in greenhouse gas (GHG) emissions resulting from fossil fuel use; energy-related CO_2 emissions resulting from fossil-fuel combustion account for 82% of all U.S. GHG emissions[1]. Further, in addition to emissions reductions via fuel-switching, conservation, and efficiency improvements, achieving 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, 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 can impact large point-source CO_2 emissions, offer large CO_2 storage capacities, and can accomplish sequestration at comparatively lower costs. In terms of large CO_2 point-sources, power plants represent the greatest opportunity due to their large-scale, stationary nature; the electric power industry accounts for 41% of all energy-related CO_2 emissions[1]. Furthermore, coal-fired plants account for 81% of that, or one-third of total energy-related CO_2 emissions. In terms of sequestration, geologic options for ‘value-added’ sequestration with multiple benefits, such as using CO_2 in enhanced oil recovery (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 of immediate interest. This paper addresses one of the options that meet these immediate program objectives—the geologic sequestration of CO_2 in deep, unmineable coalbeds.

The concept and synergies of CO_2 sequestration and enhanced coalbed methane (ECBM) recovery are illustrated in Figure 1. Here, a flue gas (presumably with some pre-treatment for contaminant and/or dilutant removal) from a power plant is injected into nearby coal seams, where the CO_2 is sequestered and methane production from the coal is enhanced. The produced methane is sold to reduce the net cost of CO_2 sequestration (and in some cases make it profitable), and increases the supply of a more environmentally friendly fossil fuel for use at the plant or elsewhere. The opportunities to actually achieve these synergies, in particular the coincidence of large power plants near deep, unminable coal deposits, are shown in Figure 2[1,2,3]. This map shows the locations of known coal deposits and large (>1,000 megawatt) coal-fired power plants. States with the greatest total CO_2 emissions are also highlighted. Clearly there appear to be many opportunities where the proposed scheme might be implemented, particularly along the Texas Gulf Coast, Northern Appalachia, and Illinois/Indiana. Additional opportunities also exist in the Mid-Continent and Rocky Mountain regions.

In response to these opportunities, in October 2000 the U.S. DOE awarded a 3-year R&D contract to Advanced Resources International (ARI) for the purpose of studying and understanding the reservoir mechanisms of CO_2 sequestration and ECBM via a combination of laboratory studies and field demonstrations. 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, including extensive single-, binary-, and ternary-component isotherm testing, which 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. (particularly those areas with synergistic opportunities as identified in Figure 2), 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, some of the merits of pure versus mixed gas (CO_2 and N_2) injection on CO_2 sequestration and ECBM performance, and the field performances to date of the Tiffany and Allison Units.

RESERVOIR MECHANISMS

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 N_2 in the adsorbed state (in an approximate ratio of 4:2:1), as shown in Figure 3. 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 (see point A in Figure 4a). As pure N_2 is injected however, 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. There is no ‘pull’ on the methane into the cleat system, rather it is ‘pushed’ from the matrix by the highly adsorptive CO_2. Consider Point B in Figure 5a. The equilibrium ratio of CH_4 to CO_2 is 1:1 in the sorbed state, but is 3:1 in the gaseous state. As pure CO_2 is injected it is quickly adsorbed into the coal matrix to achieve sorbed equilibrium, displacing sorbed CH_4 in the process.

Modeling work using ARI’s COMET2 coalbed reservoir simulator demonstrates the advantages and disadvantages of N_2 and CO_2 on ECBM recovery. Figures 6, 7, and Table 1, provide the results of a series of three simulations – one base case where no gas injection occurs, and one each for N_2 and CO_2 injection at a rate of 500 Mcfd. The simulation well pattern is a quarter 5-spot; reservoir parameters are described in reference 5, and are indicative of a San Juan Basin setting.

The model results indicate a immediate and significant gas production enhancement with N_2 injection. However, N_2 breakthrough occurs fairly quickly and becomes a high percentage of total production. Hence any enhanced recovery benefit gained by N_2 injection must be balanced against higher gas treatment costs. Injection of CO_2 also results in an immediate gas production response, albeit less so than with N_2. In the case of CO_2, however, no significant breakthrough of CO_2 is predicted over the 20-year simulation (the model assumes a homogeneous reservoir for all cases, absent of potential reservoir pathways for early breakthrough). These behaviors have an important impact on an integrated ECBM recovery and CO_2 sequestration project; to achieve the desired low net-cost for CO_2 sequestration, an injection gas consisting of both N_2 (for rapid methane recovery) and CO_2 (for sequestration), in optimised proportions, is the likely outcome. Obviously, this is attractive since power plant flue gas is comprised mostly of these two components.

Water production increases with either N_2 or CO_2 injection. The higher water response with N_2 is surmised to be a result of its lesser compressibility and higher viscosity than methane. On the other hand, CO_2 is quickly adsorbed by the coal matrix, which releases methane to the fracture system. Hence, it occupies a minimal portion of the in-situ pore space.

FIELD PERFORMANCE

There are currently only two known field sites where CO_2 and/or N_2 injection is being performed on a multi-well scale for ECBM purposes. These sites, both in the San Juan Basin, are the Tiffany Unit operated by BP and the Allison Unit operated by Burlington Resources (Figure 8). They represent unique opportunities to gain insights into the nature of full-scale CO_2 sequestration and ECBM recovery, and to verify and/or modify our understanding of the reservoir processes described above.

Tiffany Unit

BP (formerly Amoco Production Company) 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 CBM recovery. Building on the success of laboratory and pilot tests, and after acquiring numerous patents on the process, 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 directional nitrogen injection wells, and later into two additional converted production wells (in December, 1998), Figure 9. Note that a portion of this field was part of a CBM reservoir characterization R&D project in the early 1990's, also performed by ARI and funded by the Gas Technology Institute (formerly the Gas Research Institute).

Care was taken to ensure both new and existing wellbores had proper seals and integrity to ensure that the gas was injected into and confined within the coal seam. Injection volumes have averaged 24-28 MMcfd into the 12 wells. Total Tiffany Unit production prior to injection of nitrogen averaged approximately 5 MMcfd from 34 wells. In March 1999, gas production peaked at 29 MMcfd, representing a 5-fold increase in methane production (Figure 10). Nitrogen levels in the produced gas reached 16%. These results seem to confirm the quick production response (and N_2 breakthrough) predicted by reservoir modeling.

The Tiffany Unit is being evaluated for the potential of injecting a mixture of waste CO_2 and the already generated N_2. While many variables may exist, information from this already active N_2-ECBM flood will enhance understanding the effects of CO_2 injection.

Allison Unit

The Allison Unit, is the world's first experimental (pure) CO_2-ECBM recovery pilot, and is the second field demonstration site (Figure 8). The pilot comprises of four CO_2-injection wells and nine methane production wells (Figure 11). Formerly, these wells had been produced using conventional pressure-depletion methods for over five years. During 1995 Burlington drilled the four injection wells and began CO_2 injection at an initial rate of 5 MMcfd; since then a loss of injectivity has reduced injection rates to about 3 MMcfd.

Operations began with an initial 6-month period of CO_2 injection, during which time five of the production wells were temporarily shut in to facilitate CO_2/CH_4 exchange in the reservoir (Figure 12). A sharp increase in water production was observed immediately. After six months, CO_2 injection was suspended to evaluate field performance, and the five shut-in wells were re-opened. Injection resumed about 8 months later.

Breakthrough of CO_2 has been minimal during the life of the project; following almost five 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 and methane release are indeed taking place, again as predicted by reservoir modelling.

FUTURE WORK

This 3-year project, just now underway, will use the Tiffany and Allison Units as foundations for studying and understanding ECBM-recovery/CO_2-sequestration in coal seams. The reservoir studies will be supported by laboratory tests for single-, binary-, and ternary-component isotherm measurements, as well as studies into the potential impact of matrix shrinkage/swelling and geochemical reactions on CO_2 injectivity. A benchtop core-flooding experiment may also be performed to understand some of these issues in a controlled environment. Based on the results from this work, economic optimization studies will be performed, and a project screening model developed.

CONCLUSIONS

While it is too early in the project to drive any concrete conclusions, the modeling and field results suggest that both N_2 and CO_2 can enhance CBM recovery, and that coals appear to effectively sequester CO_2. It also appears that there will be an economic optimum N_2/CO_2 mix and rate for each potential project, and hence being able to determine these parameters will be important for integrated ECBM/sequestration projects to be undertaken by industry.

ACKNOWLEDGEMENTS

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5. Stevens, Scott H., Schoeling, Lanny, Pekot, Larry, “CO2 Injection for Enhanced Coalbed Methane Recovery: Project Screening and Design”, Paper 9934 presented at the International Coalbed Methane Symposium, Tuscaloosa, May 3-7, 1999.

***Table 1** – Incremental Methane Recoveries from N2/CO2 Injection (Quarter 5-Spot Pattern)*

	BASE CASE	NITROGEN	CARBON DIOXIDE
Total			

Recovery (MMcf)	1,171	2,933	2,147
Incremental Recovery (MMcf)	n/a	1,762	976

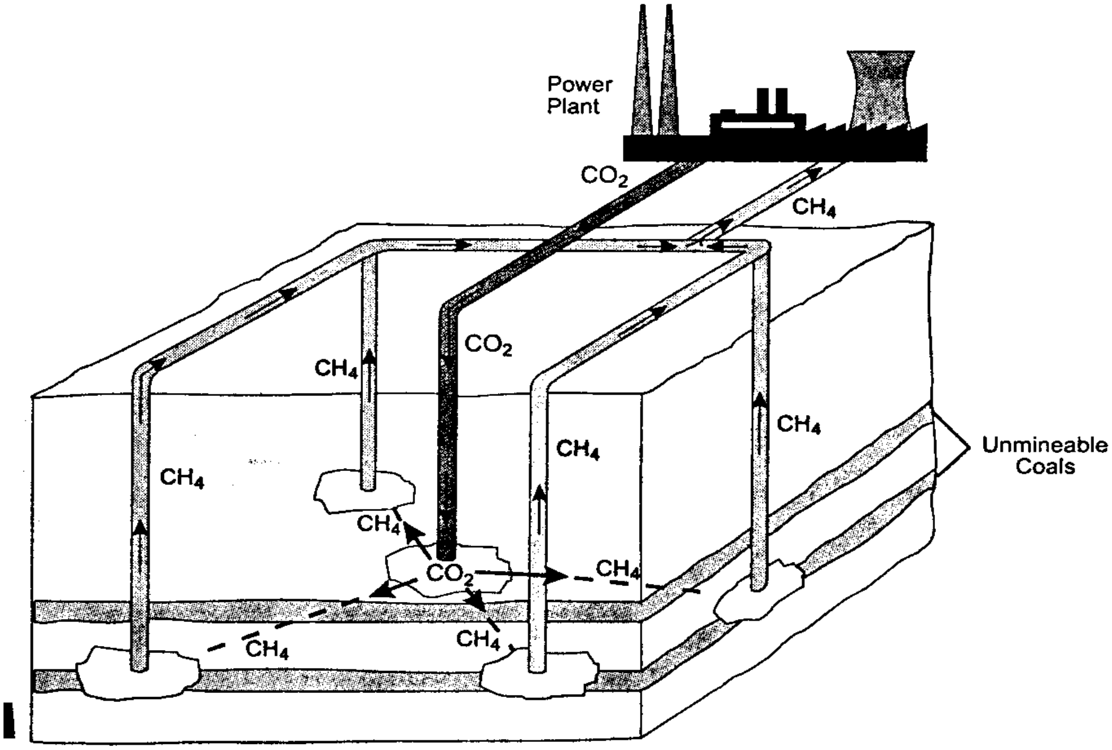


Figure 1: *The Integrated Power Generation, ECBM &* CO_2 *Sequestration Concept*

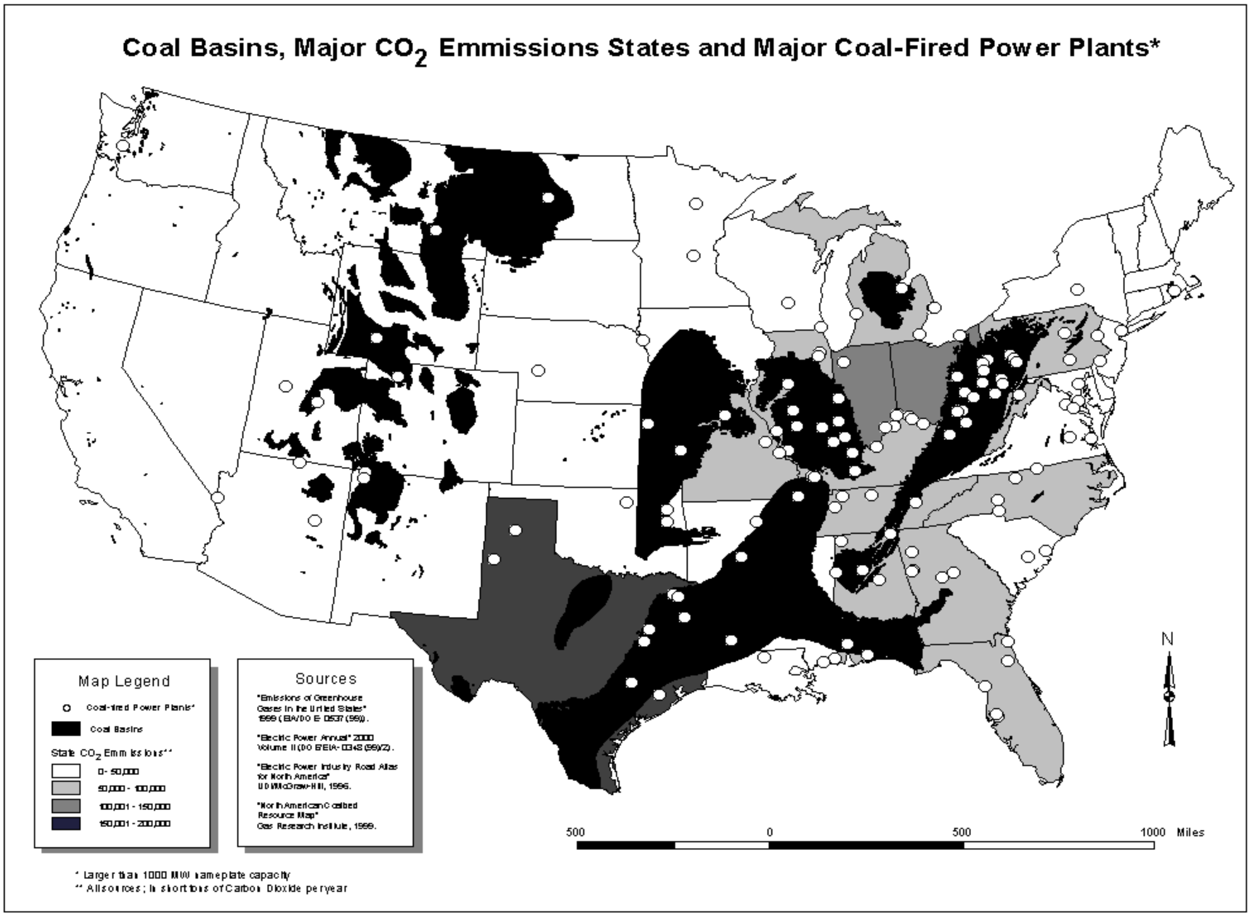


Figure 2: *Coincidence of State CO_2 Emissions, Large Coal-Fired Power Plants, and Coal Basins*

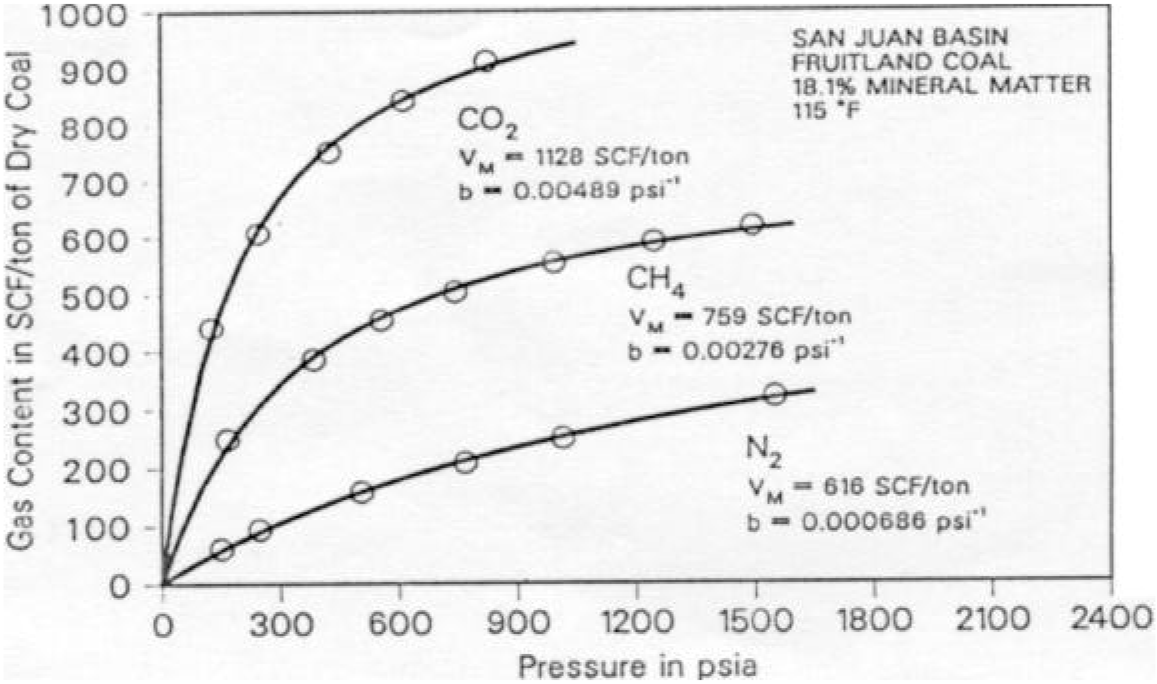
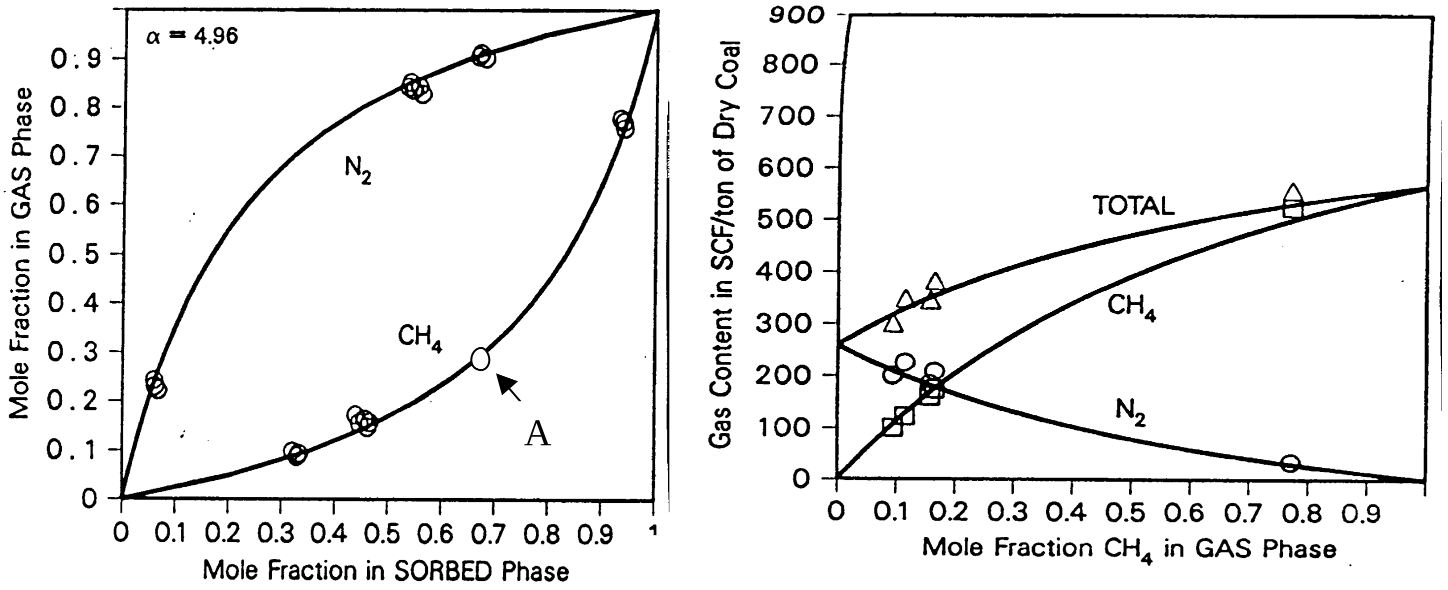
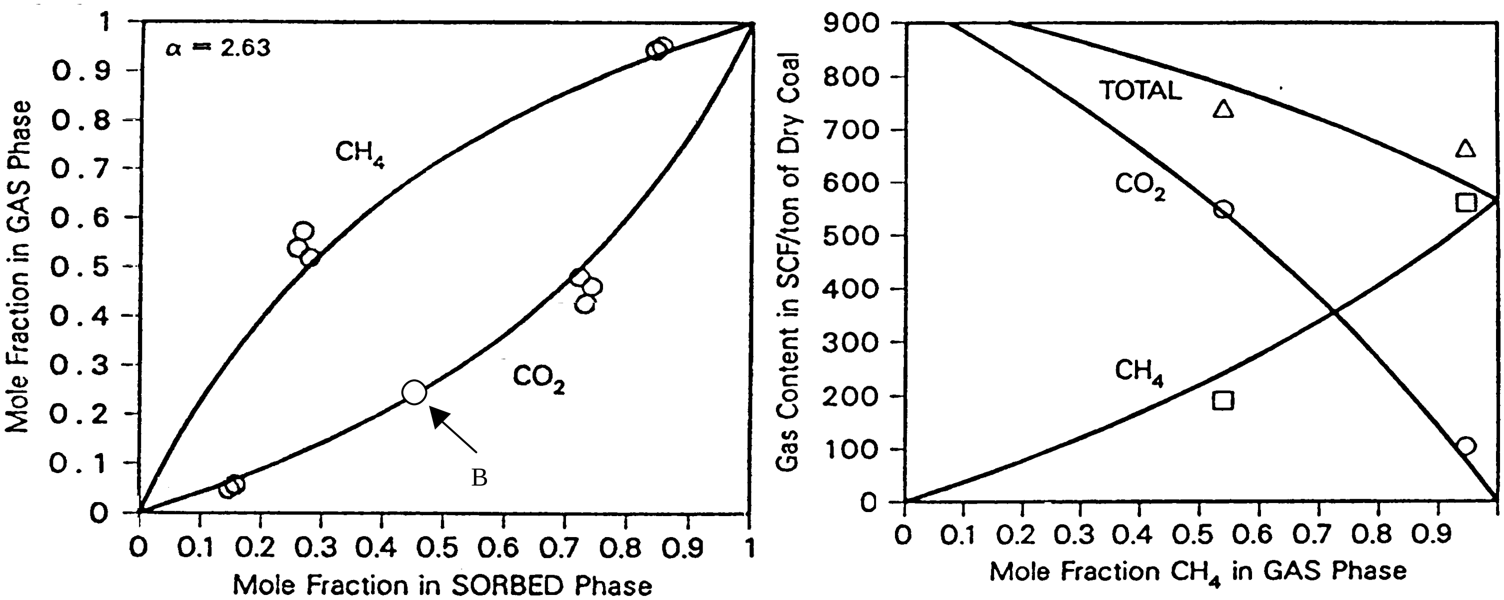


Figure 3: *Relative Adsorption Capacities of N_2, CH_4 and CO_2, San Juan Basin Coal*
(reproduced from reference 4)



(a) (b)

Figure 4: *N_2 - CH_4 Binary Sorption Behavior, San Juan Basin Coal (reproduced from reference 4)*



(a) (b)

Figure 5: *CH_4 - CO_2 Binary Sorption Behavior, San Juan Basin Coal (reproduced from reference 4)*

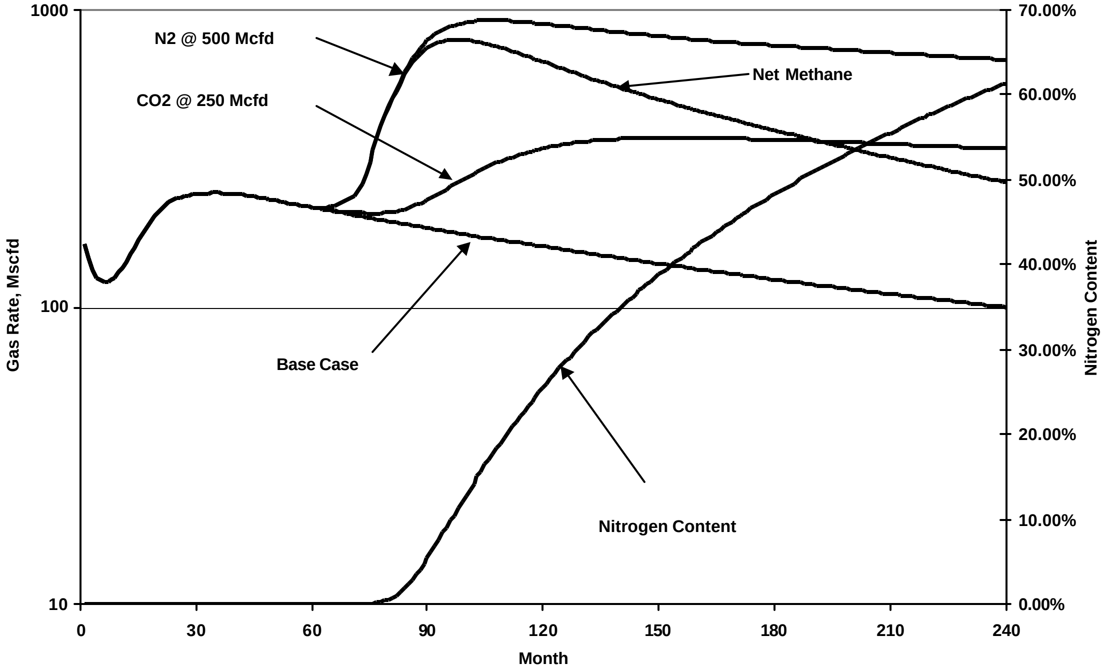


Figure 6: *Gas Production Response to N2/CO2 Flooding*

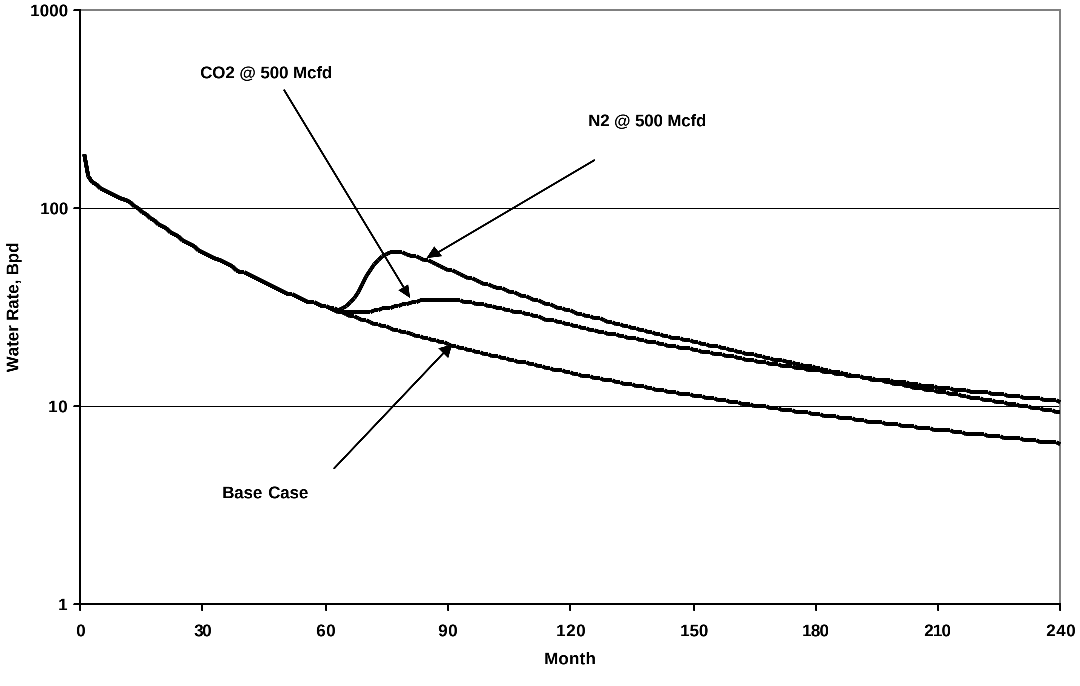


Figure 7: *Water Production Response to N_2/CO_2 Flooding*

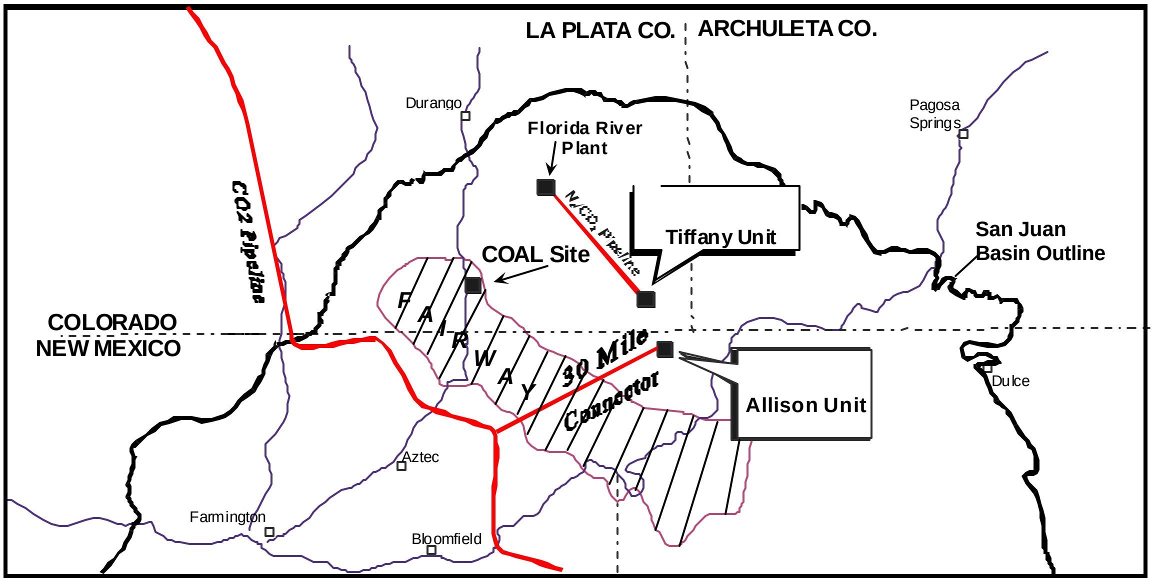


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Figure 8: *Location of N_2/CO_2-ECBM Pilots, San Juan Basin*

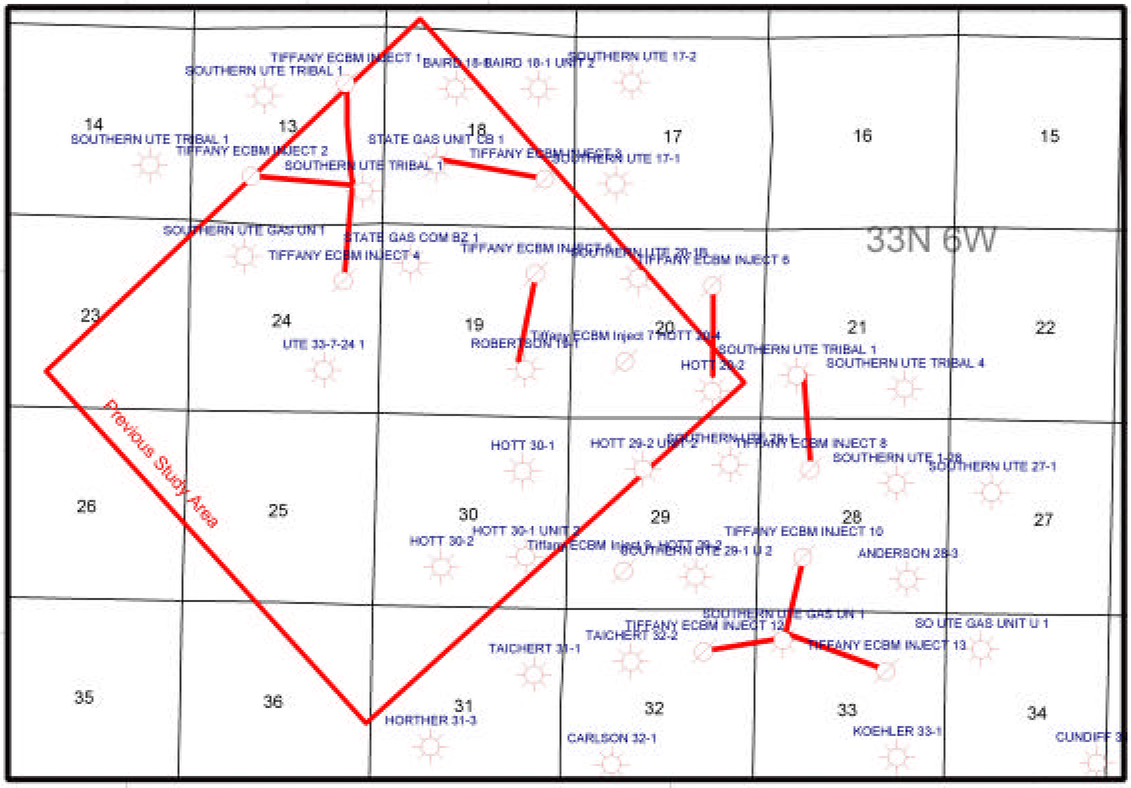

Figure 9: *Tiffany Unit N_2 – Flood Well Pattern*

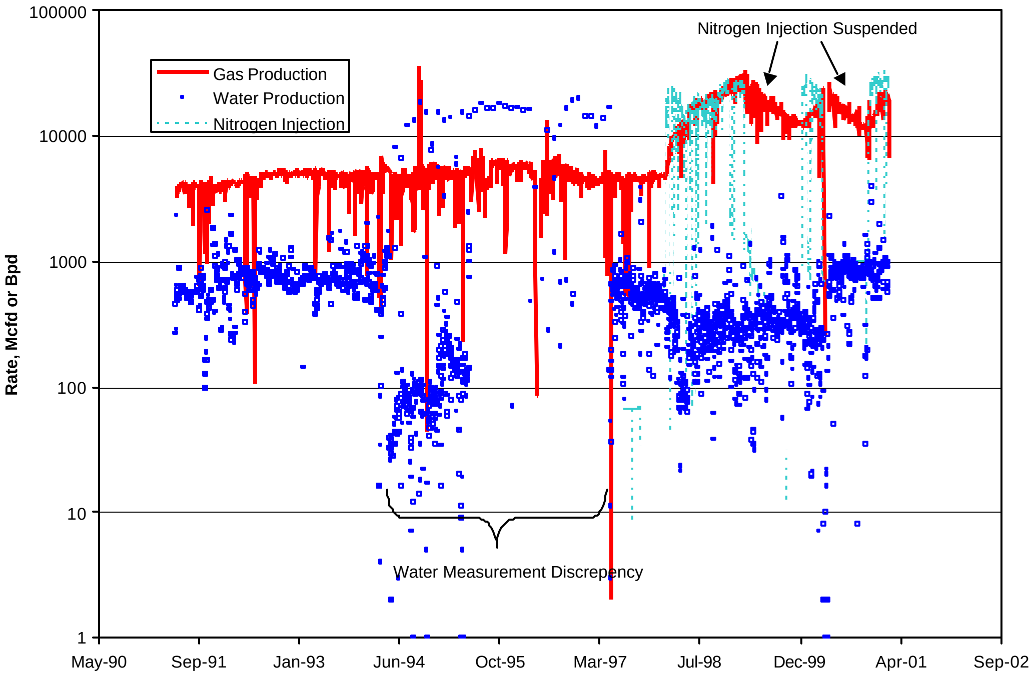

***Figure 10:** Tiffany Unit Production N_2 – Flood Pilot Area*

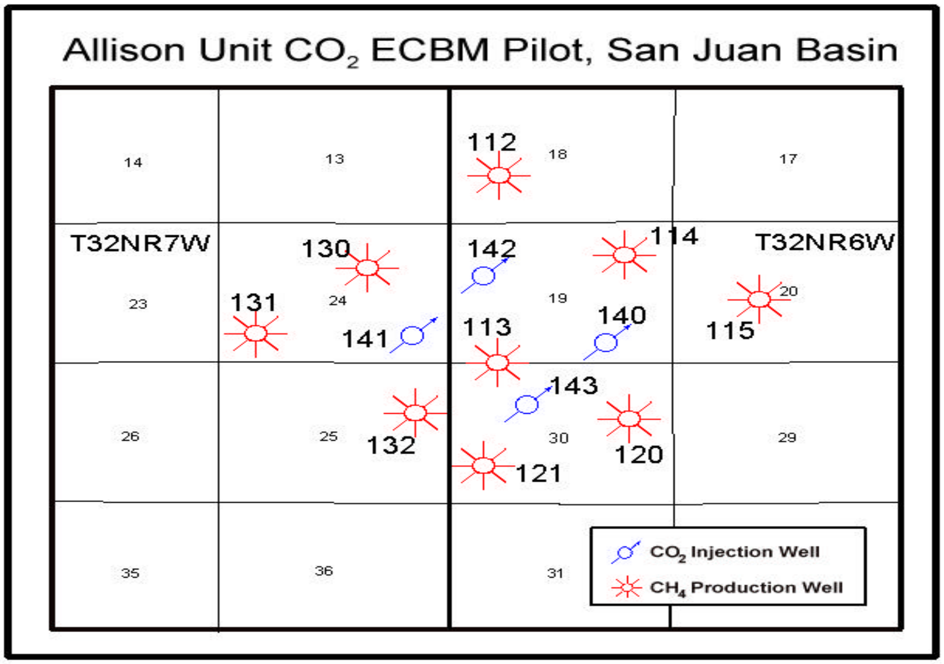

***Figure 11:** Allison Unit CO_2 – Flood Pilot Well Pattern*

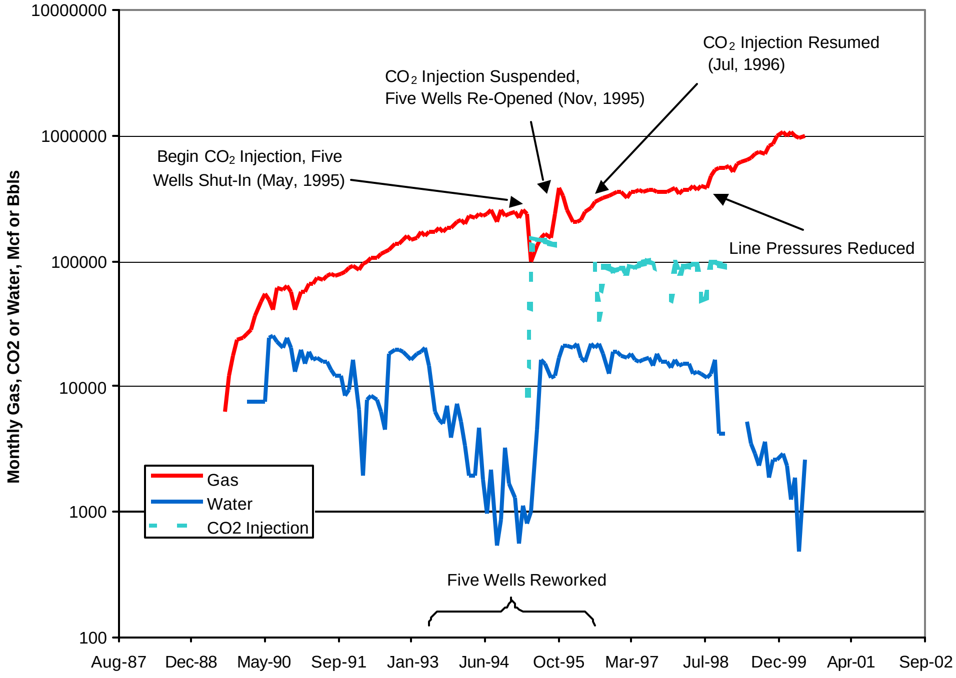

Figure 12: *Allison Unit Production, CO_2 – Flood Pilot Area*