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Reservoir Management in Tertiary CO_2 Floods

D.H. Merchant and S.C. Thakur, Amoco Production Co.

SPE Members

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Abstract

Since 1984, Amoco has operated four major enhanced oil recovery projects using CO_2 in West Texas. Due to the high cost of CO_2 injectant, the economic success of these floods depends on the ability to properly monitor and manage CO_2 utilization. This paper describes a new approach to the surveillance and management of the Slaughter Estate Unit CO_2 flood. The method described here involves real-time monitoring on a well-by-well, pattern-by-pattern basis by displaying raw as well as processed data using the "Montage" concept. Using this concept, injection, production, and other data from a well or a group of wells can be viewed simultaneously by zooming into any area of the field. Inter-well communication and gas cycling can be recognized quickly and changes in operating variables can be made. As a result, the economic performance of a CO_2 flood can be optimized by making prompt adjustments to gas-water ratio, CO_2 and water half-cycle slug sizes, and injection and production well pressures.

Introduction

During the late 1970's and early 1980's, Amoco Production Company, along with other companies in the industry, committed significant manpower to evaluate the feasibility of field scale CO_2 flooding in west Texas. Before the initiation of field scale floods, several pilots were drilled and much reservoir simulation was conducted to understand the CO_2 flooding process [1,2,3]. Today, there are over 45 active miscible CO_2 projects in the United States. The incremental oil production response from these projects is currently 142,000 barrels per day and the industry has booked 1.9 billion barrels of tertiary reserves [4].

Reservoir management in Amoco's CO_2 floods has been a continuously improving process. The favorable tertiary response from the pilots provided validation of the CO_2 flood process. In December, 1984, Amoco initiated CO_2 floods in three different units in Slaughter Field and one unit in Wasson field. A map of the location of these two fields is shown in Figure 1. A map of the location of Amoco's active CO_2 floods within Slaughter Field is shown in Figure 2. The initial design of the floods was based on reservoir simulation studies using average segments [5]. The Slaughter Estate Unit (Figure 3) in Slaughter Field was divided up into 11 areas or "segments" as shown in Figure 4. Each segment was selected based on common geology, development history, and producing characteristics. Total production and injection from each segment was divided by the number of patterns and the segment was modeled as a single repeating pattern. Once a segment model was "history-matched", flood predictions were made for a variety of scenarios to determine the most profitable manner of operation [6]. Results from these average segment models were then scaled up for the full unit performance.

Reservoir simulation has also been an integral part of the reservoir management process in CO_2 floods. Simulation

References and illustrations at end of paper.

has helped in understanding the tertiary process better, provided guidance in the design of slug sizes and gas-water ratios (GWR), and allowed us to explore alternate operating scenarios. However, a different tool was needed to effectively manage CO_2 flood performance on a day-to-day basis. An ability to monitor injection and production data on a well-by-well, pattern-by-pattern basis was necessary. Amoco developed a concept called Montage which allows an engineer to monitor the performance of the entire field, to zoom in any part of the field (single or multiple patterns), and to display graphically several different types of raw and calculated data. Any anomalies can then be recognized quickly and changes in operating variables can be made. It also allows integration of production data with the reservoir description to further aid in the understanding of reservoir performance. This paper describes the use of Montage in the reservoir management of Slaughter Estate Unit..

Slaughter Estate Unit's Historical Performance

The Slaughter Estate Unit (SEU), was formed in December, 1963 [5]. The total unit encompasses 5,752 acres. Five-spot and chicken-wire patterns are dominant (see Figure 3). The southwest portion (Tract 2) is drilled on 20-acre five-spot patterns, the southeast portion (Tract 4) is drilled on 160-acre chicken-wire patterns, while the northern portion (Tracts 1 and 3) contains 40-acre five-spot patterns. Average net pay is 79 ft, with an average porosity of 12.0% and an average permeability of 4.9 md. Table 1 gives other pertinent data.

Historical waterflood and tertiary performance of SEU is shown on Figure 5 (a-d). A detailed description of the developments during the waterflood period is presented in Ref. 5. The Unit-wide CO_2 injection began in December, 1984. Over the past eight years, reservoir management of CO_2 floods has improved continuously. Initially, the floods were operated much like our pilots. An injection of a 30% hydrocarbon pore volume (HCPV) CO_2 slug was planned. A WAG (water-alternating-gas) operating scheme was used from the start for mobility control. The flood was started with a constant 2:1 gas-water ratio (GWR: 1% HCPV CO_2 and 0.5% HCPV water). As shown in Figure 6 (a-d), the unit has gone through a series of GWR and other operational changes since that time. The changes were made to improve the profitability of the CO_2 project as a whole, which sometimes included responding to external factors such as a change in the oil price. As described below, these changes have provided improved flood performance and have added tertiary reserves by extending the life of the flood.

Operational Changes

During 1986-87, the GWR was changed twice to accelerate the CO_2 flood response. The first such change was made in August, 1986. The GWR was changed from 2:1 to 3:1 by changing the CO_2 half-cycle slug from 1% to 1.5% HCPV. In January, 1987, the GWR was further increased to 4:1 by changing the CO_2 slug to a 2.0% HCPV. The water half-cycle slug size remained the same at 0.5% HCPV during both increases. Two important lessons were learned from this experience. First, rather than a constant GWR and half-cycle slug size, it is better to start injection at a higher GWR and reduce to lower values as the flood progressed (called a "tapered" gas injection scheme). This valuable information was also learned by other CO_2 flood operators [7]. This information has since been used in designing new CO_2 floods and associated CO_2 supply and gas processing facilities. The second lesson learned from this experience was the need to continuously monitor the flood performance (also recognized by other CO_2 flood operators [8]).

By 1989, an injection scheme with tapered GWR was being used. In addition, the CO_2 flood in SEU was monitored closely with the use of the field automation system. In response to the sharply increasing gas production rate (see Figure 6b) and to a lower oil price, the CO_2 injection rate was reduced in January, 1989. The GWR was lowered from 4:1 to 0.75:1 over most of the southern part of the unit and to 1.2:1 in the northern part of the unit. The CO_2 half-cycle slug sizes were changed from 2% to 1% HCPV and the water slug sizes were adjusted to match these GWRs. The unit responded with lower gas production which nearly matched the CO_2 plant inlet capacity at the time, and new plant investments were averted. As shown in Figure 6b, this change accomplished the desired goal of "level-loading" the gas production to approximately 32 million scf/d.

This experience showed that it was possible to manage the CO_2 flood process to improve profitability by controlling the injection scheme. By controlling the gas production, we not only kept the gas inlet volume at the desired level, but also extended the predicted life of the tertiary process. It is estimated that a total CO_2 slug size greater than 80% HCPV can be injected ultimately under this operating scheme. It also proved that the flood can be accelerated or retarded in response to the changing economic conditions.

While the unit-wide changes in gas injection described above reduced gas processing costs by controlling gas production, it also resulted in a lower oil production rate (see Figure 6a). Rather than making unit-wide changes, a need to reduce injection selectively only in those parts of the unit where the gas production was excessive and to maintain injection in other areas, was realized. The results also pointed out a need to continue to use performance monitoring as an integral part of the reservoir management process.

Introduction of "Montage" to Reservoir Management in SEU CO_2 Flood

While reservoir simulation continues to provide general guidance in determining long-term operating strategy, a majority of day-to-day decisions in SEU are being made on the basis of the CO_2 flood performance to date. Several years of performance data during increases and decreases in CO_2 injection are now available.

In 1989, Amoco introduced the Montage concept for reservoir management in CO_2 floods. This concept uses "visualization" as a cornerstone to understanding reservoir performance. In large fields or leases that contain many wells, the ability to display the production behavior and reservoir description data becomes critical in both understanding and managing the reservoir. According to the American Heritage Dictionary, Montage is "the art, style, or process of making one pictorial composition by closely arranging or superimposing many pictures or designs". Amoco has developed a simple automated approach to generate displays of key data in the same "spatial" relationship as the wells in the field.

In CO_2 floods, Montage has been very useful. In today's low oil price environment, the cost of purchasing and processing CO_2 can lower profit margins and make projects uneconomical. If reservoir management is to be really effective, it must be dynamic and sensitive to changes in performance, technology, and economics. Montage incorporates data daily from the field automation system. Montage has evolved from a display of relatively simple production and injection plots to an elaborate mixture of various types of plots from which engineer can choose. Each type of plot displays information that is useful in understanding a particular phase of reservoir management, ranging from the effect of gas injection on offset performance to understanding injection well conformance.

Types of "Montage" Plots and Their Application

Injection and production rates by well

Injection and production rates are the most common form of Montage used in analyzing CO_2 flood performance. It contains injection and production rates from the wells presented in the same spatial relationship as their physical locations in the field. A sample of such a plot is shown in Figure 7. An engineer scans the injection and production rates of all the wells in the unit, and selects the area needing attention (see Figure 7, top left). Once this area (a single pattern or multiple patterns) is identified, its performance is observed in detail by zooming into that area (Figure 7, top right). It shows the interaction between wells (e.g., an injector and a producer in Figure 7, bottom), and helps in determining a need for taking an action to improve reservoir performance. For example, an excessive gas production from a well can be traced to the CO_2 injection half-cycle periods in an offset injector. An appropriate action, such as a change in GWR, half-cycle slug size, or pressure (of an injector or a producer) can then be taken. After such a change is made, the performance of the area is monitored closely on the Montage for a period of time to ensure correction of the problem. Such actions have resulted in substantial savings in gas processing costs and improvement in oil rates on several occasions. Two significant examples are described below.

Application in Conversion of Wells and GWR Adjustments

In 1990, an evaluation of the performance of the CO_2 flood in SEU showed that the tertiary flood was operating inefficiently in the Tract 4 chickenwire pattern area (see Figure 3). The Montage plots helped identify that the gas production rates were significantly higher and the oil rates were lower in Tract 4 wells than the wells in other parts of the unit. The times of gas breakthrough at the production wells were short, indicating poor sweep. To recover oil from the areas unswept by the earlier waterflood and to raise the reservoir pressure for improved tertiary performance, a sixteen-well conversion program (from producers to injectors) in Tract 4 was implemented. These conversions lowered the producer to injector ratio from 3.5:1 to 1.25:1. The improvement in oil production can be clearly seen in Figure 8. The improvement in the oil production rate as a result of the conversion was remarkable. For example, the oil rate in Well 4-61 (see Figure 8) increased from under 100 bbls/d to over 150 bbls/d. The conversion program also stopped the unit's oil rate decline as seen in Figure 6a.

The above conversion program also resulted in a 2 million scf/d reduction in gas production. The availability of this additional gas processing capacity allowed us to accelerate the CO_2 flood in selected areas in the unit. Montage plots were used to identify the areas in which the flood was performing most efficiently. In March 1990, the GWRs were increased in the central area of Tract 2 (a dense five-spot area, see Figure 8) from 0.75:1 to 2:1. In June 1990, the GWRs in this area were further increased to 4:1. In addition, GWRs were also increased from 1.2:1 to 4:1 in an area in Tract 3 (Figure 8).

In February, 1992, the performance of SEU was examined in light of increasing gas production rate. This rate of increase would have soon required additional expenses for gas compression in the gas processing plant. Examining a Montage of injection and production data helped identify the patterns in which gas production rates were high. Moreover, Montage helped identify areas where a reduction in CO_2 injection would result in reduced gas production, with the least adverse effect on the oil production rates. The GWRs in those areas (primarily in Tracts 2 and 3, where GWRs had been 4:1) were reduced to 2:1 and 3:1. The CO_2 half-cycle slug size was left unchanged (1% HCPV) in most wells, but the water half-cycle slug sizes were increased to accomplish this reduction. As seen in Figure 6b, this change leveled the total gas production rate in SEU.

Segment Analysis

A segment can be defined as an area consisting of single or multiple patterns. Segment analysis can help in understanding how a specific area is performing and how its performance compares with the other areas in the field.

For a CO_2 project to be successful, it must be managed such that it strikes a proper balance between CO_2 injection, incremental oil production, and gas production (assuming that the produced gas must be processed at considerable expense before reinjection). An injection well may influence production from several offset production wells and similarly a production well's performance may be a combined effect of the events in several offset injection wells. If a producer in an inverted five-spot pattern is producing at a high GOR and a reduction in the GWR in the central injector is being considered, the possible effect of this reduction on the other three producers' oil rate must also be evaluated. It is difficult for an engineer to do such an evaluation with individual well plots. Segment Montage was introduced to facilitate such analyses. Segment Montage is different from the well rate Montage in that it allows evaluation of the performance of any combination of injection and production wells. Segment Analysis plots also show the effects of reservoir quality and the maturity of the CO_2 flood in different parts of the field.

Three types of Segment Analysis "Montage" plots are presented in Figure 9(a-c). The oil production rate plot is shown in Figure 9a. This plot is used to monitor the oil rate during tertiary. It also includes a projected waterflood rate obtained from decline curve analysis. Therefore, the magnitude of the tertiary wedge can be seen. An engineer can thus visually scan several patterns and obtain a comparison of incremental production from the patterns.

A plot of current CO_2 utilization (a ratio of monthly-averaged CO_2 injection rate, mcf/d and incremental oil production rate, bbls/d) versus time for a segment is shown in Figure 9b. The incremental oil production rates are obtained from 9a. This plot gives the engineer an idea of the efficiency of the CO_2 flood process at any point in time. At the start of the flood the CO_2 utilization is poor (or high) and gradually improves (or decreases) with time as the oil response starts to occur.

A third type of plot, called the dimensionless CO_2 utilization plot, is shown in Figure 9c. This is a plot of a running total of incremental oil recovered, in %OOIP versus the volume of CO_2 injected, in %HCPV for a segment. This plot shows the cumulative performance of the CO_2 flood in various segments. Since this is a dimensionless plot, a comparison of the flood efficiency in various segments can be made irrespective of the segment area (e.g., a 20-acre vs. a 160-acre pattern) and pay thickness. This tool can be useful in managing the available CO_2 supply and distributing the CO_2 in various areas so as to maximize cash flow from the entire unit. Also, when faced with a limited CO_2 availability, the reduction in injection could be made in a segment where the flood is less efficient.

Application in Improving Segment CO_2 Utilization

Figure 10 shows an example of the application of Segment Montage plots in analyzing the performance of the CO_2 flood in different patterns within SEU. As described earlier, in 1990, the GWRs were increased from 0.75:1 to 4:1 in the injectors in the central part of Tract 2. A dashed line in Figure 9 shows the patterns affected by this increase. Figures 10a and 10b show the tertiary production from Pattern 2-110 (an inverted five-spot pattern within the GWR increase area) and Pattern 2-103 (an inverted five-spot pattern outside the GWR increase area). Prior to 1990, the oil production performance of the two segments was very similar. The sustained high oil production in Pattern 2-110 is the result of the increased GWR. In Pattern 2-103, in which the GWR remained at 0.75:1, the oil rate suffered a steep decline.

Figures 10c and 10d show the change in CO_2 utilization in the two segments with time. Prior to the GWR change in Pattern 2-110 in 1990, the CO_2 utilization in the two segments were comparable. However, the utilization is significantly different in the two segments after 1990. While the CO_2 flood continued to be efficient (10 to 20 mcf / incr. bbl of oil) in Pattern 2-110, it deteriorated in Pattern 2-103 (10 to 40 mcf / incr. bbl of oil). This result indicates that the 0.75:1 GWR in Pattern 2-103 was too low and needed to be increased to improve performance. Upon observing this behavior in several patterns, the GWRs in all of the Tract 2 wells which were on 0.75:1 at that time were increased to 1.5:1 in March, 1993. The oil rate response to this increase is being monitored.

Figure 11 compares the cumulative CO_2 utilization plots in two segments, pattern 2-110 (in Tract 2) and Pattern 3-70 (in Tract 3, see Figure 9 for location). It shows that the response to the CO_2 injection occurred much sooner in Pattern 2-110. Also, the flood has been more efficient in this pattern compared to Pattern 3-70. An incremental production of 11% OOIP has occurred in Pattern 2-110 after an injection of a 50% HCPV CO_2 slug, while the incremental production is only 6% OOIP in 3-70 after injecting a 70% HCPV slug. This shows the difference in reservoir quality between the two areas.

Integrated Reservoir Management

The Integrated Reservoir Management Montage is a concept where different types of production and reservoir data are displayed to aid in understanding reservoir performance. To operate effectively, a wide range of monitoring techniques have been developed and practiced by various operators in west Texas [5,7,8,9]. An effective reservoir management approach integrates production performance (e.g., recovery to date) with reservoir characterization (OOIP, petrophysical data, etc.).

The Integrated Reservoir Management Montage helps facilitate this integration by being able to display a variety of different types of plots. The two types of Montage plots presented earlier in the paper, production and segment Montage, are useful in evaluating current and overall performance of a tertiary flood. With the ability to combine this information with geologic data and down-hole injection data, the engineer can relate performance to the reservoir characteristics. Then, the engineer can address issues such as out-of-zone injection and poor sweep, which can have a negative effect on the economic success of a project. In addition, having this knowledge will provide a better understanding of the variables needed for input into reservoir simulators.

Application in Integrating Reservoir Management Information

Figure 12 is a Montage that incorporates data from three areas of reservoir engineering. The plots on the upper left represents production and injection performance data for an inverted five-spot pattern in SEU Tract 2 from 1960 to 1993. The reservoir properties in pattern is shown on the upper right. Permeability was calculated from a porosity-permeability correlation in this area and is displayed as a function of depth for each well. At the bottom, the injection profile through time are superimposed on the reservoir description.

This simple Montage shows a conformance change has occurred over time. Earlier in the life of the waterflood (1977-1979), most of the fluid injected was limited to the zones within the main pay (Figure 12). However, the lower zone (transition zone) became dominant by 1991, and currently is acting as a thief zone. The amount of CO2 entering this zone can be significant and may impact the profitability of the project. This Montage allowed detection of the out-of-zone injection. Proper techniques are now being developed to improve conformance of the injected fluid within the pay and increase tertiary recovery.

Conclusions

1. Over the past eight years, a considerable amount of experience has been gained in reservoir management of CO_2 floods. The initial designs of CO_2 slug size and gas-water-ratios needed to be modified to accelerate CO_2 flood and to adjust to the reservoir response. The ability to monitor performance on a well-by-well, pattern-by-pattern basis has been crucial in optimizing the performance at Slaughter Estate Unit.

2. The Montage makes use of the automation system's daily data gathering capability. This approach is very helpful for engineers in comprehending a large amount of data collected in fieldwide CO_2 floods. It saves considerable time by allowing ready identification of areas needing improvement.

3. Montage helps engineers in managing the flood by properly utilizing CO_2 resources. The emphasis is placed on those areas that offer the potential for the highest profitability by shifting the CO_2 resource.

4. Montage facilitates integration of field performance and reservoir petrophysical data. This helps better understand issues such as conformance and sweep, and address them in a timely fashion.

Acknowledgments

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References

1. Ader, J.C. and Stein, M.H., "Slaughter Estate Unit Tertiary Miscible Gas Pilot Reservoir Description," JPT, May, 1984.

2. Rowe, H.G., York, S.D., and Ader, J.C., "Slaughter Estate Unit Tertiary Pilot Performance," JPT, March, 1982.

3. Drennon, M.D., Kelm, C.H., and Whittington, H.M., "A Method for Appraising the Feasibility of Field-Scale CO2 Miscible Flooding," SPE 9323, 1980 SPE SPE Annual Technical Conference and Exhibition, Dallas, Sept 21-24.

4. Hadlow, R.E., "Update of Industry Experience With CO_2 Injection", SPE 24928, 67th Annual Technical Conference and Exhibition held in Washington, DC, October, 1992.

5. Stein, M.H., Frey, D.D., Walker, R.D., and G.J. Pariani, "Slaughter Estate Unit CO_2 Flood: Comparison Between Pilot and Field-Scale Performance," JPT, September, 1992.

6 Pariani, G. J., McColloch, K. A., Warden, S.L., and Edens, D.R., "An Approach To Optimize Economics in a West Texas CO_2 Flood," JPT, Sept., 1992.

7. Tanner, C.S., Baxley, P.T., Crump III, J.G., and Miller W.C. (Retired), "Production Performance of the Wasson Denver Unit CO_2 Flood," SPE 24156, SPE/DOE Eighth Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April, 1992.

8. Kittridge, M.G., "Quantitative CO_2 Monitoring, Denver Unit, Wasson (San Andres) Field," 67th Annual Technical Conference and Exhibition held in Washington, DC, October, 1992.

9. Stiles, L.H. and Macgruder, J.B., "Reservoir Management in the Means San Andres Unit," JPT, April, 1992.

TABLE 1 -Slaughter Estate Unit (Pertinent Data Sheet)

Producing area, acres	5,752
OOIP, Million bbl	283
Formation	San Andres dolomite
Depth, ft	4,985
Number of wells	
Producers	187
Injectors	163
Producing mechanisms	
Primary	Solution-gas drive
Secondary	Waterflood
Tertiary	CO_2 miscible
Average pay, ft	
Gross	140
Net	79
Average porosity, %	12.0
Average permeability, md	4.9
Oil gravity, API	32

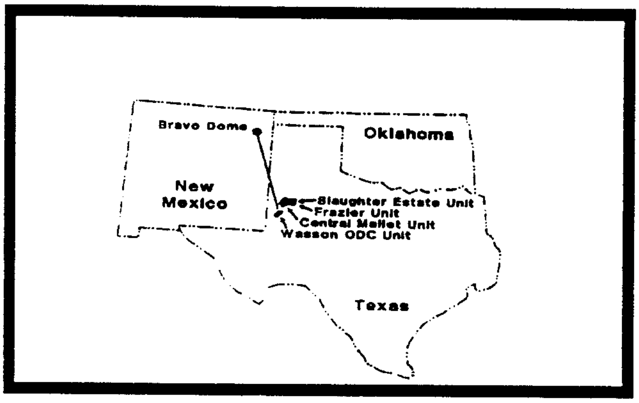


Figure 1. Field Location Map

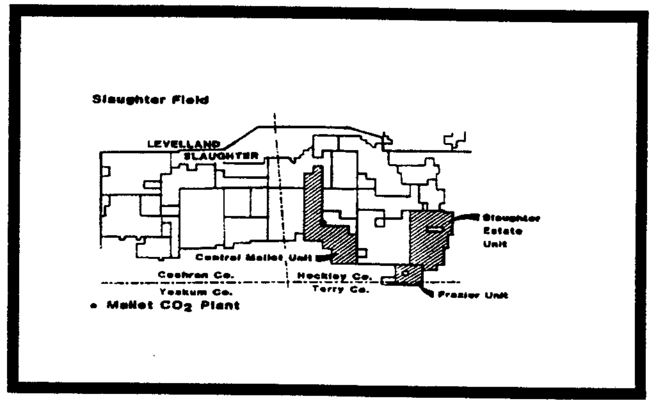


Figure 2. Active CO2 Floods In Slaughter Field

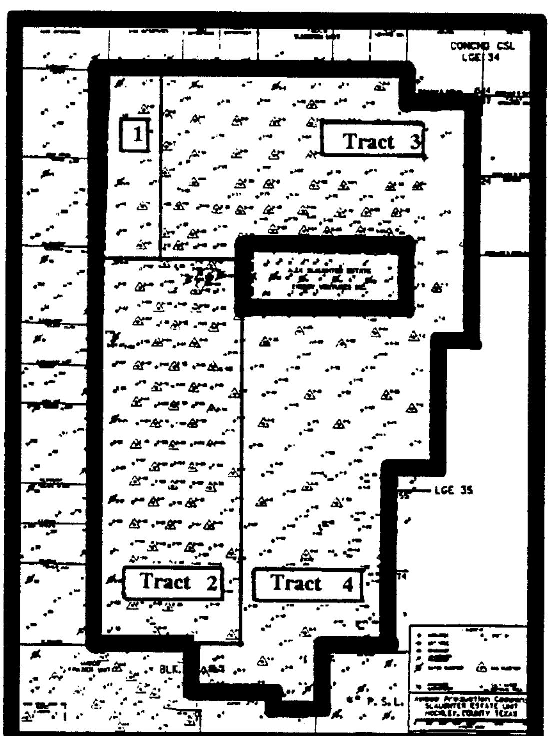


Figure 3. Slaughter Estate Unit Base Map

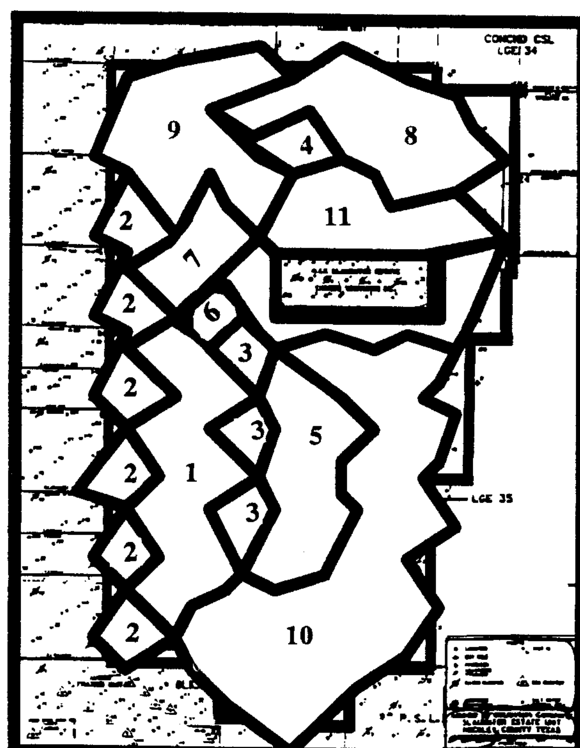


Figure 4. Slaughter Estate Unit Model Segment Map

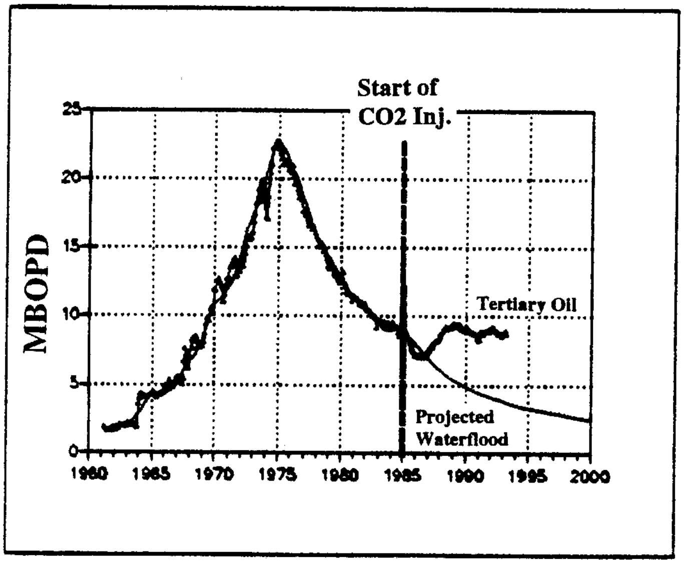


Figure 5a. Oil Production Rate - MBOPD

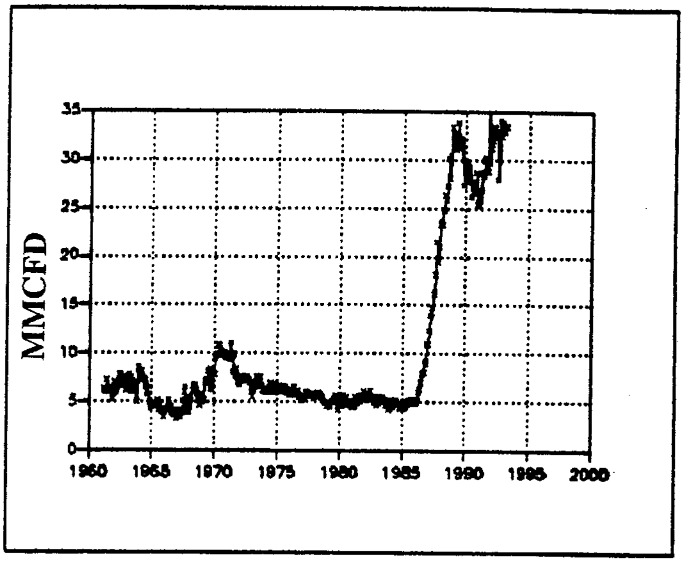


Figure 5b. Gas Production Rate - MMCFD

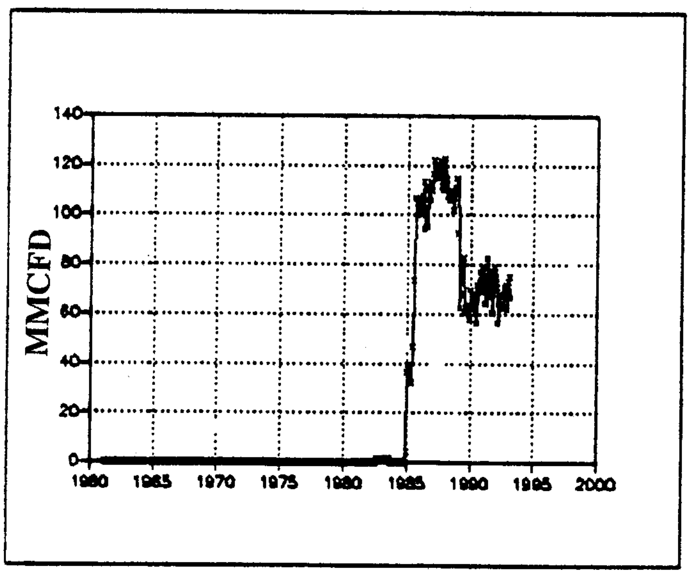


Figure 5c. CO2 Injection Rate - MMCFD

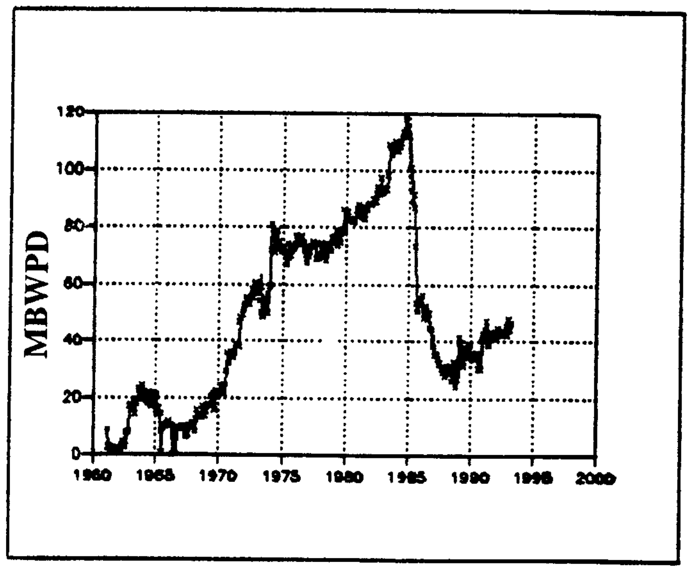


Figure 5d. Water Injection Rate - MBWPD

Figure 5(a-d). Slaughter Estate Unit Historical Performance

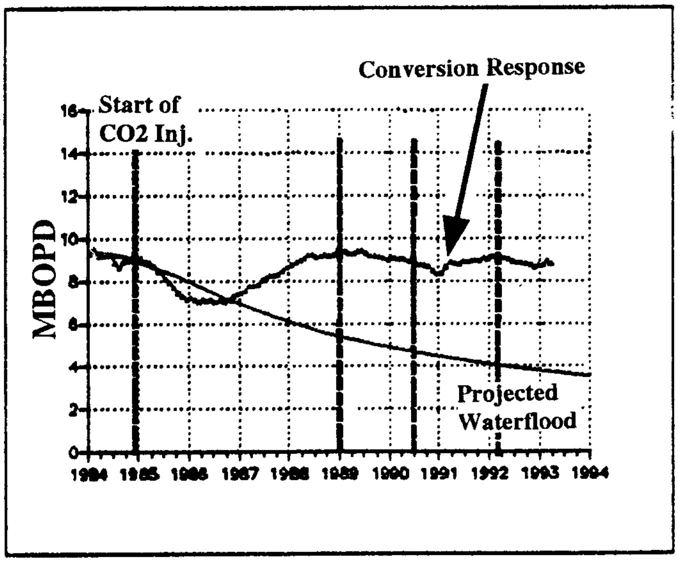


Figure 6a. Oil Production Rate - MBOPD

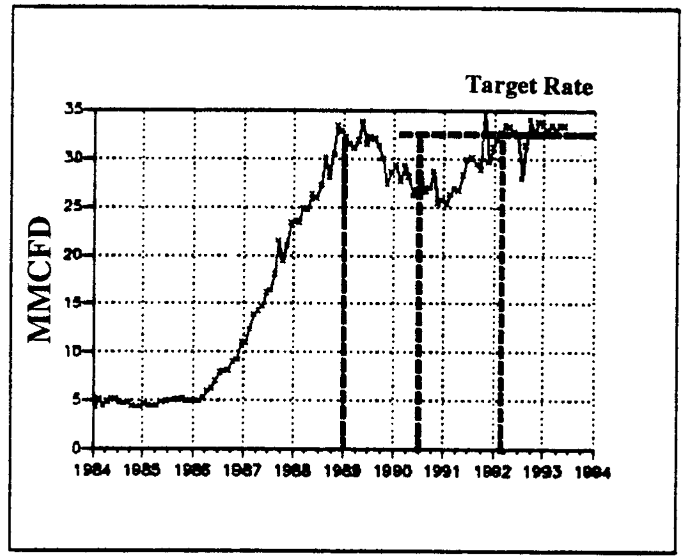


Figure 6b. Gas Production Rate - MMCFD

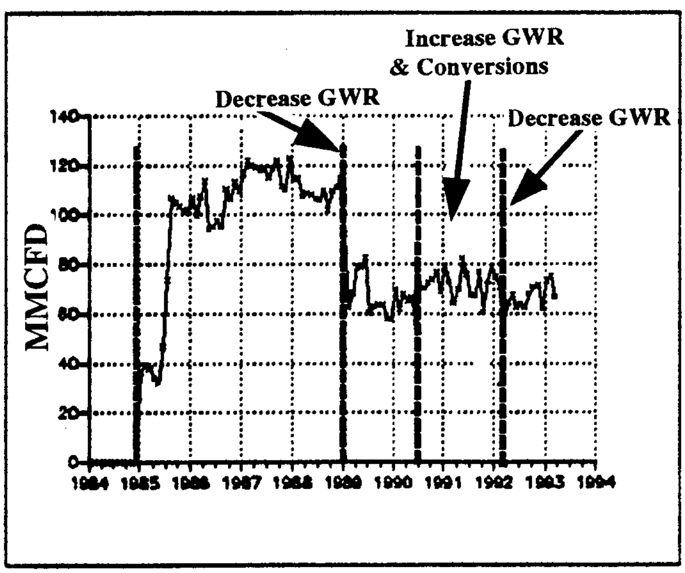


Figure 6c. CO2 Injection Rate - MMCFD

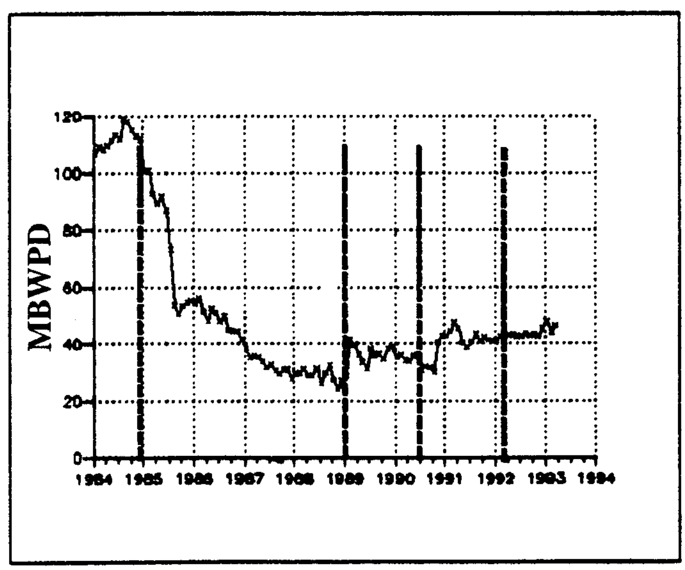


Figure 6d. Water Injection Rate - MBWPD

Figure 6(a-d). Slaughter Estate Unit Tertiary Performance

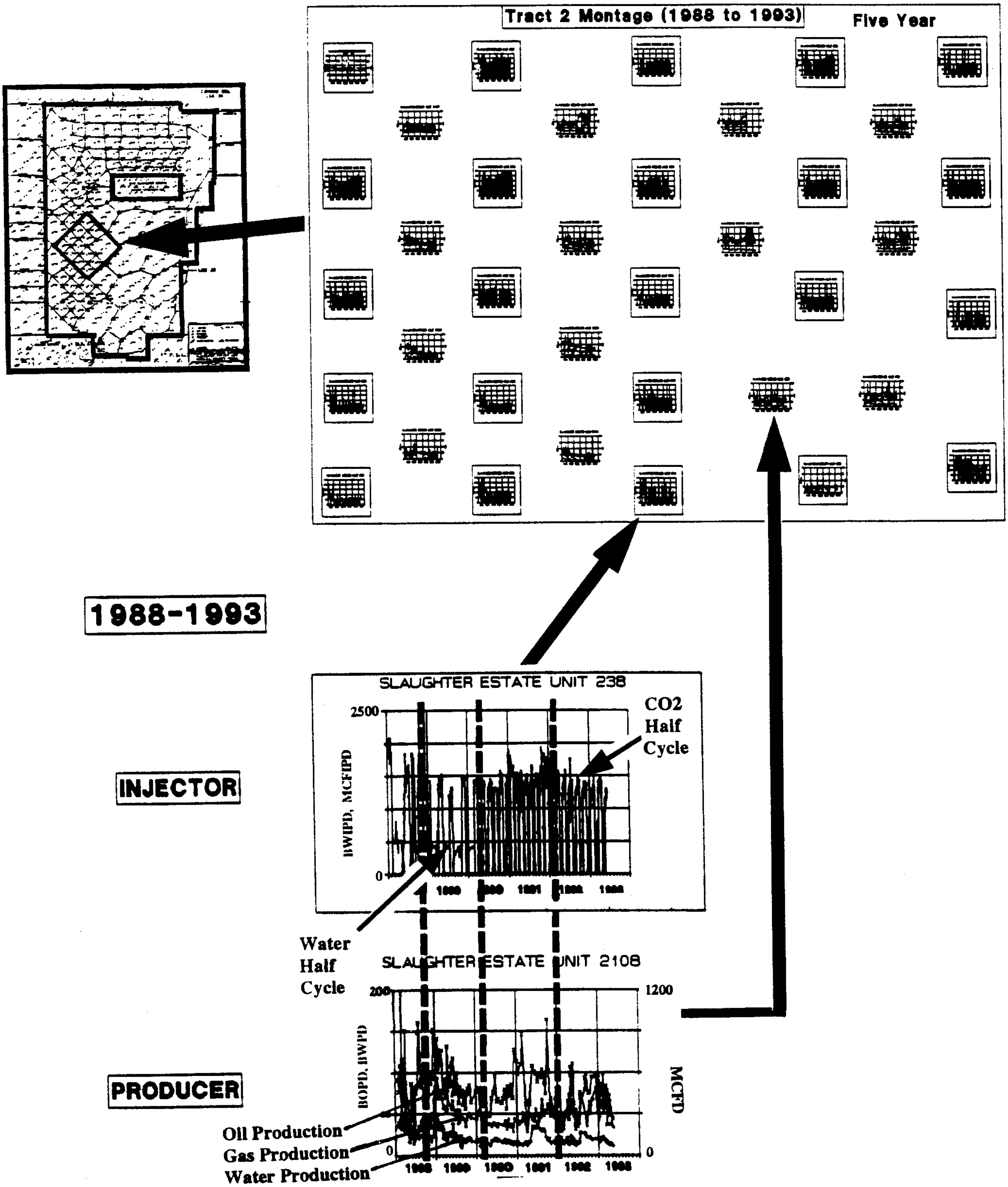


Figure 7. Production Montage Plot

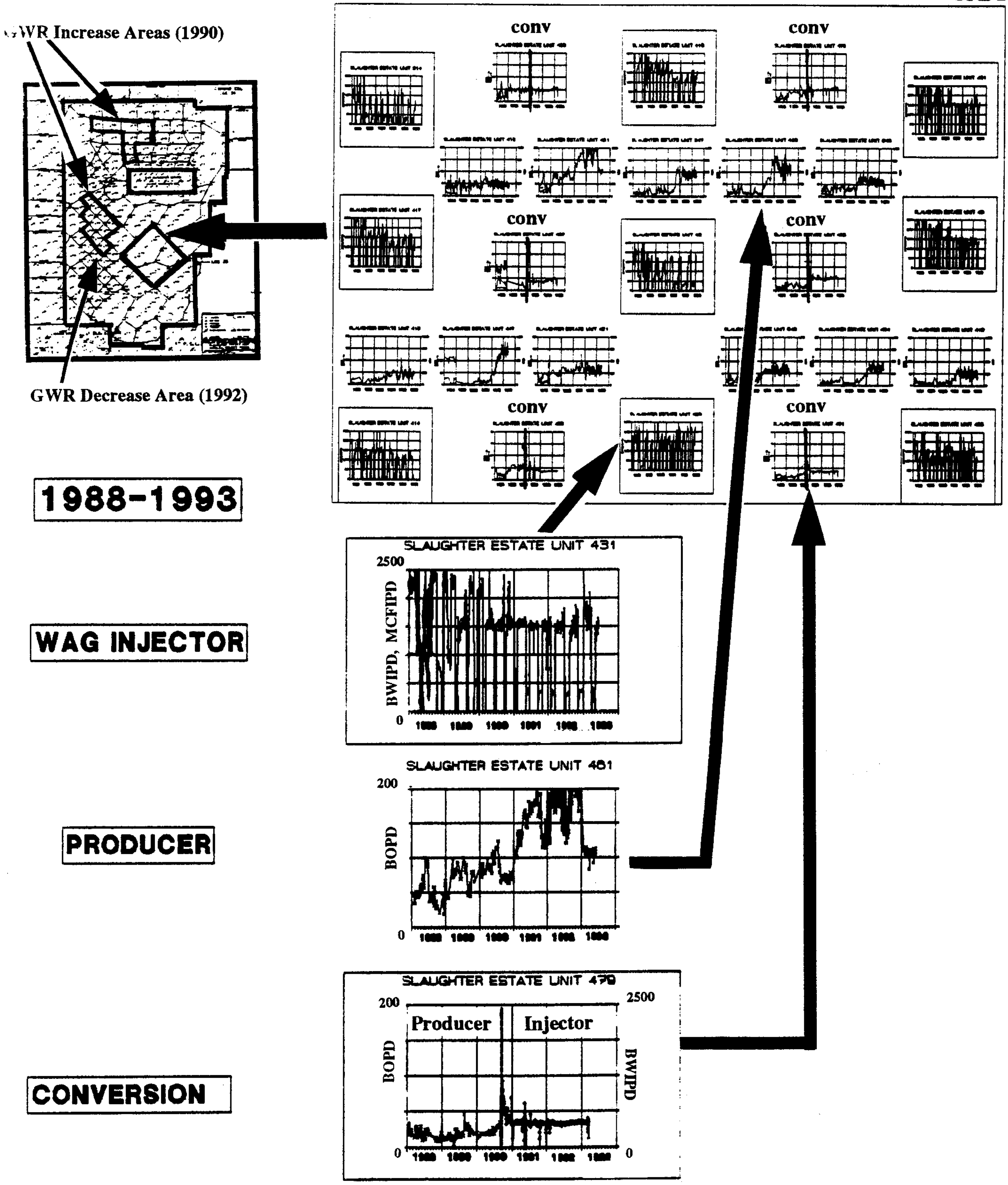
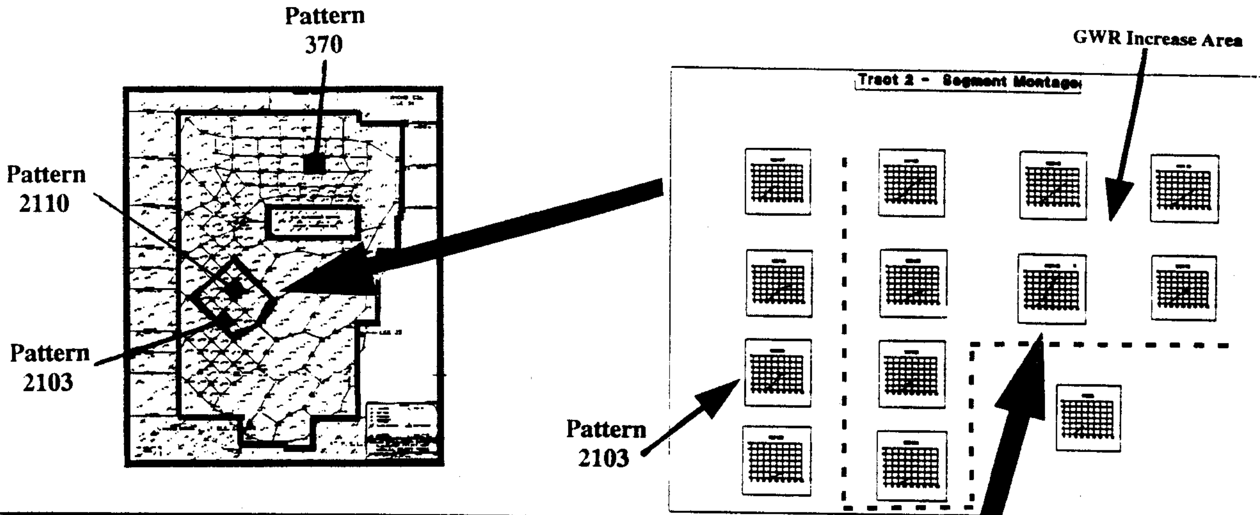


Figure 8. Chickenwire Conversion Program (1990)



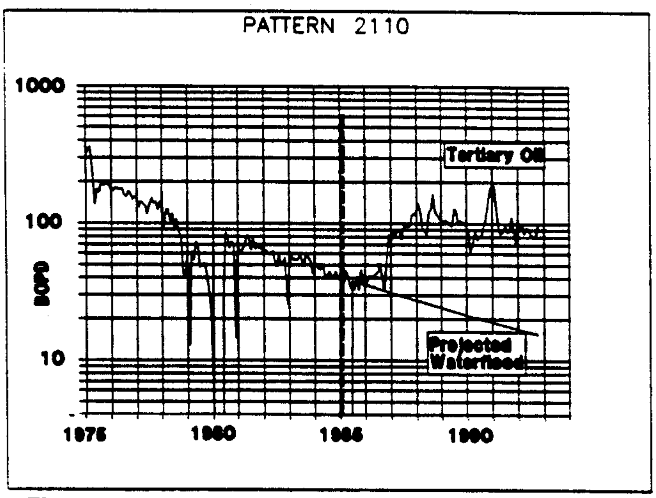


Figure 9a. Performance Plot

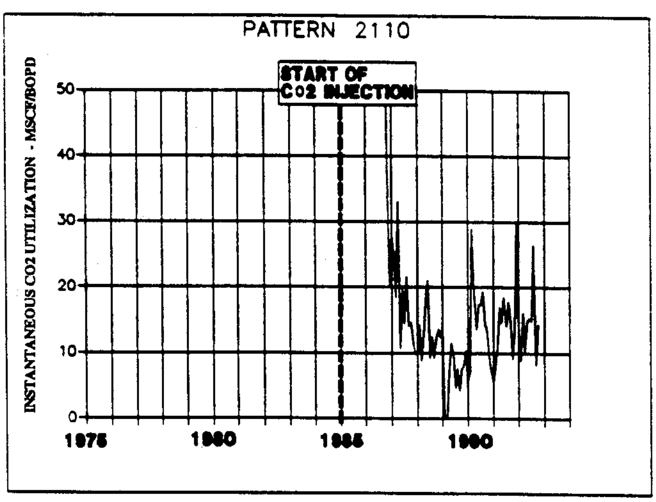


Figure 9b. Instantaneous CO2 Utilization

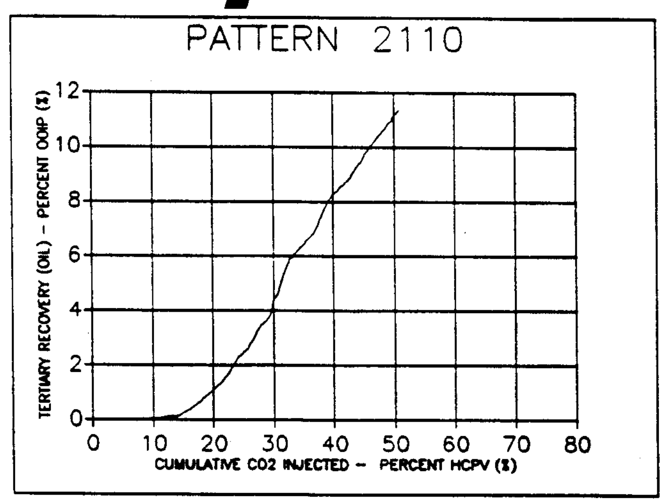


Figure 9c. Cumulative CO2 Utilization

Figure 9(a-c). Segment Montage Plot

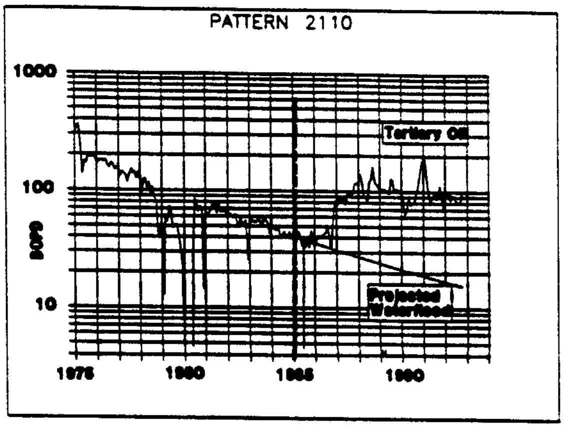


Figure 10a. Tertiary Production Plot (Well 2110)

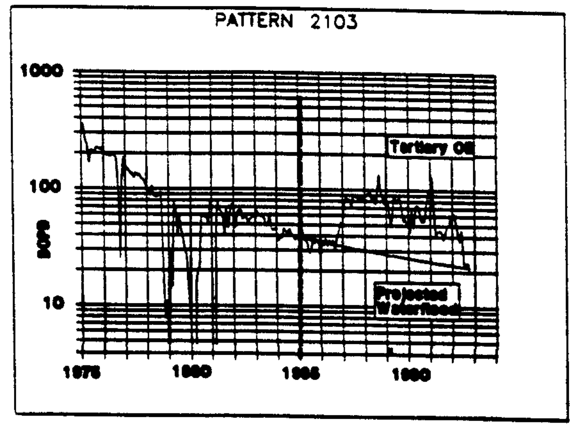


Figure 10b. Tertiary Production Plot (Well 2103)

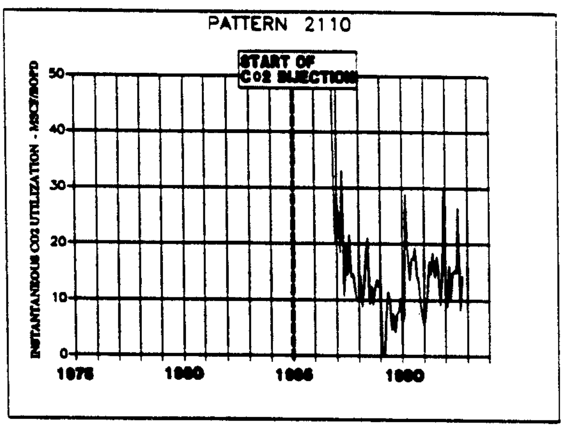


Figure 10c. CO2 Utilization Plot (Well 2110)

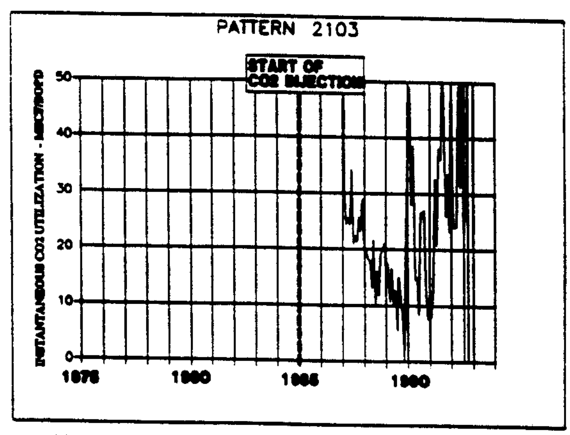


Figure 10d. CO2 Utilization Plot (Well 370)

Figure 10. Segment Comparison (Pattern 2110 and Pattern 2103)

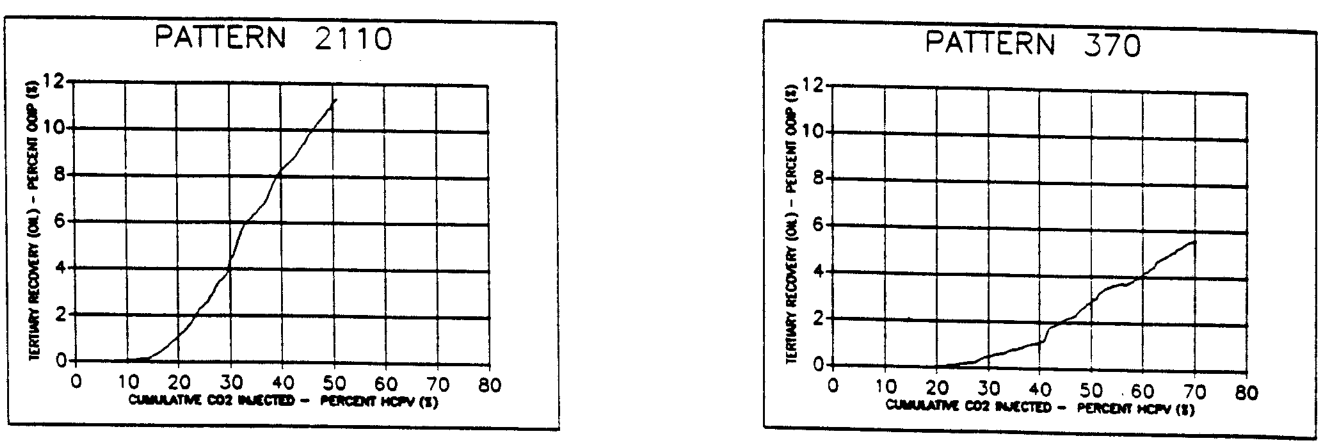


Figure 11. Segment Comparison (Pattern 2110 and Pattern 370)

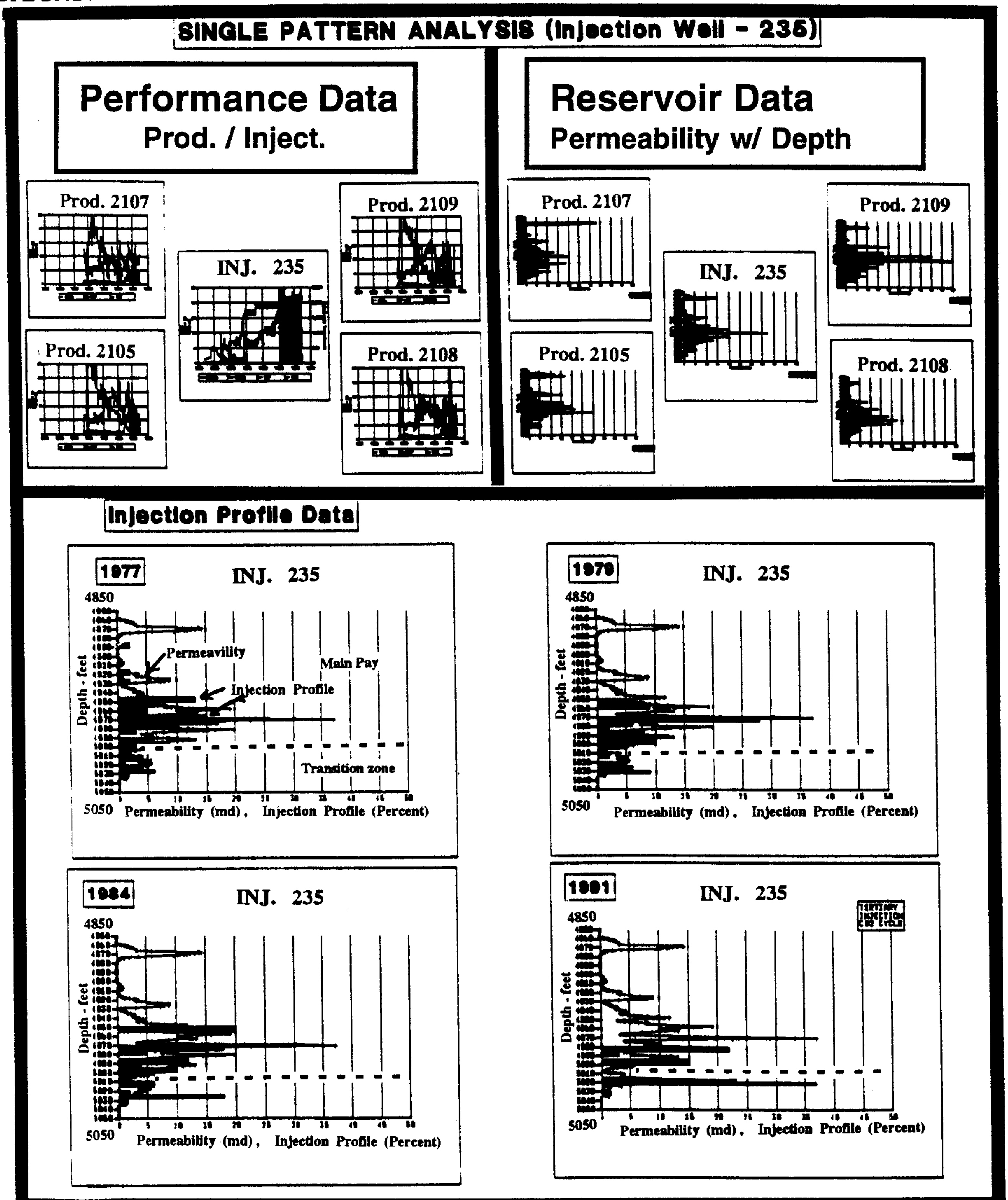


Figure 12. Montage (Integrated Approach)