

SPE 71749

## Geological Sequestration of CO<sub>2</sub> in Deep, Unmineable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

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This paper was prepared for presentation at the 2001 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, 30 September-3 October 2001.

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### Abstract

Coalseams represent an attractive opportunity for near-term sequestration of large volumes of anthropogenic CO<sub>2</sub> at low net costs. There are several reasons for this:

- Coals have the ability to physically adsorb large volumes of CO<sub>2</sub> in a highly concentrated state.
- Coals are frequently located near large point sources of CO<sub>2</sub> emissions, specifically power generation plants.
- The injection of CO<sub>2</sub> 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<sub>2</sub> sequestration in coalseams has recently been initiated. The project involves laboratory and field-testing to define critical reservoir mechanisms, including multi-component (CO<sub>2</sub>-CH<sub>4</sub>-N<sub>2</sub> ternary) sorption behavior. Two existing fields in the San Juan Basin, the most prolific coalbed methane basin in the world, are currently under CO<sub>2</sub> and/or N<sub>2</sub> injection. These two fields, the Tiffany Unit (operated by BP) – now under N<sub>2</sub> injection (but with mixed CO<sub>2</sub>/N<sub>2</sub> injection being studied), and the Allison Unit (operated by Burlington Resources) – under CO<sub>2</sub> injection since 1995 will be thoroughly studied via reservoir simulation to understand CO<sub>2</sub> sequestration and enhanced coalbed methane recovery performance, using both pure CO<sub>2</sub> and N<sub>2</sub>, as well as CO<sub>2</sub>/N<sub>2</sub> mixtures. This paper

presents the fundamental reservoir mechanisms of CO<sub>2</sub> 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<sub>2</sub>) 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<sub>2</sub> emissions resulting from fossil-fuel combustion account for 82% of all U.S. GHG emissions<sup>1</sup>. 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<sub>2</sub> emissions, offer large CO<sub>2</sub> storage capacities, and can accomplish sequestration at comparatively lower costs. In terms of large CO<sub>2</sub> 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<sub>2</sub> emissions<sup>1</sup>. Furthermore, coal-fired plants account for 81% of that, or one-third of total energy-related CO<sub>2</sub> emissions. In terms of sequestration, geologic options for ‘value-added’ sequestration with multiple benefits, such as using CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> in deep, unmineable coalbeds.

The concept and synergies of CO<sub>2</sub> 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<sub>2</sub> is sequestered and methane production from the coal is enhanced. The produced methane is sold to reduce the net cost of CO<sub>2</sub> 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, unmineable coal deposits, are shown in Figure 2<sup>1,2,3</sup>. This map shows the locations of known coal deposits and large (>1,000 megawatt) coal-fired power plants. States with the greatest total CO<sub>2</sub> 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<sub>2</sub> 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 will be performed, including extensive single-, binary-, and ternary-component isotherm testing, to provide a strong research foundation for understanding the performance of the field projects. This understanding will be used to assess the feasibility of CO<sub>2</sub> sequestration in a broad set of coal and CO<sub>2</sub> 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<sub>2</sub> sequestration in coal seams, some of the merits of pure versus mixed gas (CO<sub>2</sub> and N<sub>2</sub>) injection on CO<sub>2</sub> sequestration and ECBM performance, and the field performances to date of the Tiffany and Allison Units.

## Reservoir Mechanisms

The mechanism by which CO<sub>2</sub> (or N<sub>2</sub>) can enhance the coalbed methane recovery process, and CO<sub>2</sub> 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<sub>2</sub> than either methane (CH<sub>4</sub>) or N<sub>2</sub> 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<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>), 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<sub>2</sub> injection. Under certain conditions, the equilibrium ratio of CH<sub>4</sub> to N<sub>2</sub> in the adsorbed state is 2:1, but is 1:3 in the gaseous state (see point A in Figure 4a). As pure N<sub>2</sub> is injected however, it flushes the gaseous methane from the cleats, creating a near 100% N<sub>2</sub> 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<sub>2</sub>-ECBM recovery process is referred to as methane stripping.

On the other hand, as CO<sub>2</sub> 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<sub>2</sub>. Consider Point B in Figure 5a. The equilibrium ratio of CH<sub>4</sub> to CO<sub>2</sub> is 1:1 in the sorbed state, but is 3:1 in the gaseous state. As pure CO<sub>2</sub> is injected it is quickly adsorbed into the coal matrix to achieve sorbed equilibrium, displacing sorbed CH<sub>4</sub> in the process.

Modeling work using ARI's COMET2 coalbed reservoir simulator demonstrates the advantages and disadvantages of N<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> 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<sub>2</sub> injection. However, N<sub>2</sub> breakthrough occurs fairly quickly and becomes a high percentage of total production. Hence any enhanced recovery benefit gained by N<sub>2</sub> injection must be balanced against higher gas treatment costs. Injection of CO<sub>2</sub> also results in an immediate gas production response, albeit less so than with N<sub>2</sub>. In the case of CO<sub>2</sub>, however, no significant breakthrough of CO<sub>2</sub> 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<sub>2</sub> sequestration project; to achieve the desired

low net-cost for CO<sub>2</sub> sequestration, an injection gas consisting of both N<sub>2</sub> (for rapid methane recovery) and CO<sub>2</sub> (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<sub>2</sub> or CO<sub>2</sub> injection. The higher water response with N<sub>2</sub> is surmised to be a result of its lesser compressibility and higher viscosity than methane. On the other hand, CO<sub>2</sub> 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<sub>2</sub> and/or N<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>, CO<sub>2</sub>, 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<sub>2</sub>-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<sub>2</sub> breakthrough) predicted by reservoir modeling.

The Tiffany Unit is being evaluated for the potential of injecting a mixture of waste CO<sub>2</sub> and the already generated N<sub>2</sub>. While many variables may exist, information from this already

active N<sub>2</sub>-ECBM flood will enhance understanding the effects of CO<sub>2</sub> injection.

**Allison Unit.** The Allison Unit, is the world's first experimental (pure) CO<sub>2</sub>-ECBM recovery pilot, and is the second field demonstration site (Figure 8). The pilot comprises of four CO<sub>2</sub>-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<sub>2</sub> 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<sub>2</sub> injection, during which time five of the production wells were temporarily shut in to facilitate CO<sub>2</sub>/CH<sub>4</sub> exchange in the reservoir (Figure 12). A sharp increase in water production was observed immediately. After six months, CO<sub>2</sub> 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<sub>2</sub> has been minimal during the life of the project; following almost five years of injection, current CO<sub>2</sub> concentrations at the production wells average 6%, which is only slightly above initial pre-injection levels of 4%. This suggests that the physical processes of CO<sub>2</sub> 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<sub>2</sub>-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<sub>2</sub> 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<sub>2</sub> and CO<sub>2</sub> can enhance CBM recovery, and that coals appear to effectively sequester CO<sub>2</sub>. It also appears that there will be an economic optimum N<sub>2</sub>/CO<sub>2</sub> 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

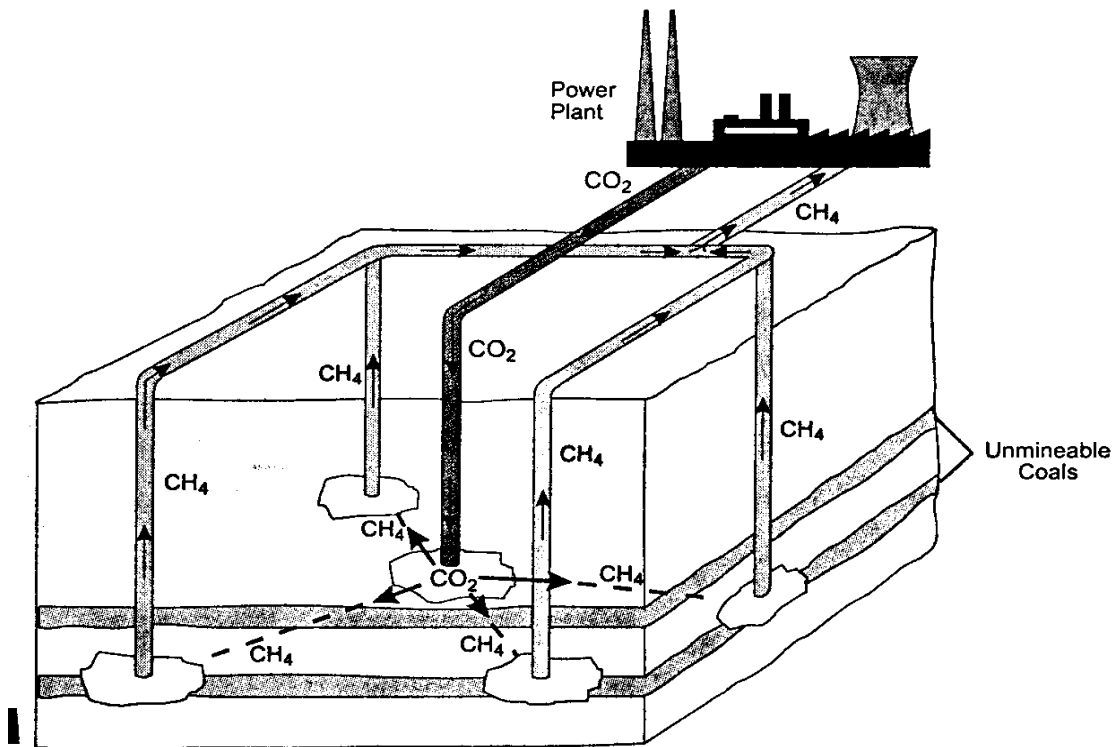
This work is being sponsored by The U.S. Department of Energy under contract DE-FC26-00NT40924, "Geologic Sequestration of CO<sub>2</sub> in Deep, Unmineable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project"; DOE's Technical Manager is Mr. Charles Byrer.

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2. *Electric Power Annual*, 2000 (DOE/EIA-0348(99)/2).
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5. Stevens, Scott H., Schoeling, Lanny, Pekot, Larry, "CO<sub>2</sub> 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 N<sub>2</sub>/CO<sub>2</sub> Injection (Quarter 5-Spot Pattern)*

	<b>BASE CASE</b>	<b>NITROGEN</b>	<b>CARBON DIOXIDE</b>
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<sub>2</sub> Sequestration Concept*

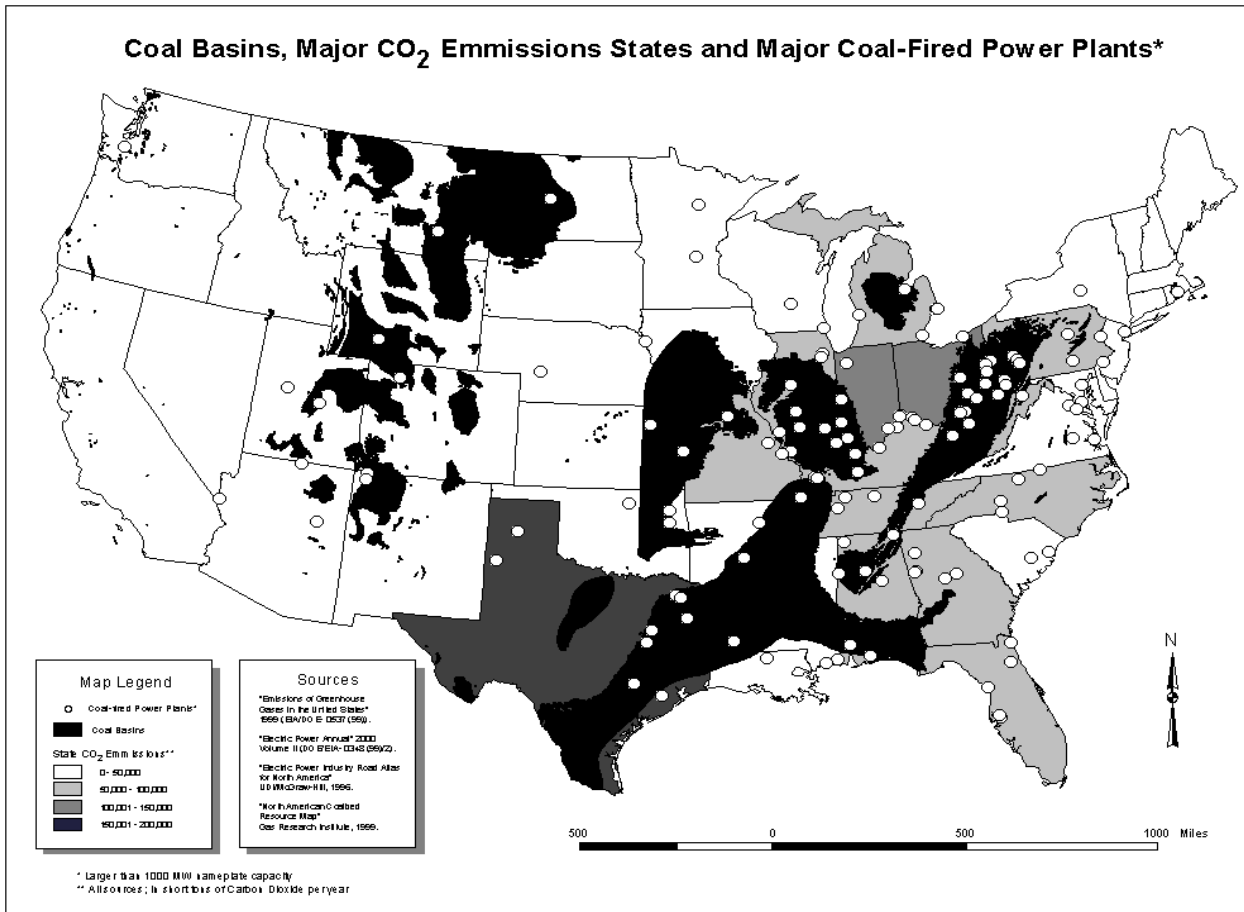


Figure 2: Coincidence of State CO<sub>2</sub> Emissions, Large Coal-Fired Power Plants, and Coal Basins

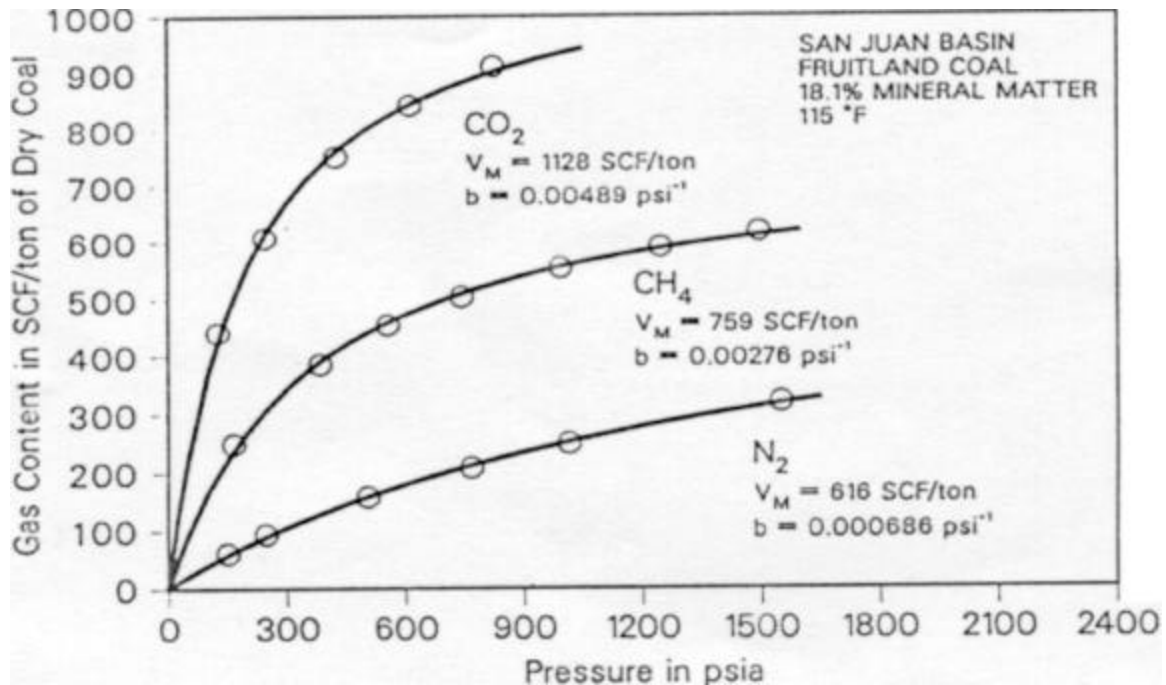


Figure 3: Relative Adsorption Capacities of N<sub>2</sub>, CH<sub>4</sub> and CO<sub>2</sub>, San Juan Basin Coal (reproduced from reference 4)

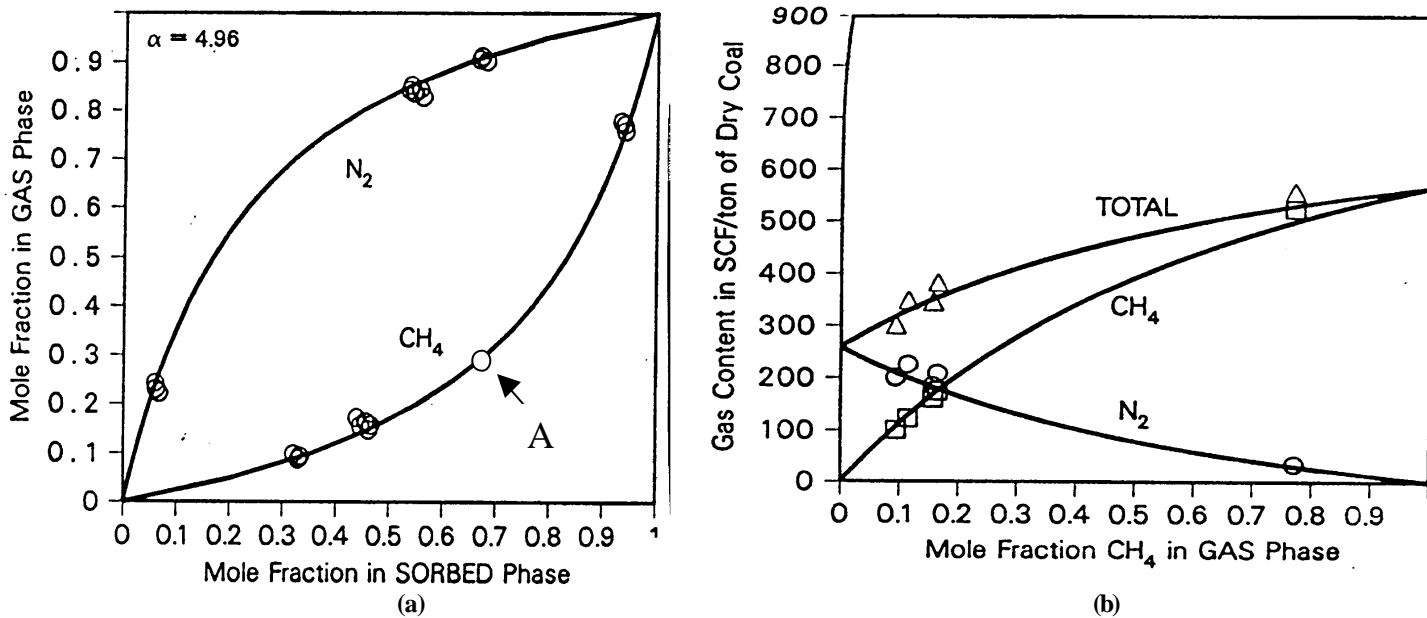


Figure 4: N<sub>2</sub> - CH<sub>4</sub> Binary Sorption Behavior, San Juan Basin Coal (reproduced from reference 4)

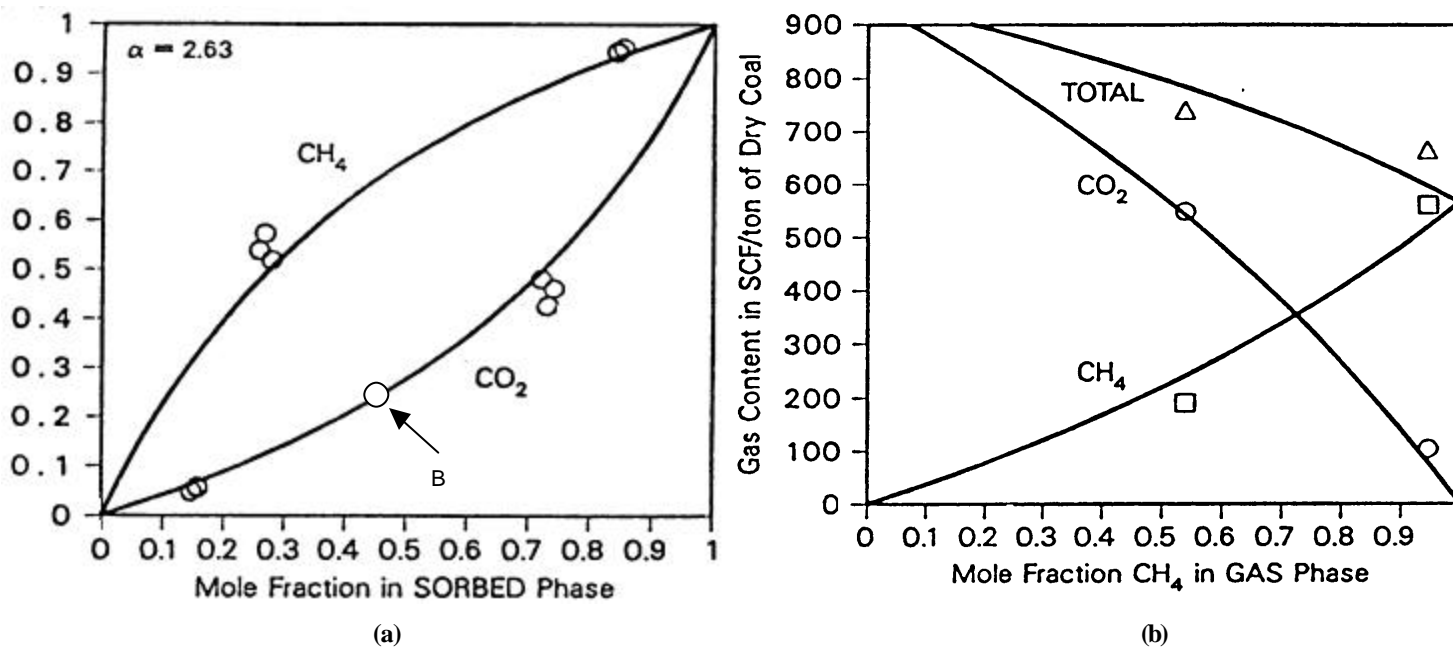


Figure 5: CH<sub>4</sub> - CO<sub>2</sub> Binary Sorption Behavior, San Juan Basin Coal (reproduced from reference 4)

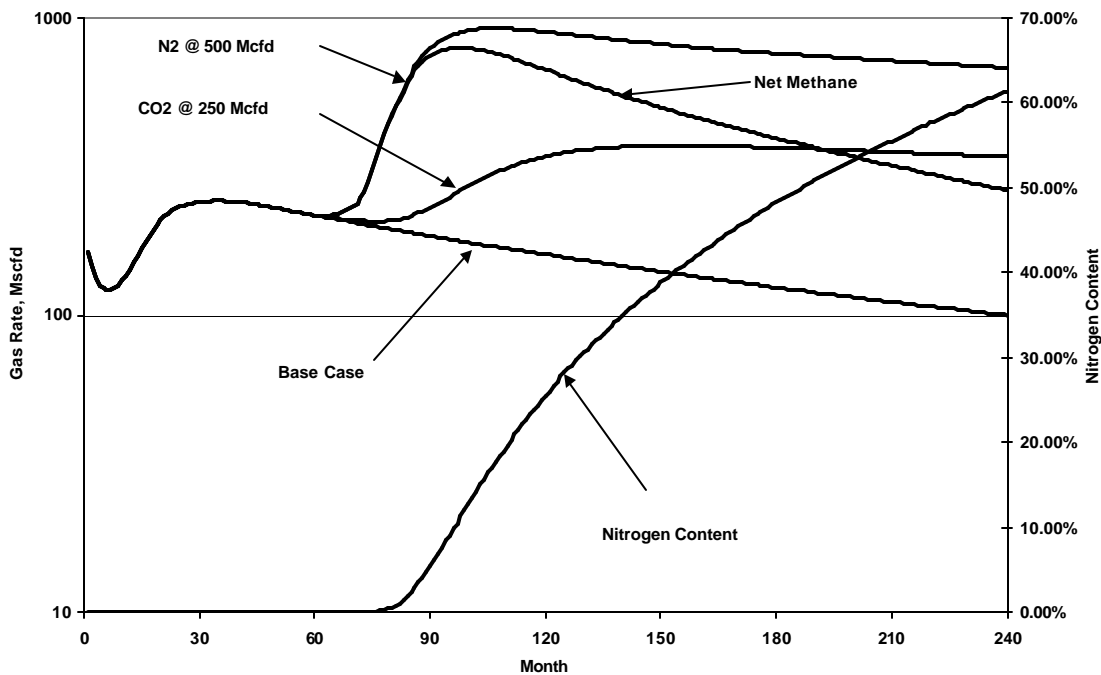


Figure 6: Gas Production Response to N<sub>2</sub>/CO<sub>2</sub> Flooding

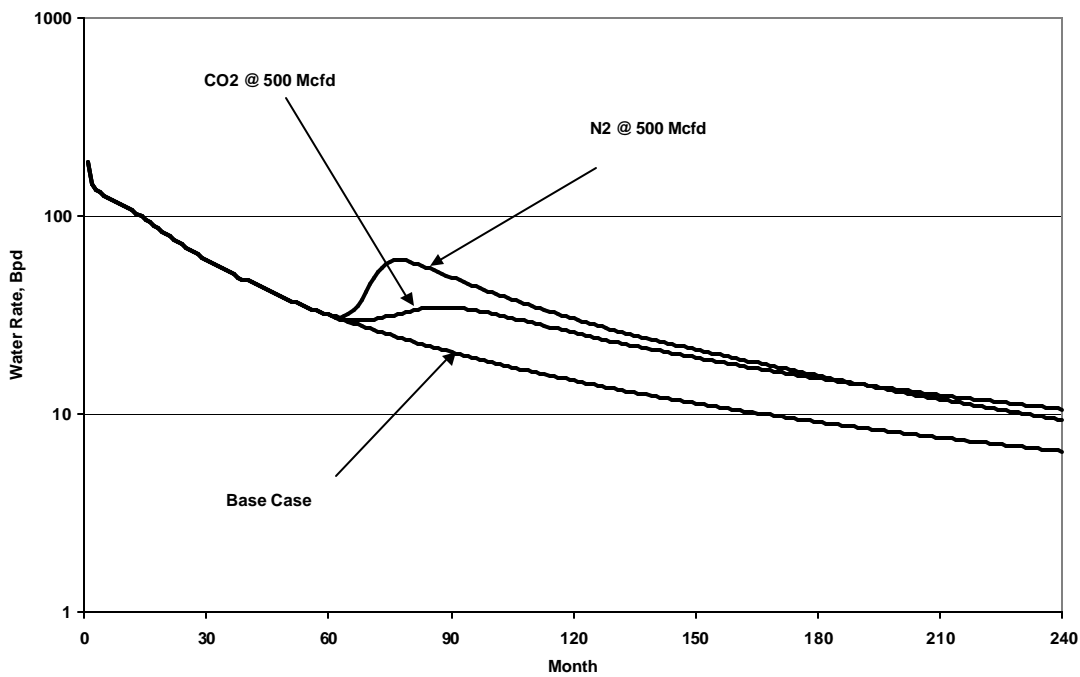
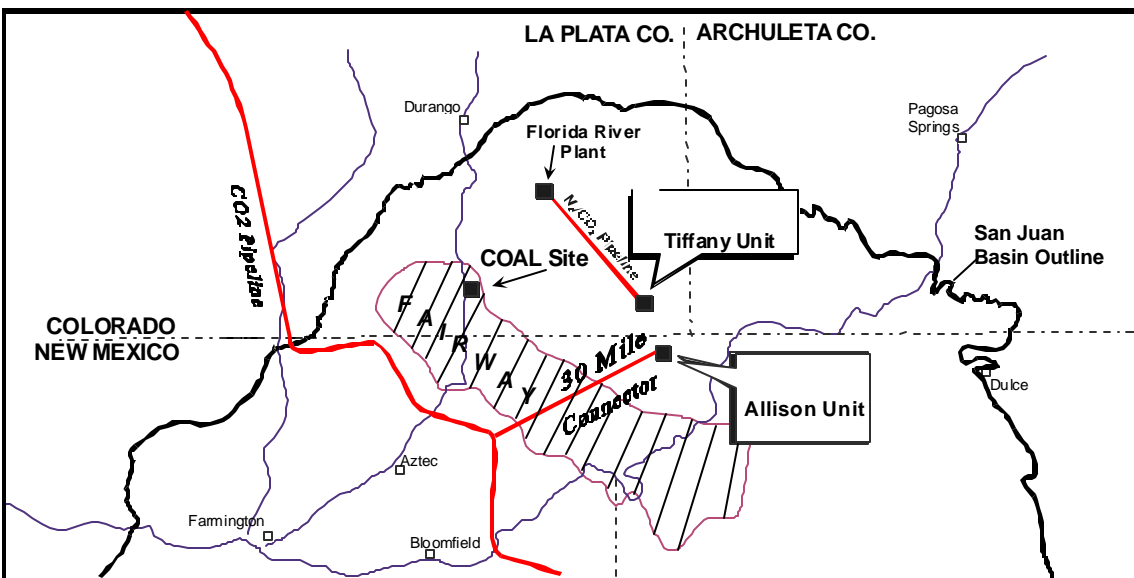


Figure 7: Water Production Response to N<sub>2</sub>/CO<sub>2</sub> Flooding



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Figure 8: Location of N<sub>2</sub>/CO<sub>2</sub>-ECBM Pilots, San Juan Basin

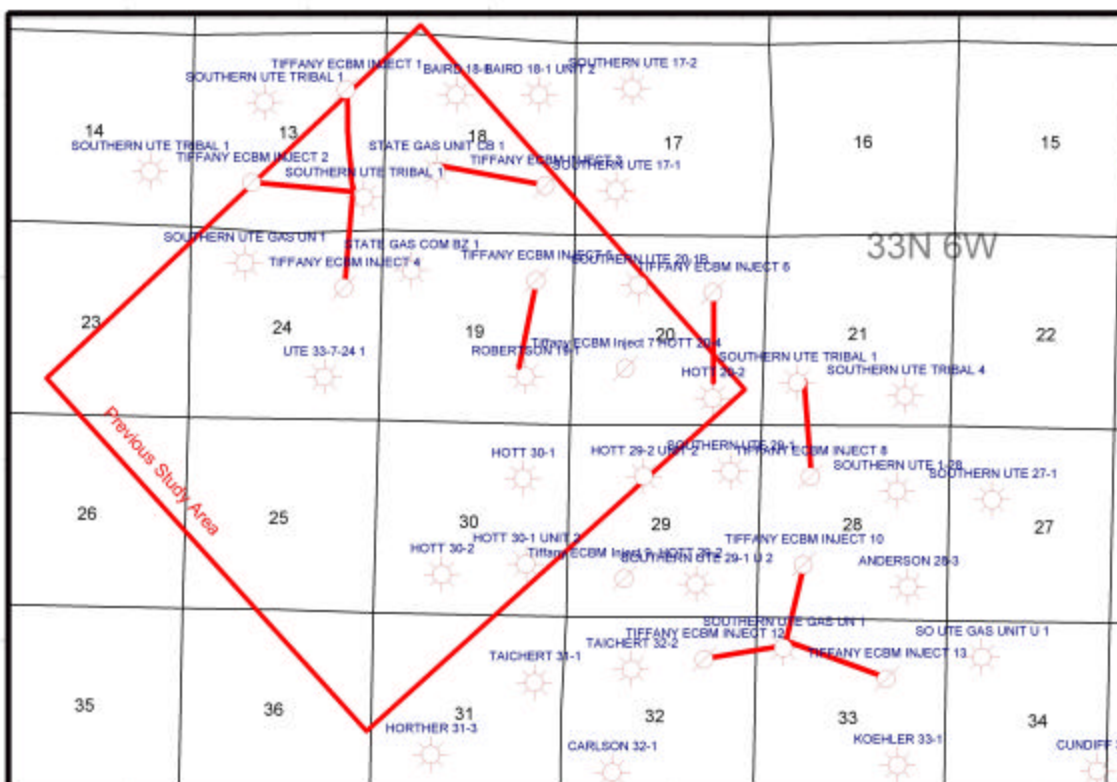


Figure 9: Tiffany Unit N<sub>2</sub> – Flood Well Pattern

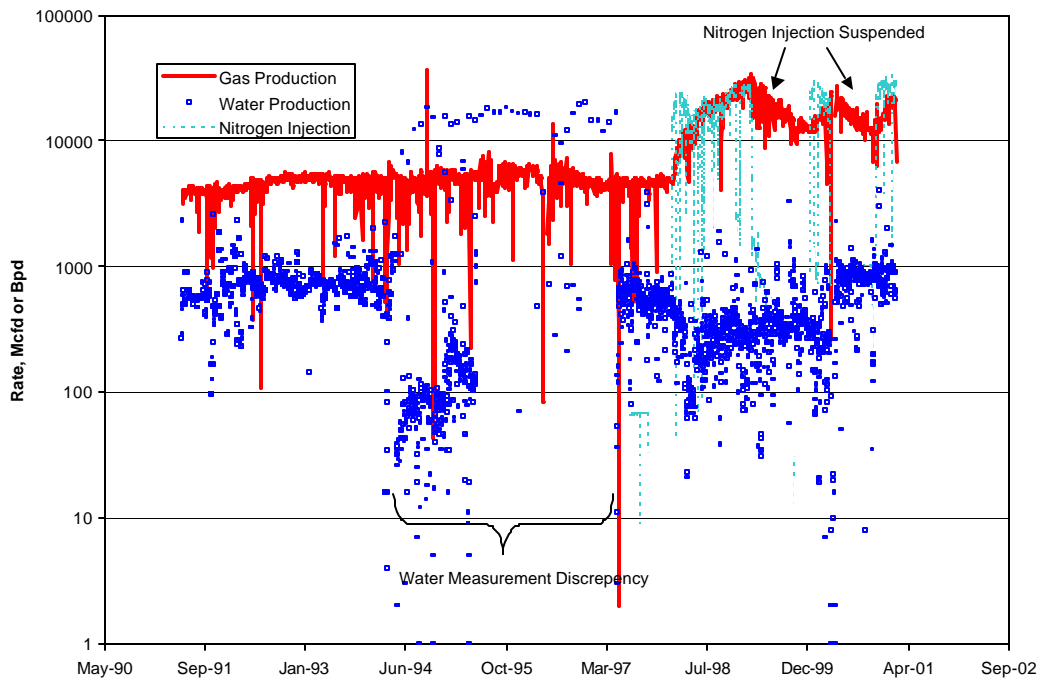


Figure 10: Tiffany Unit Production N<sub>2</sub> – Flood Pilot Area

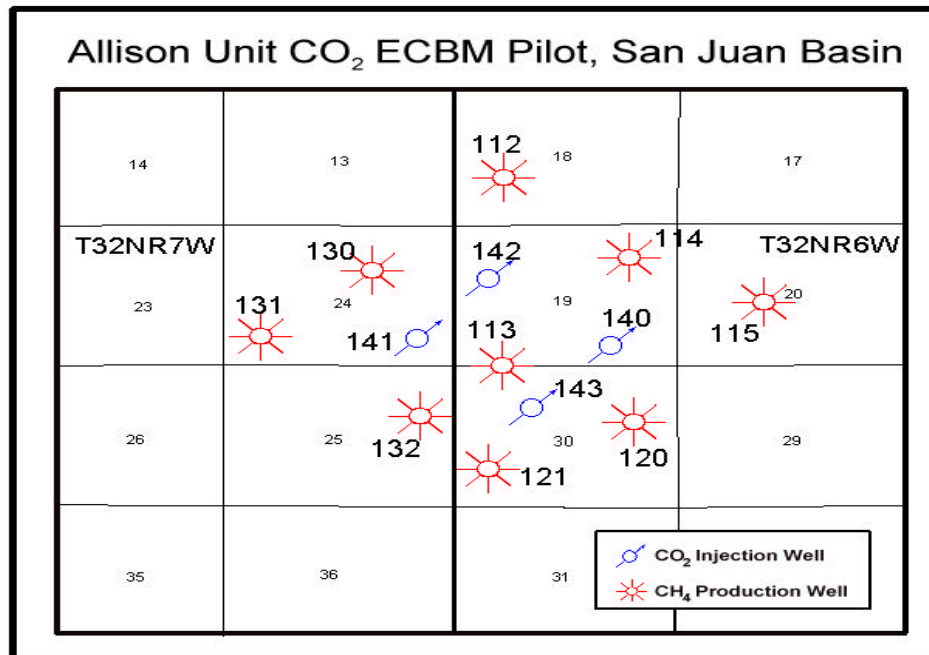
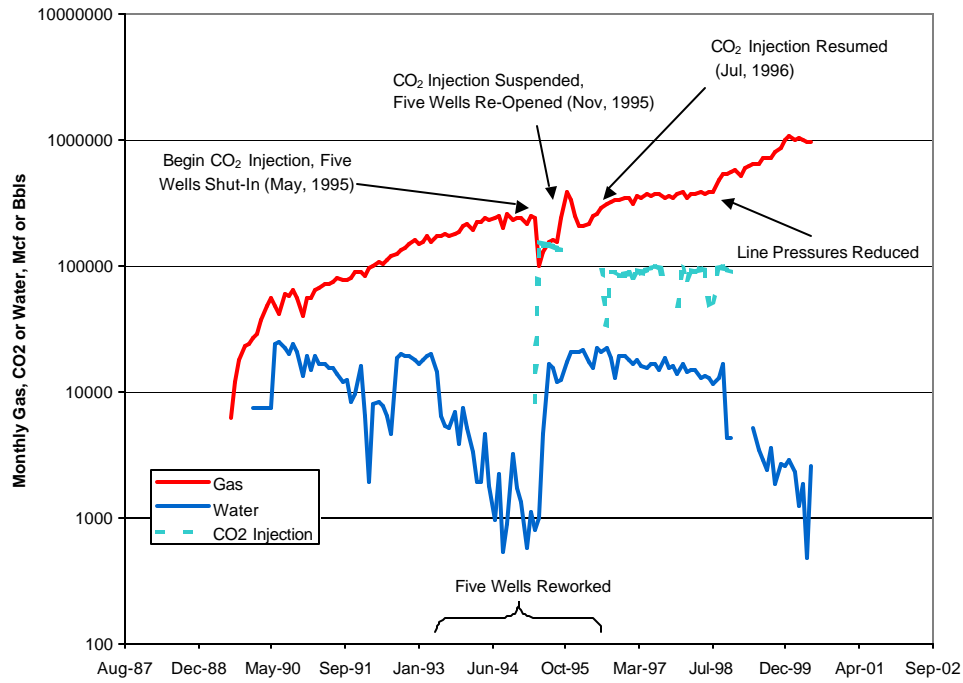


Figure 11: Allison Unit CO<sub>2</sub> – Flood Pilot Well Pattern



**Figure 12:** Allison Unit Production, CO<sub>2</sub> – Flood Pilot Area