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GAS INJECTION AND BREAKTHROUGH TRENDS AS OBSERVED IN ECBM SEQUESTRATION PILOT PROJECTS AND FIELD DEMONSTRATIONS

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ABSTRACT

Enhanced coalbed methane (ECBM) recovery is of growing interest primarily because its' synergistic application with carbon sequestration (in the case of carbon dioxide (CO_2) injection), and the potential to unlock coalbed methane (CBM) resources that are sub-economic to produce via conventional means (in the case of nitrogen (N_2) injection). However there is limited field experience with ECBM technology, and the experience that does exist suggests that the reservoir dynamics at play with ECBM are more complex than those under primary CBM production. While laboratory studies provide a valuable foundation upon which to base working hypotheses for understanding reservoir behavior, reconciling these hypotheses to field observations is an important element of the learning process. Based upon the experiences at three ECBM/sequestration pilots projects and field demonstrations – the Allison CO_2-ECBM pilot in the San Juan basin, the Tiffany N_2-ECBM pilot, also in the San Juan basin, and the RECOPOL CO_2-sequestration demonstration in Poland – trends regarding gas injection and breakthrough are emerging, most generally consistent with current understanding of reservoir behavior, but some not. Specifically, as predicted by laboratory experiments, coal permeability (i.e., injectivity) is reduced with CO_2 injection due to swelling, and is enhanced by N_2 injection. Rapid breakthrough of N_2 also occurs, as one would expect based on relative sorption capacities. However, an apparently "disperse" flood front at the Allison Unit, and rapid CO_2 breakthrough at the RECOPOL project, was unexpected. While a number of possible mechanisms have been put forth to explain these observations, primarily based upon reservoir simulation studies, uncertainty remains. The experience gained from these pilots and demonstrations suggests that while a sound fundamental understanding of the ECBM/sequestration process is believed to exist, there is still much to learn, particularly regarding how CO_2 and coal interact.

INTRODUCTION

Enhanced coalbed methane (ECBM) recovery is the process of injecting a gas into a coal reservoir to enhance the desorption and recovery of in-situ coalbed methane (CBM). Depending upon whether the injected gas exhibits a greater or lesser sorption capacity on coal than methane, the process is either dominated by displacing the CBM from sorption sites within the coal matrix blocks into the cleat system, or stripping it from the coal matrix with a low partial pressure to methane in the cleat system. The two gases with which industry has ECBM field experience with are carbon dioxide (CO_2), which exhibits a greater adsorptive capacity than methane, and nitrogen (N_2), which exhibits a lesser adsorptive capacity than methane. Figure 1 (a) provides a set of example methane, CO_2 and N_2 isotherms for coal. It should be noted that while CO_2 always exhibits a greater sorption capacity than methane, and N_2 a lesser capacity, the ratio of sorption capacity between the gases is strongly dependent upon coal rank.

Another important concept relevant to the ECBM process is how different gases affect coal permeability. The concept of pressure-dependent and concentration-dependent permeability during primary CBM recovery is well accepted. While gas species will not impact the pressure-dependent component of coal permeability behavior, it most certainly impacts the concentration-dependent component. Specifically, on the “steep” (i.e., low-pressure) portion of the isotherm where the greatest volumes of gas are adsorbed for a given pressure increase, gases with greater adsorptive capacities (i.e., CO_2) tend to “swell” the coal more, causing greater permeability reduction. This has a negative impact on gas injectivity, thus compromising the overall effectiveness of the ECBM process. A less adsorptive gas, such as N_2, has the opposite effect – permeability will increase. Figure 1 (b) illustrates how coal permeability changes with pressure, gas concentration, and gas species.

To briefly describe the CO_2-ECBM process, when CO_2 is injected into a coalseam, its’ strong affinity to coal causes it to be immediately adsorbed within the coal matrix blocks, displacing in-situ methane from its sorption sites and into the cleats, where it can be produced from a nearby production well. This results in a “shock” displacement front characterized by a CO_2/methane mixing zone at the flood front that is quite narrow. “Shock” flood fronts typically exhibit efficient volumetric displacement and delayed gas breakthrough. In the case of N_2-ECBM, due to its’ lesser sorption capacity, much of the injected N_2 remains in the cleats, thus reducing the partial pressure to methane. This reduction of methane partial pressure causes the methane to desorb from and diffuse though the matrix blocks into the cleat system, where it can be produced. As one can envision, this results in a “disperse” flood front, characterized by a N_2/methane mixing zone at the flood front that is much wider. “Disperse” flood fronts typically exhibit inefficient volumetric displacement and early gas breakthrough. An illustration of “shock” and “disperse” flood fronts based on laboratory experiments (a) and reservoir modeling studies (b) are illustrated in Figure 2 [1,2]. While the dominant ECBM reservoir behavior differs depending upon whether the injection gas is more or less adsorptive on the coal than methane, the underlying physics is the same in either case. In simple terms, then, these are the fundamental concepts of ECBM recovery, founded largely upon laboratory and theoretical studies.

The objective of this paper is to examine how the above concepts are manifested in actual, albeit limited, field experience. Specifically, three field tests were examined - the Allison CO_2-ECBM pilot in the San Juan basin, the Tiffany N_2-ECBM pilot, also in the San Juan basin, and the RECOPOL CO_2-sequestration demonstration in Poland - to find evidence of “shock” versus “disperse” flood fronts, and coal permeability changes with CO_2 and N_2 injection. Figures 3 and 4 provide the locations and well patterns associated with each of these pilots/demonstrations, and Table 1 provides some basic information on their size, scope and reservoir conditions.

ALLISON UNIT N_2-ECBM PILOT

The Allison CO_2-ECBM pilot in the San Juan basin provided industry’s first significant opportunity to examine this process [3,4]. Several important observations emerged from that pilot. First, pressure transient tests on 12 wells in the vicinity of the pilot indicated relatively high initial absolute coal permeability, on the order of +/- 100 millidarcies (md). Injection was performed under constant bottomhole pressure to minimize the likelihood of exceeding formation fracturing pressure, and injection rate was allowed to vary. The injection rate profile for one of the injectors, which was typical, is provided in Figure 5. Note the decline in injectivity over the first two years of injection, to about half the initial level, presumably as a result of coal swelling and permeability reduction. At the conclusion of the pilot, in August, 2001, the four CO_2 injectors were shut-in and bottomhole pressures measured for pressure transient analysis purposes. The results of those tests indicated coal permeabilities on the order of +/- 1 md, almost two orders of magnitude less than the estimated initial conditions at the site. Thus permeability and injectivity reduction with CO_2 injection was observed, as expected. However the gradual increase in injectivity after the initial reduction was unexpected.

To investigate this, production, injection and reservoir pressure data (as recorded in a pressure observation well within the pilot pattern) were examined (Figure 6). From this information it was clear that since reservoir withdrawal volumes (i.e., CBM production) in the vicinity of the pilot were far greater than the CO_2 injection volumes, overall reservoir pressure continued to decline even during injection. This caused CO_2 adsorbed near the injection wells to desorb and migrate further from the well, thus reversing the near-well swelling. The hypothetical permeability history near the injection wells is conceptually illustrated in Figure 7. Starting at the right side of the figure, at initial reservoir pressure, and moving towards the left (lower reservoir pressures), one would expect some reduction in coal permeability even before the injection well was drilled due to pressure-dependent permeability effects. Once the well was drilled, and CO_2 injection initiated, the permeability profile shifted from the methane curve to the CO_2 curve, causing the observed injectivity reduction. Once on the CO_2 curve however, continued migration to the left (with pressure reduction) induces matrix shrinkage effects, even to the CO_2-saturated coal near the injection wells, and permeability and injectivity increase. Thus, while at first glance surprising, this behavior, too, can be reasonably explained based upon current understanding of ECBM reservoir mechanics.

Another noteworthy observation from the Allison Unit was the character of the displacement front (i.e., “shock” or “disperse”). For insight into this issue, the CO_2 breakthrough profile at the one well where CO_2 breakthrough was actually observed (the central well of the pattern, #113), was examined (Figure 8). One would expect that, for a “shock” front, as we would expect with CO_2, once the CO_2 arrived at the production well it would rise in concentration quite quickly, as illustrated in Figure 2. Contrary to this expectation however, after the initial CO_2 breakthrough occurred in July 1996, approximately 17 months after initial injection in April, 1995, the CO_2 concentration had only risen from its pre-injection level of 5% to about 9-1/2% three and half years later. This seems more in character with a “disperse” flood front. It should be noted that the timing of CO_2 arrival at the subject well was easily explained via reservoir modeling, but the CO_2 content profile was not. While the reasons for this remain uncertain, it could be due to reservoir heterogeneity (e.g., CO_2 breakthrough initially occurring in only one coal layer, with delayed breakthrough in the others).

TIFFANY UNIT N_2-ECBM PILOT

The Tiffany Unit N_2-ECBM pilot is the only long-term N_2-ECBM pilot against which to benchmark our understanding of this process [5,6]. Besides injecting a different gas, this pilot was different from the Allison Unit pilot in that, based upon prior reservoir studies of the area, the coal permeability was much lower (+/- 1 md at Tiffany vs. +/- 100 md at Allison).

A plot of injection rate and pressure for one of the injectors is provided in Figure 9. One can clearly observe from this figure that injectivity improved over time (note that N_2 was injected intermittently at this pilot). This is as expected; the hypothetical permeability history for an injector at Tiffany is illustrated in Figure 10. A plot of N_2 content of the produced gas in which N_2-breakthrough was observed is presented in Figure 11. Clearly there is considerable variation in response, but N_2 breakthrough was very rapid, also as expected. Note that the spacing between injectors and producers at Tiffany was about the same as at Allison.

It is interesting to contrast that at Tiffany, N_2 injection rates on the order of 90,000 - 100,000 thousands of cubic feet (Mcf) per well per month, or 3,000 – 3,300 Mcf/day, were being achieved at (surface) injection pressures of 1,500 – 1,700 pounds per square inch (psi), whereas at Allison, CO_2 injection rates on the order of 10,000 – 20,000 Mcf/well/monthly (330 – 660 Mcf/day) were being achieved at (bottomhole) pressures of 2,400 – 2,500 psi. The N_2 exhibits superior injectivity presumably because of a higher near-well permeability (~10 md at Tiffany vs. ~1 md at Allison under injection conditions – as compared to initial permeabilities of ~1 md and ~100 md respectively), as well as a lower viscosity for N_2. Higher N_2 injectivity also likely contributed to the earlier gas breakthrough at Tiffany.

Thus it appears that the N_2-ECBM process, at least as it appeared to perform at the Tiffany Unit, is reasonably well understood.

RECOPOL CO_2-SEQUESTRATION DEMONSTRATION

The RECOPOL CO_2-sequestration demonstration in Poland was the first of its kind outside of North America [7]. Due largely to the low coal permeability at the site, estimated at ~1 md, injection rates were extremely low, and the order of 200 – 800 cubic meters per day (M^3/day) (Figure 12). While this was successfully overcome with a hydraulic fracture treatment in the latter stages of the demonstration, one can nevertheless observe CO_2 breakthrough after only small volumes of CO_2 were injected (Figure 12), and in a gradual manner more characteristic of a "disperse" flood front than a "shock" one. This was a surprising result since the coal was already highly undersaturated with gas, and one would expect that any CO_2 injected would first fully saturate the coal to the prevailing reservoir pressure, before being able to migrate to the production well.

To replicate this behavior in a reservoir simulator, and thus begin to gain insights into what may be occurring (at least within the framework of our current understanding of reservoir mechanics), a number of approaches have been applied, all of which have one thing in common – the existence of a high-conductivity pathway enabling CO_2 to breakthrough to the production well quickly. Some of the approaches have included a high-conductivity natural fracture between the injector and producer, a high degree of permeability heterogeneity and/or anisotropy (e.g., a high-permeability coal layer and/or high permeability orientation between injector and producer), and gravity segregation and override (CO_2 traveling along a thin zone of high gas saturation at the top of the coal seam) [8]. Each of these approaches has serious shortcomings. First, the likelihood of a high-permeability natural fracture in the precise location and orientation required to achieve the observed breakthrough response seems remote. So too is the likelihood of having the degree of permeability heterogeneity and anisotropy required. Gravity segregation and override seems a much more plausible explanation, except that at RECOPOL the coal was so highly under-saturated that the coal would have adsorbed all CO_2 injected, even just at the top of the coal. This approach only works when coupled with a drastic (and unrealistic in the opinion of the authors) reduction in CO_2 adsorption capacity for the coal.

These findings, taken together with the uncertainty surrounding CO_2 breakthrough behavior at Allison, begin to imply an incomplete understanding of reservoir mechanics, particularly related to CO_2 injection. While the various phenomena described above will almost certainly always play a role in the ECBM process, within realistic bounds, there seems to be other effects at play, whether "conventional" and just not yet properly accounted for, or altogether new and "unconventional" ones.

One "unconventional" possibility regarding potential reservoir mechanisms at play may be related to some work performed regarding the effect CO_2 may have on coal mechanical integrity [9]. While controversial, some independent evidence of coal weakening and even failure under CO_2 injection conditions has been observed from R&D being performed under the Coal-Seq II Consortium [10]. If real, and a contributing factor to the observations discussed in this paper, this highly "unconventional" reservoir behavior will need to be much more thoroughly investigated and understood before the performance of CO_2-ECBM/sequestration projects can be reliably evaluated.

FINAL REMARKS

While laboratory studies provide a valuable foundation upon which to base working hypotheses for understanding reservoir behavior, reconciling these hypotheses to field observations is an important element of the learning process. Based upon the experiences at three ECBM/sequestration pilots projects and field demonstrations – the Allison CO_2-ECBM pilot in the San Juan basin, the Tiffany N_2-ECBM pilot, also in the San Juan basin, and the RECOPOL CO_2-sequestration demonstration in Poland – trends regarding gas injection and breakthrough are emerging, most generally consistent with current understanding of reservoir behavior, but some not. Specifically, as predicted by laboratory experiments, coal permeability (i.e., injectivity) is reduced with CO_2 injection due to swelling, and is enhanced by N_2 injection. Rapid breakthrough of N_2 also occurs, as one would expect based on relative sorption capacities. However, an apparently "disperse" flood front at the Allison Unit, and rapid CO_2 breakthrough at the RECOPOL, was unexpected. While a number of possible mechanisms have been put forth to explain these observations, primarily based upon reservoir simulation studies, uncertainty remains. The experience gained from these pilots and demonstrations suggests that while a sound fundamental understanding of the ECBM/sequestration process is believed to exist, there is still much to learn, particularly regarding how CO_2 and coal interact.

ACKNOWLEDGEMENTS

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Table 1: Basic Description of ECBM/Sequestration Pilots/Demonstrations

	Allison Unit	Tiffany Unit	RECOPOL Project
Location	San Juan Basin, USA	San Juan Basin USA	Upper Silesian Basin, Poland
Operator	Burlington Resources (now ConocoPhillips)	Amoco (now BP)	Metanel (with TNO)
Start	1995	1998	2003
Duration	6 ½ years, continuous injection	4 years intermittent injection	1 year continuous injection
No. Injection Wells	4	12	1
Volume Injected	6.4 Bcf	15.0 Bcf	14.5 MMcf
Depth	3,100 ft	3,000 ft	3,200 ft
Thickness	43 ft	47 ft	35 ft
Rank (% V_R)	Med vol bit (1.33%)	Med vol bit (1.33%)	High vol bit (0.80-0.85%)
Permeability	~100 md	~1 md	~1 md

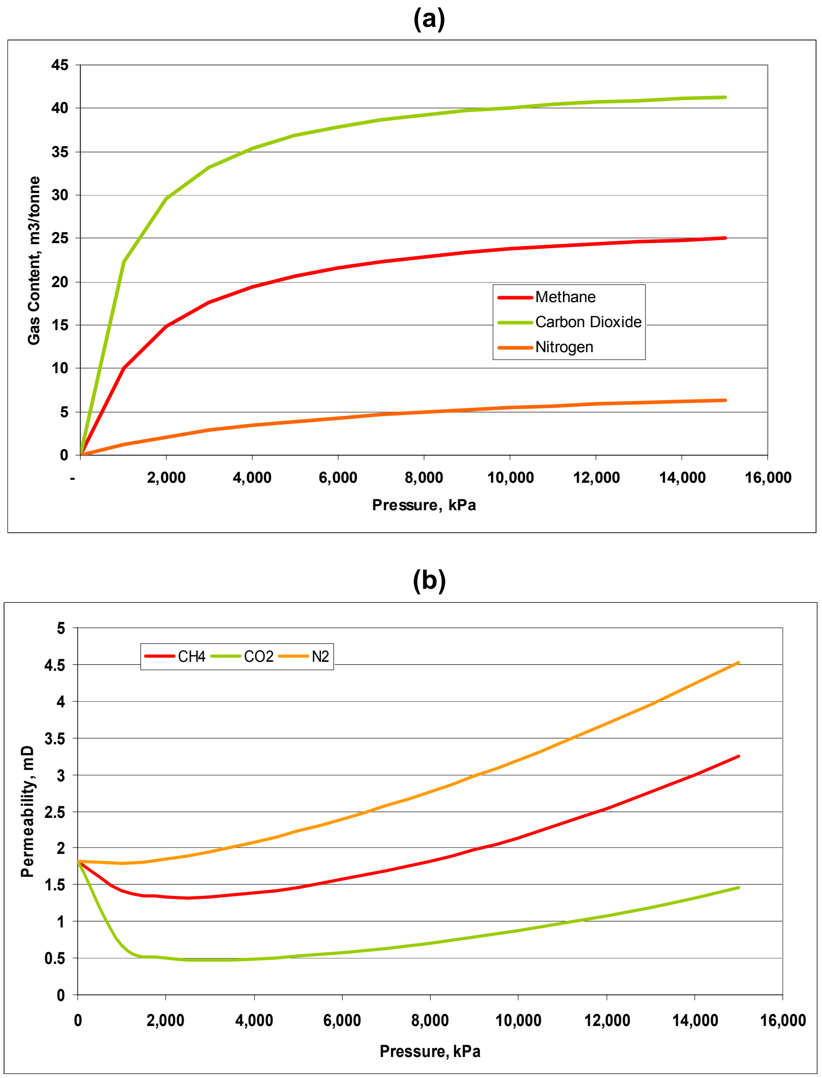
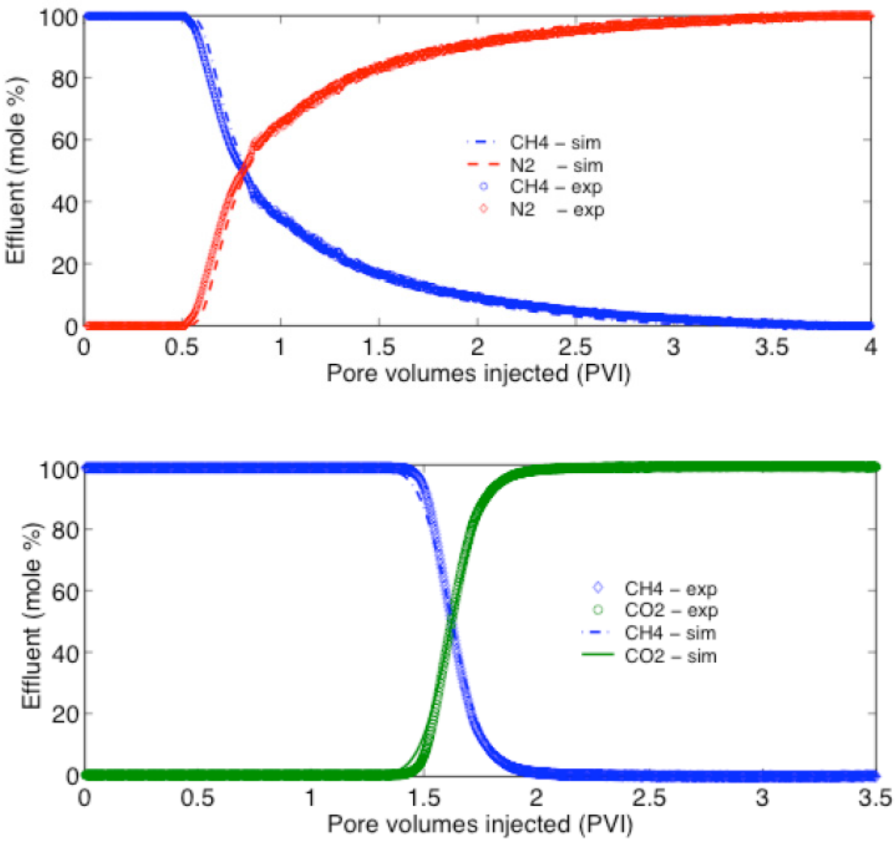


Figure 1: Example Isotherms and Permeability Changes in Coal

(a)



(b)

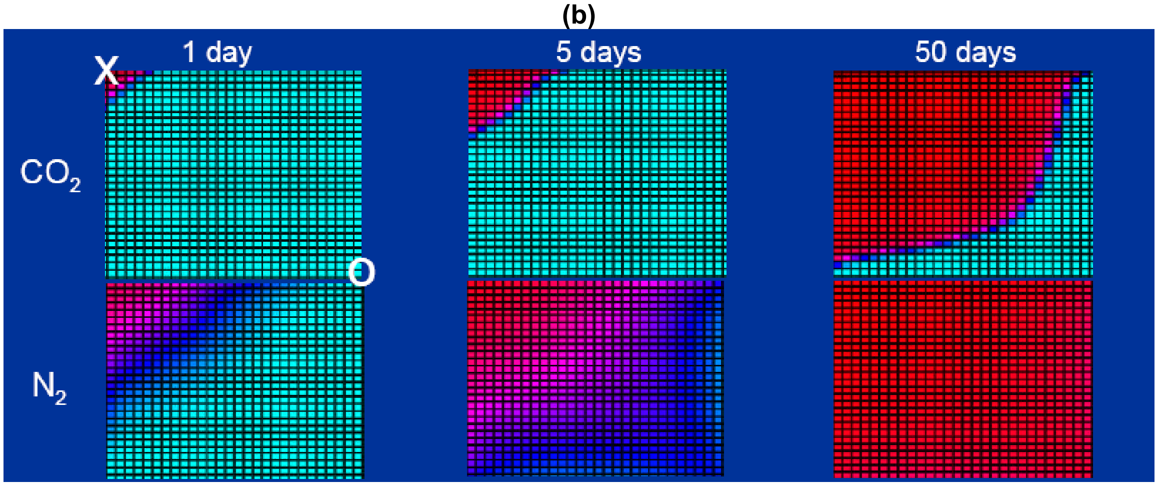


Figure 2: Examples of “Shock” (CO$_2$) and “Disperse” (N$_2$) Flood Fronts

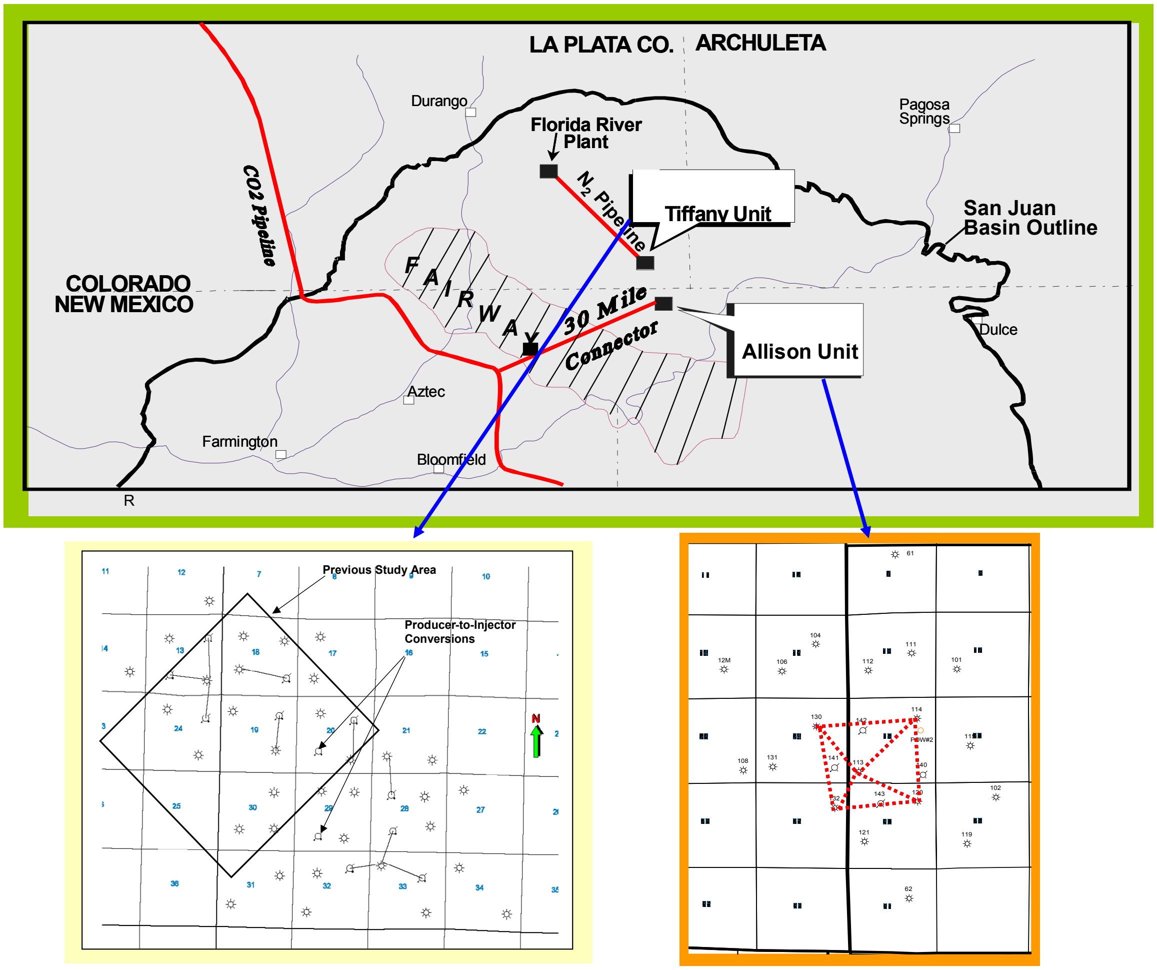


Figure 3: Location and Well Patterns of the Allison and Tiffany ECBM Pilots, San Juan Basin

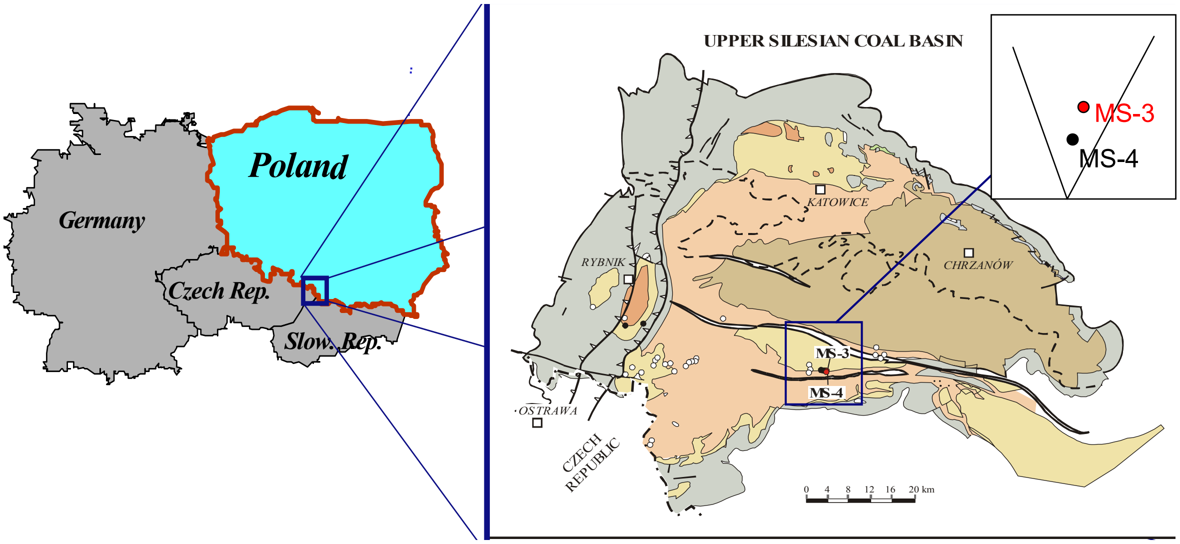


Figure 4: Location and Well Pattern of the RECOPOL CO_2 Sequestration Demonstration, Poland

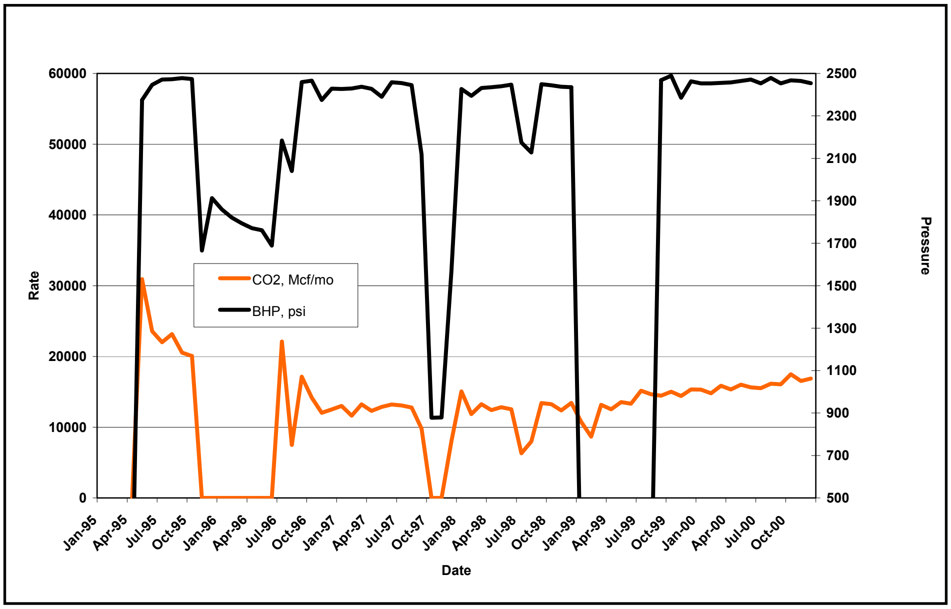


Figure 5: CO_2 Injection Rate and Pressure Profile, Allison Unit Injection Well

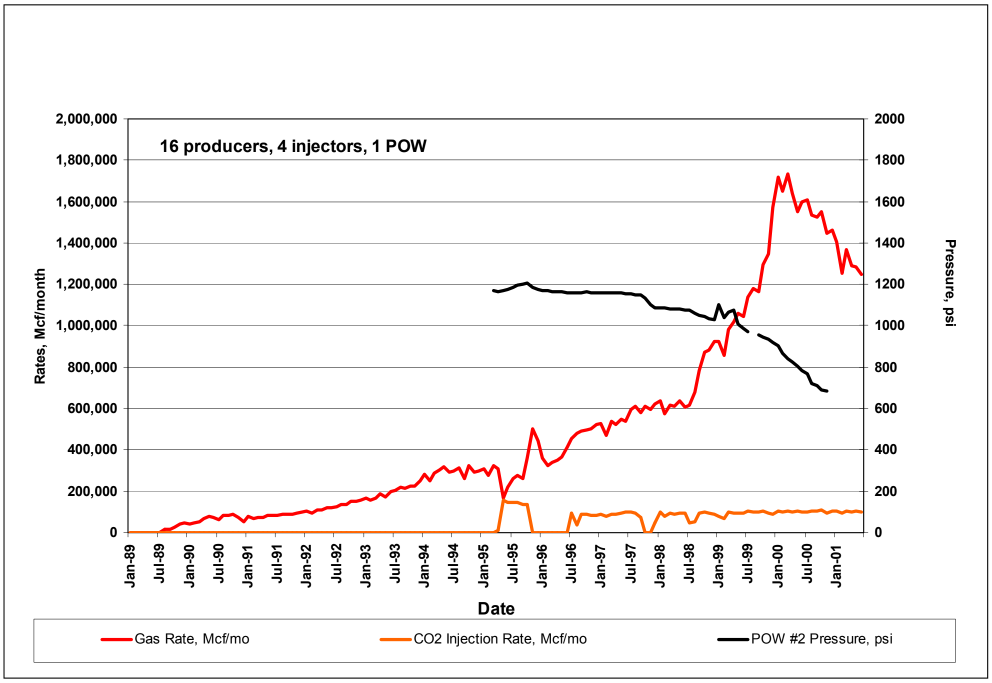


Figure 6: Production, Injection and Reservoir Pressure History, Allison Unit ECBM Pilot

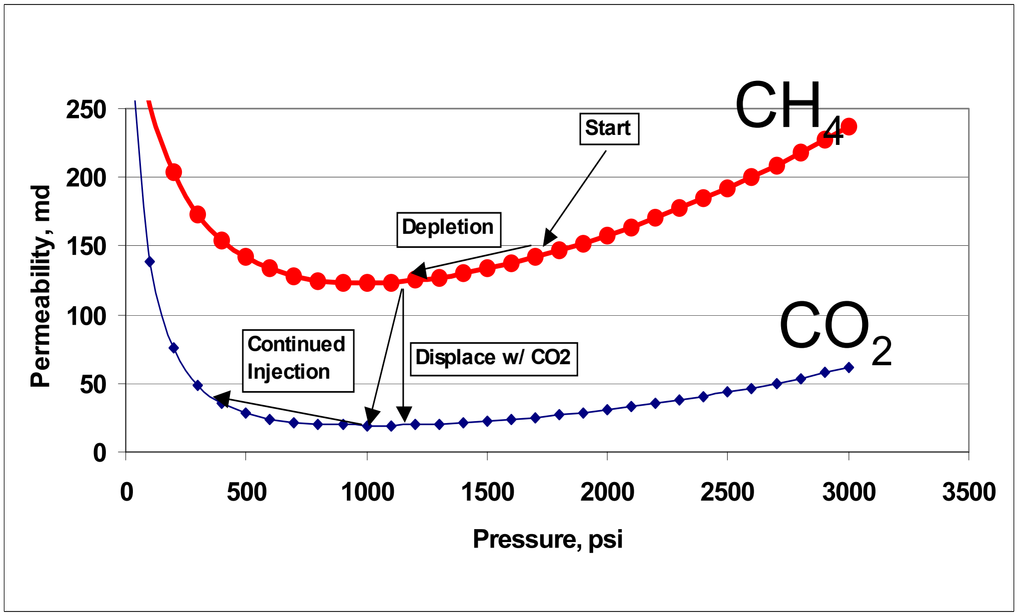


Figure 7: Permeability History, Allison Unit CO_2 Injection Well

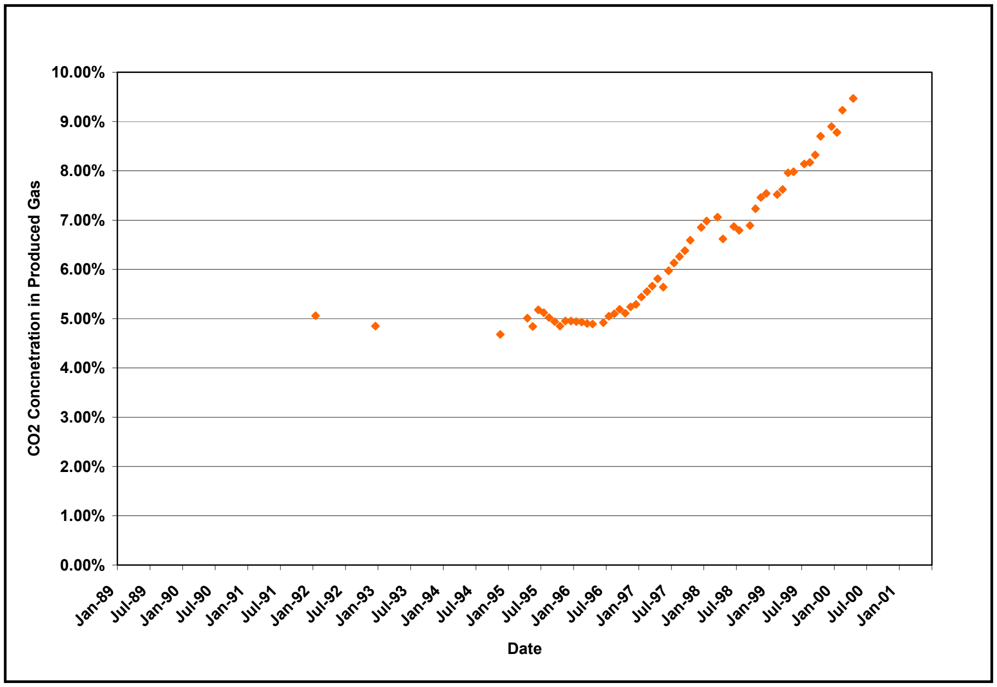


Figure 8: CO_2 Concentration in Produced Gas, Allison Unit #113

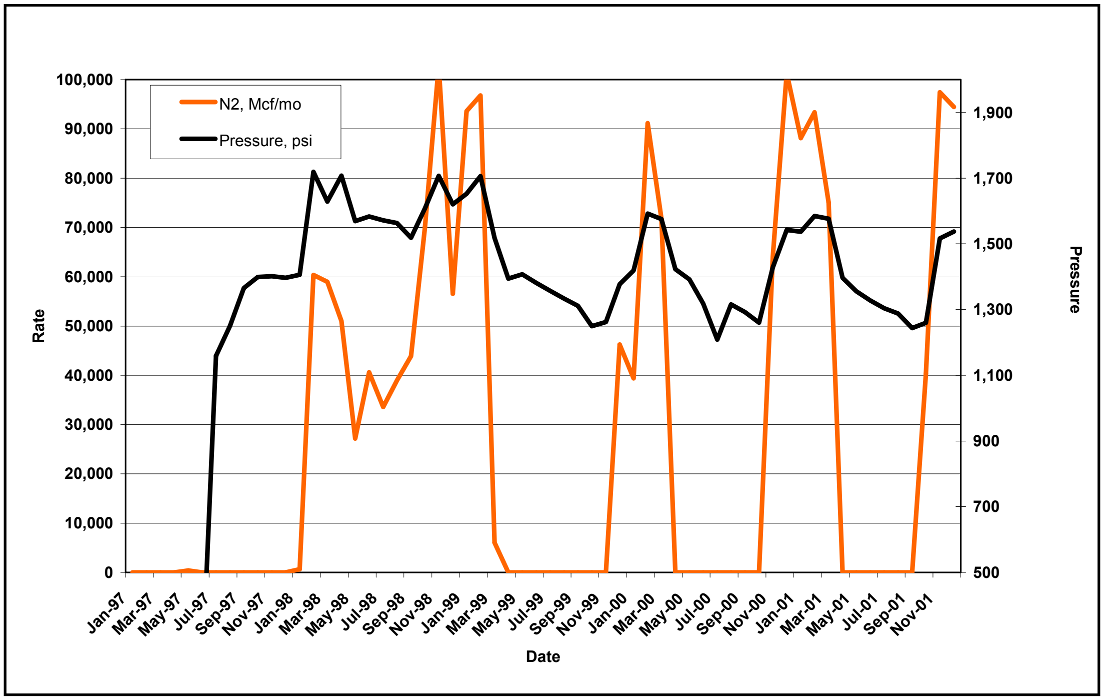


Figure 9: N_2 Injection Rate and Pressure Profile, Tiffany Unit Injection Well

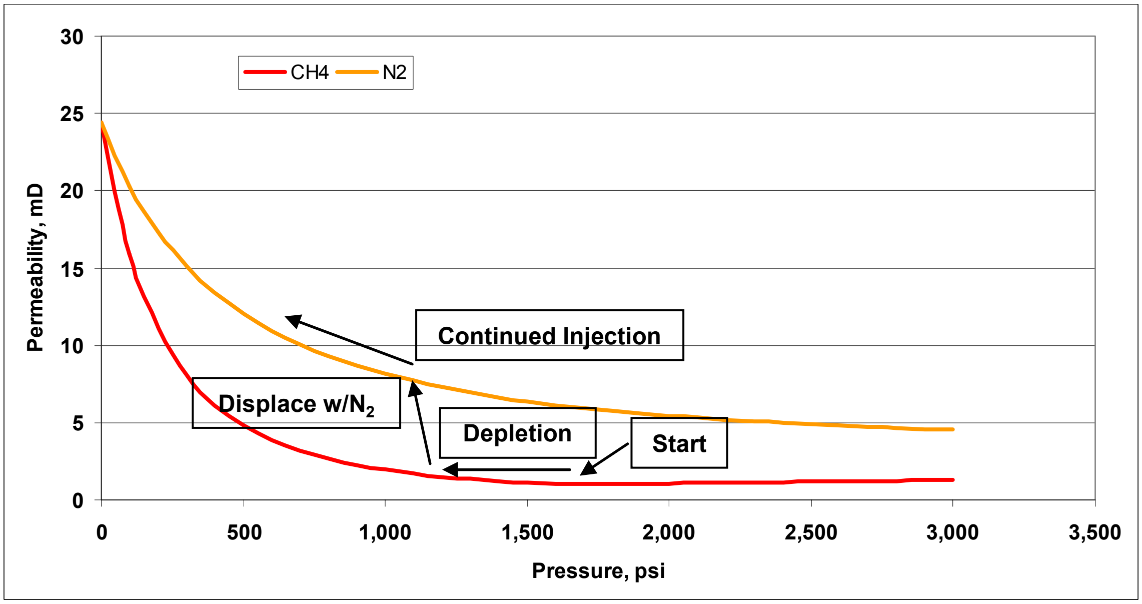


Figure 10: Permeability History, Tiffany Unit N_2 Injection Well

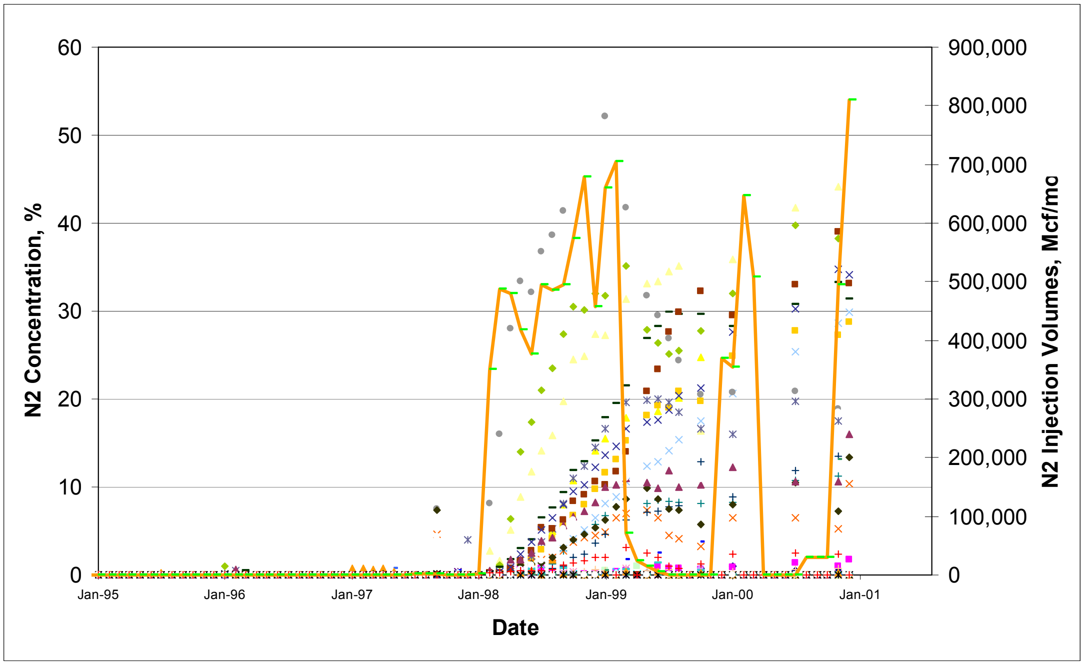


Figure 11: N_2 Content of Produced Gas, Tiffany Unit Production Wells

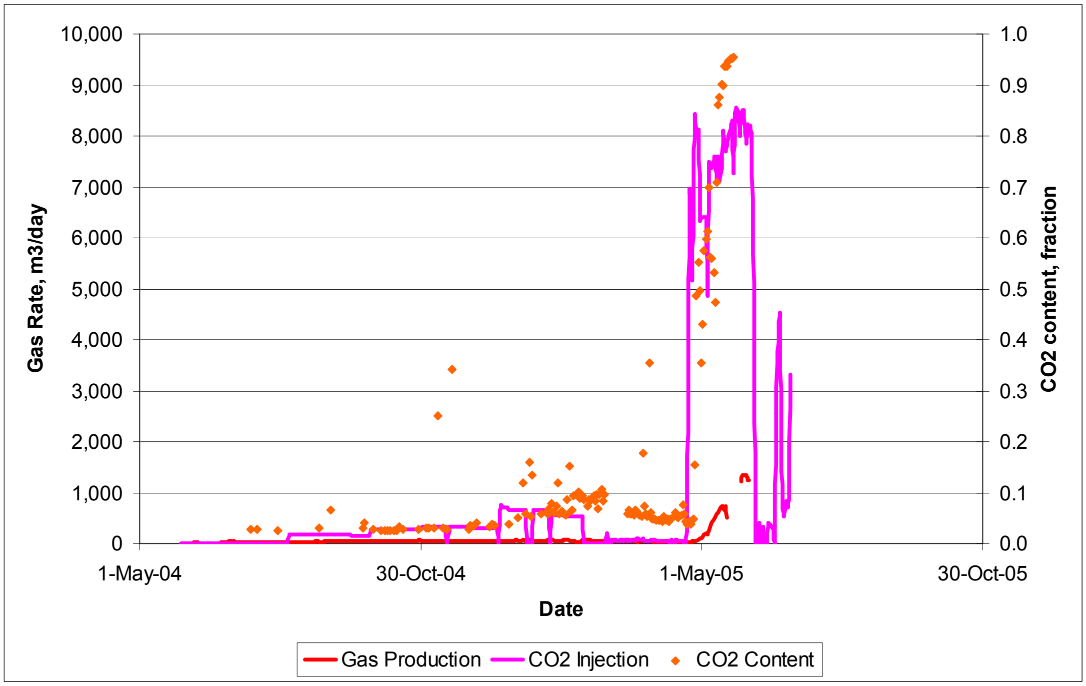


Figure 12: Production, Injection and CO_2 Content History, RECOPOL Project