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# MICROBIOLOGICAL TECHNIQUES FOR PARAFFIN REDUCTION IN PRODUCING OIL WELLS

Final Report

By
Carl H. Oppenheimer
Franz K. Hiebert

April 1989

Performed Under Contract No. FG19-86BC14014

Alpha Environmental Corporation
Austin, Texas

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

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Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

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LIST OF TABLES ..... 3

LIST OF FIGURES ..... 4

ABSTRACT ..... 6

CHAPTER ONE. INTRODUCTION ..... 7

BACKGROUND ..... 7

OBJECTIVES ..... 9

MATERIALS AND METHODS ..... 9

RESEARCH PROGRAM ..... 13

CHAPTER TWO FIELD STUDIES ..... 19

LAVERNIA FIELD ..... 19

VORPHAL LEASE ..... 26

PENSHORN LEASE ..... 28

WISEMAN LEASE ..... 28

LONGWOOD FIELD ..... 35

WEST GEFF FIELD ..... 39

PENNINGTON/STEVENSON LEASE ..... 42

CHAPTER THREE. SUMMARY OF RESULTS, DISCUSSION AND CONCLUSIONS ..... 48

REFERENCES ..... 54

APPENDIX ..... 57

Vorphal Monthly Total Oil Production from April 1986 to Nov. 1987 ..... 57

Penshorn Total Monthly Production from April 1986 to November 1987 ..... 58

Boynton Heirs Lease, Longwood Field Monthly Production from January 1985 to June 1987 ..... 60

Martin Vorphal Lease, Population of Hydrocarbon Bacteria ..... 64

Wiseman Lease, Population of Hydrocarbon Bacteria ..... 65

Boynton Heirs Lease, Population of Hydrocarbon Bacteria ..... 66

Pennington/Stevenson Lease, Population of Hydrocarbon Bacteria ..... 67

# LIST OF TABLES

1. Reservoir data for the LaVernia Field.....23

2. Formation water chemistry: Vorphal Lease.....24

3. Reservoir data for the Boynton Heirs Lease.....36

4. Formation water chemistry: Boynton Heirs Lease.....37

5. Reservoir data for the Pennington/Stevenson Lease...44

6. Oil volumes produced and percent incremental increase by lease.....49

## LIST OF FIGURES

Figure 1. Conceptual drawing of oil, water, and MEOR bacteria in a water-wet oil reservoir.....12

Figure 2. Location map of the three oil fields treated and studied during this project.....20

Figure 3. Structure-contour map on top of the Navarro Formation in the area of the LaVernia Field treatment sites.....21

Figure 4. Structure-contour map on top of the Goodland Limestone, Boynton Heirs Lease, Longwood Field, Texas.....22

Figure 5. Pre- and post-treatment oil production with actual and extrapolated decline curve for five wells drilled in January, 1986 on the Vorphal lease, LaVernia Field, Texas.....29

Figure 6. Population of hydrocarbon degrading bacteria in six wells of the Vorphal lease, LaVernia Field, Texas.....30

Figure 7. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Penshorn Lease, LaVernia Field, Texas.....31

Figure 8. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Wiseman Lease, LaVernia Field, Texas.....32

Figure 9. Population of hydrocarbon degrading bacteria in the five wells of the Wiseman lease, LaVernia Field, Texas.....33

Figure 10. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Boynton Heirs Lease, Longwood Field, Texas.....40

Figure 11. Population of hydrocarbon degrading bacteria in twelve wells of the Boynton Heirs Lease, Longwood Field, Texas.....41

Figure 12. Structure-contour map on the base of the Lower Renault formation, Pennington/Stevenson Lease, West Geff Field, Illinois.....45

Figure 13. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Pennington/Stevenson Lease, West Geff Field, Illinois.....46

Figure 14. Population of hydrocarbon degrading bacteria in seven wells of the Pennington/Stevenson Lease, West Geff Field, Illinois.....47

## ABSTRACT

Alpha Environmental has completed an eighteen month field oriented, cooperative research program with the U.S. Department of Energy (Grant DE-FG 19-86BC 14014) to demonstrate a new economically viable process using petroleum degrading microorganisms, a biocatalyst, formation water and inorganic nutrients to recover residual oil from reservoirs. Alpha's mixed community of micro-organisms decomposes crude oil to produce detergents, $CO_2$, and new cells, thus mechanically and chemically releasing oil from reservoir pores. The naturally-occurring bacteria utilized in this project were previously selected by screening and isolating microorganisms from soils contaminated with crude oil and petroleum products. The activity and level of salt tolerance (to 20% salinity) of the bacteria is enhanced by a biocatalyst,previously developed by Alpha Environmental. Field evidence suggests that the biocatalyst provides catalytic oxygen to the microorganisms in the reservoir, which augments low levels of in-situ molecular oxygen.

Five leases in three different oil reservoirs were treated with the oil-degrading microorganisms. Results from field tests show promising increases in oil production. Three leases producing from the Navarro formation located in central Texas were treated and experienced oil production increases of between 22 and 27 percent. One lease in the Goodland Limestone located in eastern Texas experienced no significant increase. An entire small oil field in the Aux Vases formation located in central Illinois experienced a 41 percent increase. Operators of Microbial Enhanced Oil Recovery (MEOR) leases reported a decrease in paraffin problems in oil wells and flow lines and a reduction of Basic Sediment and Water (BS&W) in oil storage tanks, however no quantitative data were collected. The materials and methods of treatment, data on microbial population and distribution in treated reservoirs, and oil production data before and after microbial treatment are presented.

# CHAPTER ONE. INTRODUCTION

## BACKGROUND

The principal role of microorganisms in nature is to form and destroy organic matter. Without this latter oxidative cycle, essential nutrients would be irreversibly bound in protoplasm. Photosynthesis and chemosynthesis result in the transformation of carbon dioxide to organic matter. Up to one percent of the organic matter of living organisms is comprised of hydrocarbon, from simple methane to complex carotenoids. Hydrocarbons accumulate and are preserved only in highly reducing sedimentary environments. In oxidizing environments, hydrocarbons have been continually decomposed by bacteria since life began. Products of hydrocarbon degradation and co-oxidation are metabolic byproducts, such as organic acids and carbon dioxide, and microbial cells. Early microbiologists (Davis, 1967) suggested that the different types of crude oil found in various reservoir environments were the result of different types of microbial activities and depositional settings.

Oil originates from organic matter generated, deposited, and preserved under sedimentary conditions, and geochemically altered through time (Hunt, 1979). Organic matter is converted to crude oil by biological, chemical, and physical processes which include pressure and temperature,the activity of microorganisms, natural catalysts and geologic time (Beerstecher, 1954, Oppenheimer, 1965). Microorganisms also play a part in the migration of oil through sediments (Davis, 1967).

Since microorganisms are associated with the genesis of petroleum, it is logical to investigate microbial activities that may be responsible for the movement, concentration, and recovery of commercial amounts of petroleum. Oppenheimer (1980) described the role of microorganisms in the ecological cycles of oil in the environment. A survey of the literature concerning MEOR field tests indicates that a variety of microbial mechanisms, including microbial production of carbon dioxide and other gases, formation of detergents as fatty acids, changes in hydrogen ion concentration, and the displacive action of microbial cells during growth on hydrocarbons can release petroleum trapped in

pores of reservoir rock (see Hitzman 1983, for an extended review of MEOR field applications).

Petroleum microbiology has been experimentally studied for over 100 years. However, the field has attracted major scientific attention only in the last 30 years as investigators applied concepts of microbial ecology and degradation to solve problems in oil pollution clean up and in developing techniques of enhanced oil recovery (see API Oil Spill Annual Conferences 1969 to present, and King and Stevens, 1987).

The application of bacteria to oil reservoirs as a tool for secondary enhanced oil recovery is not a new concept or process (ZoBell, 1946, Shennan and Vance, 1987). ZoBell (1946) was awarded U.S. Patent #2,413,278 for a process to use bacteria to remove oil from sediments. He described the salt tolerant bacterium *Desulfovibrio* that used indigenous organic material in sediments as an energy source to reduce inorganic sulfates to acids and to produce detergents. Oil field operators found however, that *Desulfovibrio* was responsible for pipe and equipment corrosion. The patent of ZoBell was field tested but never accepted because of the corrosion impact on pipes and oilfield storage tanks.

La Riviera (1955) demonstrated the release of hydrocarbons from laboratory sediment cores by *Desulfovibrio,* using lactate as an energy source. He suggested detergent production as the oil release mechanism. ZoBell (1956) described a process to reduce paraffin in oil wells by microbial action, but the process was not economic at that time and was never commercially implemented.

Bacteria, which utilize organic substances as an energy source, produce acids which in turn react with carbonate minerals to produce $CO_2$. Detergents and biomass are two by-products of bacterial metabolism and co-oxidation. Microbial oil-release mechanisms may involve acid-base equilibria, detergents, physical displacement and other surfactant phenomena. All of the above can act at an oil-rock or oil-water interface and have been shown to act in concert to release oil from sediment surfaces in laboratory experiments (Yen, A State of the Art Review on MEOR).

Up to the present, there has been no published economical commercial application of MEOR (King and Stevens, 1987). The primary deterrent to the process has been the high cost of production and field application of MEOR bacteria, and the inability of microorganisms to survive and be active at the high salt and low oxygen concentrations found in oil field brines. Mechanical plugging of reservoir-rock pores and oil field pipes by bacteria cells and introduced nutrients is another process inhibitor (Updegraff, 1982). Temperature is a limiting factor for MEOR, but as many oil fields are within the temperature tolerance range of microorganisms this latter becomes a deterrent only for deep, hot formations. Pressure does not appear to be a problem as bacteria can tolerate high pressures (Morita, 1974) and also can produce gas pressures up to 9000 psi (Oppenheimer, 1951).

As a student of Professor ZoBell, and a petroleum microbiologist, Oppenheimer has studied MEOR since ZoBell's patent in 1946. The problems of low microbial salt tolerance and the low oxygen content of oil reservoirs have remained the primary technical obstacles to MEOR.

## OBJECTIVES

The objective of the research program was to demonstrate a new and financially viable method of MEOR using the products and growth of naturally occurring hydrocarbon-oxidizing micro-organisms. The target of the process was that portion of original oil unrecoverable by conventional production techniques in shallow, low-production oil fields. A practical financial objective is to develop a treatment cost below the value of incremental oil produced as a result of the microbial treatment.

## MATERIALS AND METHODS

### MICROORGANISMS AND BIOCATALYST

The microorganisms used in the field and laboratory tests were isolated as the result of 20 years of collecting naturally occurring microorganisms from tropical to polar environments where hydrocarbons contaminated soil environ-

ments. Composite soil and water samples were cultivated in inorganic nutrient-enriched sea water and fresh water, with crude oil as the only organic energy source. The oils used as culture substrate ranged from light South Texas and heavy Kuwaiti crude to Bunker C fuel oil. Enrichment media were made from either filtered tap water or filtered sea water to which inorganic nitrogen and phosphate were added at 1 and .01 percent and adjusted to pH 7.6.

The continuous cultivation of these worldwide enrichment cultures on a wide variety of crude oils has produced a mixed culture of aerobic and microaerophilic microorganisms, primarily bacteria, that actively decompose many types of crude oil. During the progress of several research projects at the Florida State University and the University of Texas, the rate of degradation of crude oil and the molecular fingerprint of changes in the crude during microbial activity was measured (Miget, *et. al.* 1969; Kator, 1972; Oppenheimer,*et. al.* 1971). The enriched cultures repeatedly utilized both aliphatic and aromatic molecules of a wide range of molecular weight in the various crude oil tested.

Alpha Environmental's mixed cultures have been actively maintained in simple fermenters in the laboratory for several years and continue to be very active oil degraders, utilizing on average one ml of oil per liter of sea water medium in less than 24 hours. Under optimal conditions the oil can be utilized in 12 hours. The oil is converted to fatty acids, other metabolic by-products, and microbial cells. The inocula for MEOR are harvested from these fermenters.

Sterile, filtered sea water collected from the Gulf of Mexico at Port Aransas, Texas was selected as the culture medium. Seawater media substantially reduces the chance that MEOR cultures might be infected with human pathogens. Unpolluted natural seawater has been shown to be effectively free from human pathogens (Sindermann, 1970).

The bacteria consist of motile and non-motile rods, cocci and spirilli. The microorganisms actively grow in temperatures up to 60°C and in salinities from 0 to 20 percent, and in nearly anaerobic conditions. When introduced to an oil-water emulsion they aggregate at the oil-water interface where they are very active as oil degraders In the enriched sea water the cells grow consis-

tently to concentrations up to $10^{12}$ cells/ml. The microbes are harvested from the mass culture and mixed into a dry biodegradable powder which has a viability of $10^{12}$ cells per gram. This dry material has a shelf life of approximately one year.

For this research project, Alpha Environmental selected enrichment cultures of microorganisms that converted crude oil hydrocarbons to detergents with an acid reaction. The microorganisms were selected to mobilize hydrocarbons in the oil reservoir at oil/water/rock interfaces by three mechanisms: (1) to decrease the adhesion between oil/rock and oil/water surfaces by microbial production of acids which act as surfactants, (2) to physically displace oil by growing between the oil and rock, and (3) to produce an acid condition in which carbonates dissolve producing carbon dioxide (Figure 1). It is possible that the microorganisms produce gases other than $CO_2$., but this is not investigated in this research.

Alpha has a proprietary biocatalyst that opens a pathway for overcoming the historical impediments of low microbial salt tolerance and lack of sufficient oxygen in the oil reservoir environment. The biocatalyst allows aerobic microorganisms to be cultivated and thrive in high salt concentrations. Alpha's mixed community of aerobic hydrocarbon degrading microoganisms has adapted to live and be active in brines of up to 20% salt. The biocatalyst also stimulates microbial growth. The addition of biocatalyst to laboratory microbial fermenters has increased the normal biomass produced in a given time period by up to three orders of magnitude. Alpha harvests the microorganisms grown in the fermenters and packages them in a dry powder form. The efficient laboratory production of a highly concentrated hydrocarbon degrading, salt-tolerant microbial community, combined with a method of preserving the bacteria in a dry powder form has facilitated Alpha's development of the MEOR material tested in this research

Alpha Environmental believes that the biocatalyst is responsible for increasing the environmental tolerance levels of the hydrocarbon degrading microbes. The catalyst is used both to cultivate the microorganisms in laboratory fermenters and is added to the injected oil well treatment mixture and brine in the field applications. The catalyst is a natural, water-based product that is non-toxic and contains no visible turbidity or hydrocarbons.

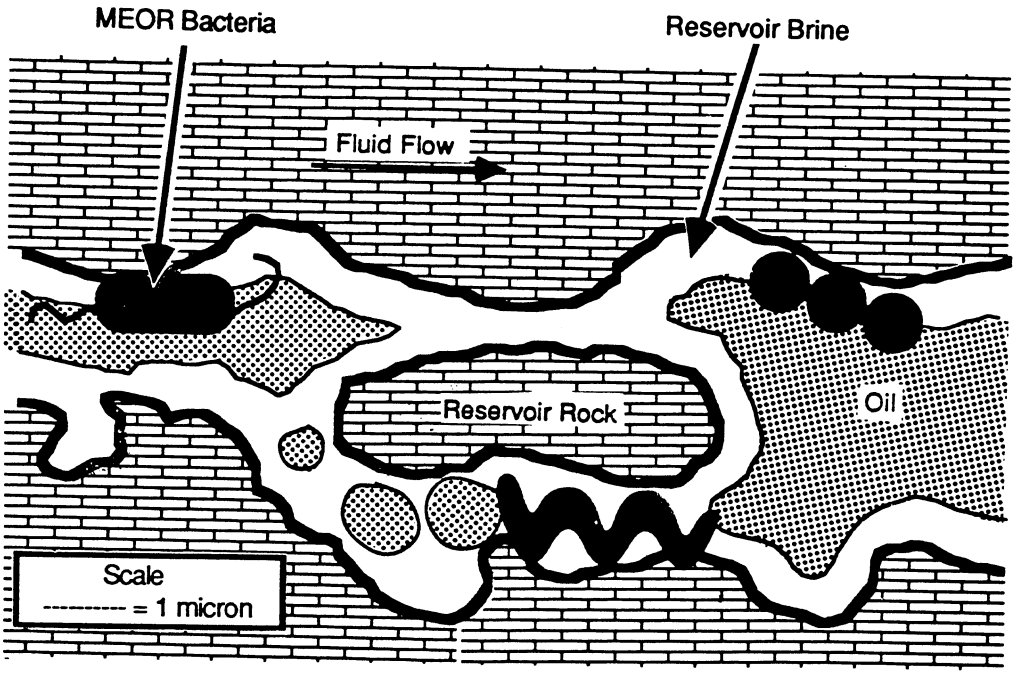



**Figure 1. Conceptual drawing of oil, water, and MEOR bacteria in a water-wet oil reservoir.** The oil release mechanism may be roughly summarized as follows: Hydrocarbon-degrading microorganisms transported by formation brines attach to rock and oil surfaces. As the microbes metabolize oil, they produce organic fatty acids (which act as surfactants), gases (primarily $CO_2$), and new cells. The net effect of the metabolic by-products is to chemically and physically release oil droplets from rock surfaces and pore throats. An incremental amount of the previously immobile oil is now available to be swept to production wells in the oil/brine emulsion.

## RESEARCH PROGRAM

The field, laboratory, and data collection and analysis methods used by Alpha Environmental throughout this project are presented below. Refinements based upon the experience of each successive field demonstration in the design and execution of treatment techniques and analysis were incorporated into the planning of following treatments. In all the treatment fields, produced oil from individual wells was collected in multi-well tank batteries. Therefore it was impossible to measure oil production on a well by well basis. Production figures are reported on a well cluster or lease-wide basis.

### Pre-treatment Field Survey and Analysis.

A geologic and engineering review of each lease and oil reservoir was conducted prior to site selection for treatment. Published literature, consultant reports, well logs, geologic maps, core, cuttings, and other data as well as interviews with the lease operator and field crew were analyzed to determine the suitability of each reservoir for microbial enhanced oil recovery and to pick the location and number of wells for optimum field treatment. Engineering, workover, and operator records were studied in order to customize the treatment process to the individual reservoir and well characteristics.

The production history for a lease to be treated was compiled from the operator's daily oil storage-tank readings and from records collected by state oil and gas regulatory bodies (i.e. Texas Railroad Commission). Production data are reported in units of barrels per month (BBLS/M) for the entire lease, except for Pennington/Stevenson lease production, which is reported as a weekly average of daily oil production (BBLS/D). A decline curve, which best describes the lease production performance, was calculated from the record of historical production. The decline curve was extrapolated into the future as a baseline from which to compare post-treatment production.

All reservoir characteristics, map, and oil production data were supplied by the treatment field operators or cited in published literature. All data on microbial population levels in the treated reservoirs are from the laboratory of Alpha Environmental.

Treatment Protocol.

Two different methods for introducing microorganisms into a target oil reservoir have been tested: the Single Well Treatment, and the Water Flood Treatment. In both techniques bacteria, biocatalyst, and inorganic nutrients are mixed with water produced from the formation to be treated. The components are mixed until all solids are in suspension. Each lease was treated only once per test.

The Single Well Treatment protocol is as follows: Mix the bacterial solution and gravity-flow or pump the solution into the reservoir through the annulus of the well. The bacterial solution enters the target formation through perforations in the casing. The treated well is shut-in for five to ten days, during which surrounding producing wells are pumped on their normal schedule. The leases in the LaVernia and Longwood fields were treated with the Single Well technique.

As the LaVernia Field tests reached their projected observation time limit, some previously treated and some untreated wells were treated again with the single well MEOR system. The dates of these treatments are reported on the charts of oil production for each treatment location. Analytical facilities, personnel, time, and funding were not sufficient to follow the results of these treatments as closely as the initial single-well injections. Little data was taken on the results of these late injections and therefore these treatments are not discussed in detail. The primary purpose of these later treatments was to guide the planning of the subsequent controlled field tests. In this respect, experience gained from late treatments was informative.

The Water Flood Treatment protocol is similar to the Single Well method except that the bacteria are delivered to the target reservoir via an existing water flood system rather than through an oil producing well. The MEOR solution is added to the existing water flood storage tanks and pumped into the formation at the normal flooding schedule and rate. The Pennington/Stevenson lease in Illinois was treated with the Water Flood technique.

Field Sampling for Microbes.

A series of oil and formation water samples from each well on a lease to be treated were collected before and after treatment. The samples were analyzed in Alpha Environmental's microbiology laboratory for toxicity, hydrocarbon degrading bacteria population and activity. The bacterial enumeration procedure is described in the following section.

The duration of the microbe sampling program spanned the pre-treatment field survey, treatment, and post-treatment analysis. A pre-treatment survey for indigenous microbial activity to establish a baseline for post-treatment comparison was conducted in each oil field several weeks in advance of treatment, except in the Penshorn Lease where microbial activity was not expected because of the long distance of these wells from the Vorphal treatment well. Samples were taken from every available well on a lease. A second sample was taken from each well immediately prior to treatment to verify the pre-treatment microbial population status.

Samples were collected in sterile 500 ml glass bottles at the wellhead during normal pumping operations. The bottles were cooled, packed in ice and transported to the lab by project staff, or in the case of long distance shipping, posted by express mail to the lab in cooled containers within twenty-four hours.

Throughout treatment, the bacterial solution was sampled to test for viability. Sampling of each treated lease for microbial population and activity began on a weekly basis and as the project developed proceeded on a monthly basis.

Laboratory Analysis of Oil-Degrading Microbe Population and Activity.

Samples of oil and formation water before and after treatment were analyzed in the lab for microbial population and activity. Field samples received at the lab were refrigerated until analyzed. Biological activity was determined as follows:

1. Samples are brought to room temperature. Growth medium is seawater plus nitrogen, phosphorus and crude oil as the only energy source. The medium is adjusted to pH 7.6 (Oppenheimer *et al.*, 1979).

2. Samples are agitated for one minute to form an oil-water emulsion.

3. Duplicate analysis flasks containing 50.0 ml sea water medium are inoculated with 5.0 ml of the water phase of the sample. After mixing each dilution, successive 5.0 ml aliquotes are taken to a final dilution factor of $10^{-8}$.

4. Six drops of sterilized crude oil (energy source) are added to each dilution flask.

5. A duplicate set is incubated aerobically and agitated for three to four days at room temperature.

6. Upon completion of incubation, several drops of sample are transferred to a glass microscope slide. Bacteria are counted utilizing a microscope with differential interference contrast and epifluorescence optics.

The slide is completely scanned in a statistically prescribed pattern. Ten fields of view which contain one or more bacteria per field of view is considered a positive reading. This indicates a concentration of bacteria in the dilution bottle of approximately $10^5$ cells/cc of fluid. Numbers of bacteria in the original sample are calculated from the last positive dilution bottle.

Presentation of Oil Production Data

In this report, success of the MEOR system is measured by the amount of incremental oil recovered after MEOR treatment. The following equation is used to calculate the volume of incremental oil produced during a given time period:

**Actual oil - Expected oil = Incremental oil.**
(Prats 1982, and Lake 1988)

**Actual oil** is defined as the total volume of oil produced during a given time period. **Expected oil** is de-

fined as the volume of oil predicted to be produced by the extrapolation of an oil production decline (a best-fit exponential regression curve), calculated from the maximum amount of reliable historic production data. **Incremental oil** is defined as that volume of oil greater than the expected volume. As a test of the accuracy of the decline curve in describing historical and predicted oil volumes, a confidence factor was calculated by applying the incremental oil algorithm to pre-test production. The resulting value for a given time period should theoretically be equal to zero. In practice, there usually is a difference from zero, (zero would indicate a perfect description of production history). The variance from zero is reported as the percent error inherent in the decline curve and percent incremental increase. Incremental oil volumes and percent production changes for each treatment are summarized in Table 6.

Alpha has developed a computer program (using the spreadsheet program Microsoft EXCEL) to display oil production volumes with a decline curve calculated from pre-MEOR treatment production history. The horizontal axis of oil production graphs represents time in units of months or weeks The vertical axis measures volume of oil produced in barrels per month or in average barrels per day (seven days of production are averaged and reported in units of barrels per day for a given week). The decline curve is calculated from historical production up to the date that the lease is treated with microbes. The decline period, over which the decline curve was calculated, varied with each treatment site, and was determined to best represent the field's natural decline rate. The decline curve is extrapolated from the historical data into the future to serve as a measure of the field's expected oil production performance. Production volumes recorded after the target lease was treated are plotted on the same graph over the extrapolated decline curve for ease in comparing actual versus expected production. Oil production charts are presented in a rate vs time format on a normal arithmetic, not semi-log scale. The incremental oil produced after MEOR treatment began is attributed to the effect of the treatment.

Variations in field operations that might have positively or negatively affected pre- and post-treatment production volumes (well shut downs, pump changes, well servicing, etc.) were held to a minimum. When field operations may have affected production volumes or oil quality,

the alteration was incorporated into the interpretation of oil production totals.

Computer and Software for Data Storage, Reduction, and Analysis.

Independent oil producers will be the prime beneficiaries of the application of Alpha Environmental's microbial enhanced oil recovery process. In order to facilitate the transfer of technology and techniques developed by Alpha during this demonstration grant from the D.O.E., Alpha Environmental chose to utilize widely available personal computers and existing software packages for data analysis. All data were stored, analyzed, and reports generated with Apple Macintosh computers and Microsoft Word, Paint, Draw, and EXCEL software.

# CHAPTER TWO. FIELD STUDIES

Alpha Environmental treated and studied five producing oil leases in three different types of oil fields. The locations of the fields and wells are illustrated in Figures 2, 3, and 4. Three leases in the LaVernia Field near San Antonio, Texas, one lease in the Longwood Field on the Texas-Louisiana border, and the entire West Geff Field in central Illinois were treated.

Field application of Alpha's MEOR system was preceded by a geological and engineering survey to characterize the producing reservoir and to locate optimal wells for injection. A summary of reservoir data and reservoir brine chemistry for the first demonstration site is presented in Tables 1 and 2. Historical data on well completion, well service, chemical treatments, and oil production were collected and analyzed to build a baseline field characterization for comparison with post-treatment results.

Prior to treatment, samples of oil and brine from injection and observation wells were tested for microorganism compatibility, toxicity, and for the occurrence of indigenous hydrocarbon-oxidizing microorganisms. After injection,all wells were sampled for hydrocarbon microorganisms at frequent intervals. The population and activity of hydrocarbon-oxidizing microorganisms were monitored at each well in order to determine if, and at what rate, they moved through the formation from the injection well. Numbers of microorganisms in each sample analyzed were determined by standard dilution viable count methods, as described in the Materials and Methods section.

## LAVERNIA FIELD

LaVernia oil field is located SE of San Antonio in Wilson County, Texas. The field produces small amounts of medium gravity oil ( 30-33 API) from thin shale and sand lenses of the uppermost Cretaceous Navarro formation.

The Navarro formation is a shallow marine deposit characterized by interbedded calcareous organic-rich shales

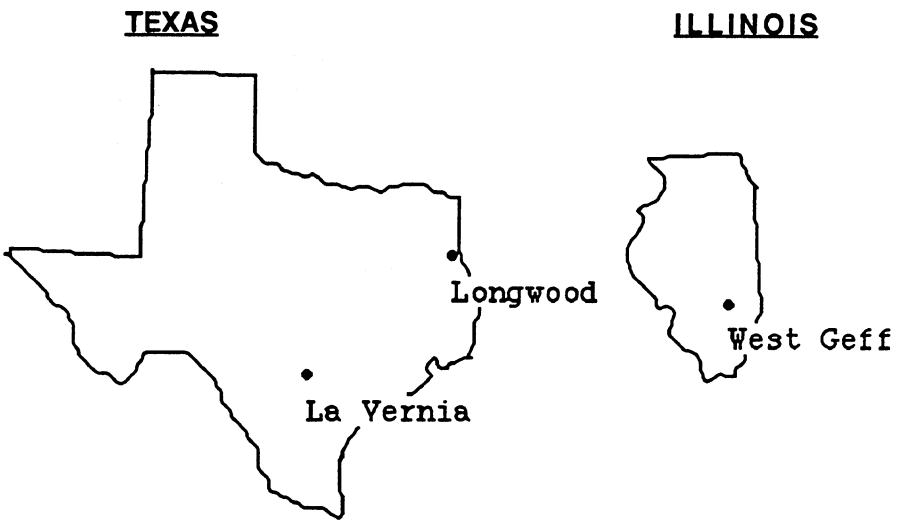



**Figure 2. Location map of the three oil fields treated and studied during this project.** La Vernia and West Geff Fields are clastic sandstone reservoirs, Longwood Field is a carbonate reservoir.

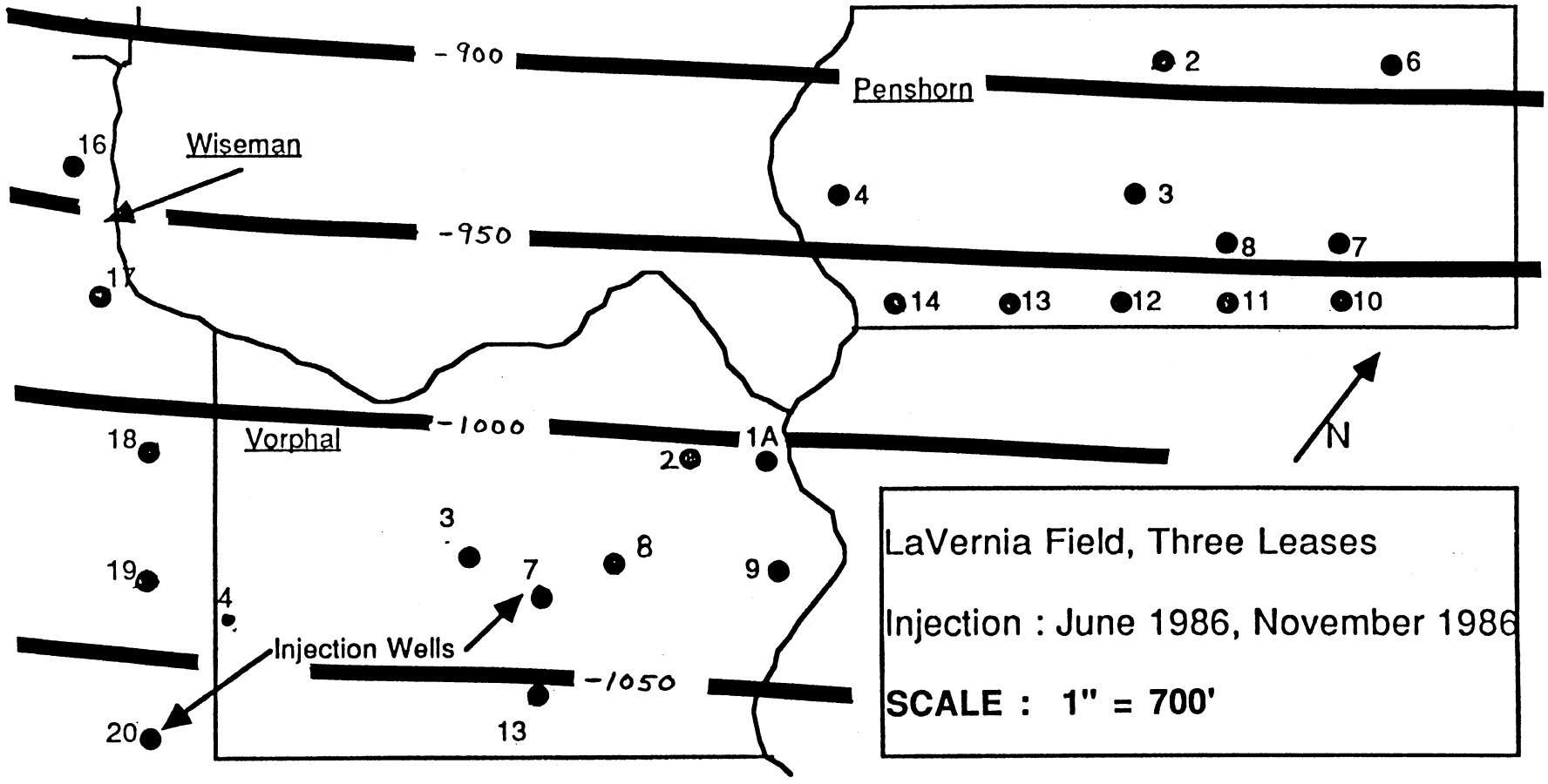



**Figure 3. Structure-contour map on top of the Navarro Formation in the area of the LaVernia Field treatment sites.** Contour interval = 50 ft. Injection wells are labeled. Most of the remaining wells served as "observation wells" for changes in microbial population and oil production.

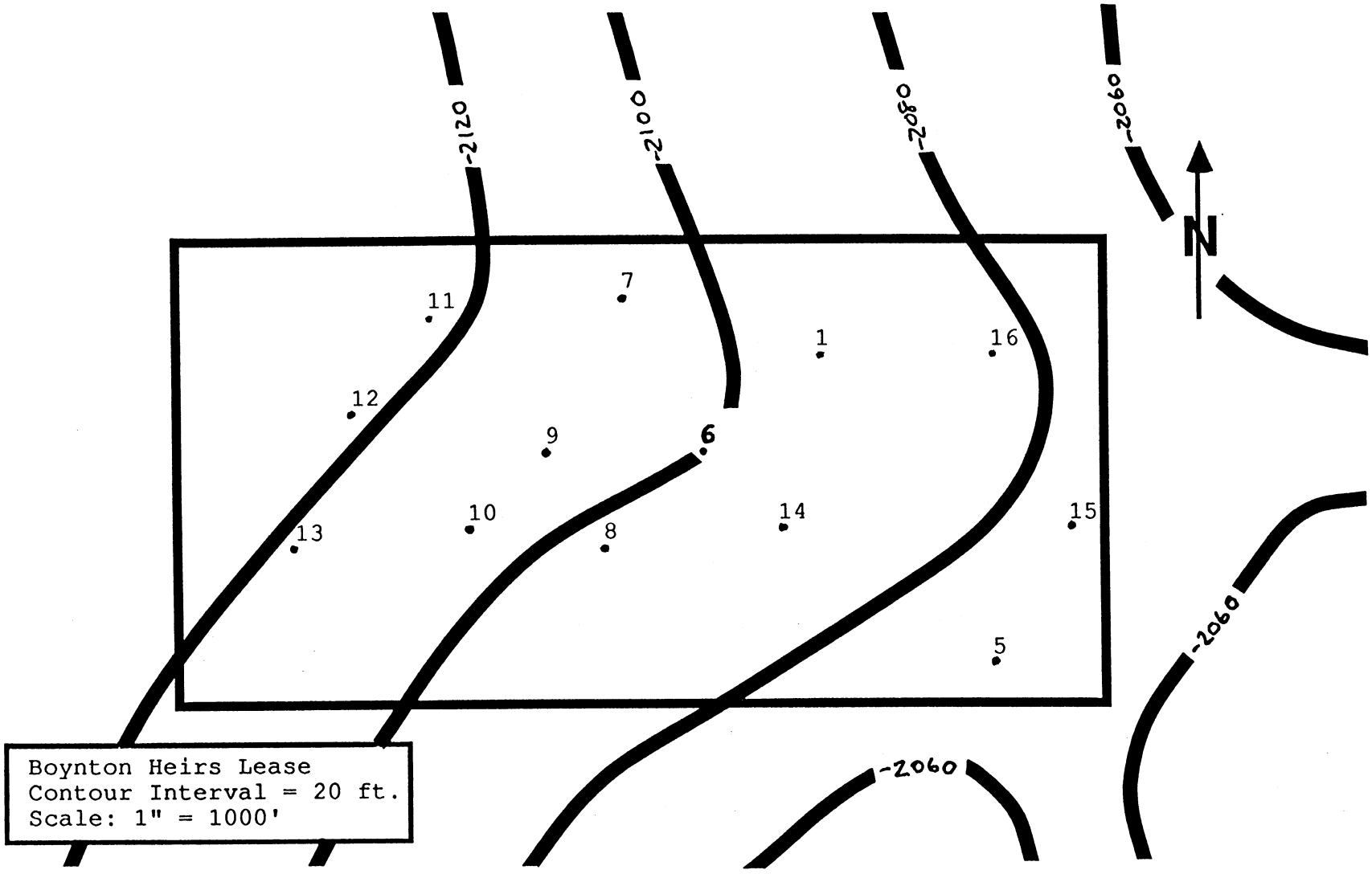



**Figure 4. Structure-contour map on top of the Goodland Limestone, Boynton Heirs Lease, Longwood Field, Texas.** Contour interval = 20 ft. Injection wells = 1 and 11. Observation wells = 1, 5, 6, 7, 8, 11, 12, 13, and 14. Wells 9, 15, and 16 were not sampled for microbial activity due to mechanical pump problems during sampling visits.

| | |
|---|---|
| **FIELD NAME** | LaVernia |
| **LOCATION** | Wilson County, Texas, SE of San Antonio |
| **FORMATION** | Navarro, U. Cret. |
| **PERMEABILITY** | 37-49 md |
| **POROSITY** | 16-25% |
| **RESERVOIR DEPTH** | 1450-1500 ft. sub sea |
| **GROSS PAY THICKNESS** | 1-10 feet of broken sands |
| **LITHOLOGY** | Fine-grained, shaley, carbonate-rich sand, with swelling clays |
| **TRAP** | Regional monocline dipping SSE, subtle local stratigraphic traps |
| **OIL** | API gravity 30-33. |
| **WELL STIMULATION** | 22,000 lbs sand frac with 28 bbls lease oil. |
| **WELL SERVICE** | Pumps serviced for occasional sanding. Slight paraffin plugging. |
| **NUMBER OF WELLS** | 24 on three leases |
| **WELL SPACING** | 10 acre, wells drilled along strike, no standard pattern |
| **PREVIOUS EOR** | none |

**Table 1. Reservoir data for the LaVernia Field, Wilson County, Texas.**

| | |
|---|---|
| pH | 7.30 |
| Ca | 206 mg/L |
| Mg | 93.2 mg/L |
| Chlorides | 8780 mg/L |
| HCO3 | 230 mg/L |
| Na | 5730 mg/L |
| K | 30.7 mg/L |
| Fe (total) | <0.1 mg/L |
| Al | < 1.0 mg/L |
| Mn | 0.81 mg/L |
| Ti | < 0.3 mg/L |
| Sr | 19.1 mg/L |

Analysis by Mineral Studies Lab of the Bureau of Economic Geology, University of Texas at Austin.

**Table 2. Formation water chemsitry of the Vorphal #7 well, LaVernia Field, TX.**

and lenticular shaley sand bodies ranging from several inches to one foot thick. The sand bodies have not been characterized as any distinct facies type. Regional structure consists of a northeast-southwest striking monocline which dips slightly to the south-southeast.

The LaVernia field trends northeast-southwest and is about one mile wide. The northeast-southwest extent of the field has yet to be definitively established. Total sand thickness varies by well from several inches to several feet. The sands allow fluids to communicate vertically between strata when the wells have been hydraulically fractured. The state of horizontal fluid communication is unknown (except between well #7 and #3 on the Martin Vorphal lease where communication was established during well completion). The entire Navarro formation is part of the Olmos brine aquifer which underlies much of south Texas.

The exact trapping mechanism for the Navarro oil is unknown. It is likely that the LaVernia field is producing from a stratigraphic trap. The calcareous shale which surrounds the sand lenses may provide both the source and cap rock for Navarro oil. It is also possible that oil is trapped by offset faults. The LaVernia field is located directly along the trend of the Luling fault system to the north. No faults have been mapped however, in the area of the present study.

The Navarro sands were first drilled in the LaVernia field in the early 1950's. The operator during Alpha Environmental's MEOR treatments acquired three LaVernia leases and in 1985 initiated a drilling program to extend the field limits. The wells were drilled along the strike trend of current production within a one mile wide corridor.

Wells were treated according to the following protocol:

<u>MEOR Solution Formula:</u>

26 BBLS (42 gal/bbl) Formation Water

20 lbs dried bacteria ($10^{12}$ cells/gm)

3 lbs Nutrient (N-P-K:20-20-20)

1 BBL biocatalyst

Equipment

Tank with circulating pump,

55 gal. mixing tank and stirring device,

Transfer pumps,

Catalyst transport and storage drums,

Safety and sampling equipment.

Procedure

The treatment formula was mixed and injected in five 26 bbl batches (42 gal/bbl) for each well in the folowing procedure:

1. Fill test tank with uncontaminated formation water.
2. Add nutrient and catalyst to formation water and agitate until solids are completely suspended.
3. While agitating, mix bacteria in formation water/catalyst solution.
4. Add bacteria solution to mixture in tank and agitate until entire solution is consistent and all solids in suspension.
5. Sample injection mixture for lab analysis
6. Gravity flow complete mixture into well.
7. Time rate of flow into well.

**VORPHAL LEASE**

Well History

Wells # 1A, 7, 8, 9, and 13 were drilled, completed and stimulated in a similar manner in late 1984 and early 1985. All five wells began production into a single tank battery on the Vorphal lease on September 15, 1985.

Wells #2, 3, and 4 were drilled in 1954-55. No completion or stimulation data were available. Each well is

rarely pumped except #3, which produces less than half a barrel every other day. These wells produce into a separate tank which is collected twice a year. Wells #2 and 4 were not active and so were not observed for microbial population.

Treatment Plan

The first field test was initiated in the Vorphal Lease in June, 1986. Well #7 was selected as the first treatment well. It is centrally located between three "observation wells", #3, #8, and #13, each about 350 to 400 feet from #7. The original plan was to observe just these four wells, as microbial migration was not expected beyond the distance of the observation wells. Within days of the treatment, however, increased production in the NE direction from well #7 caused Alpha to expand the microbe sampling program to as many wells as possible on the Vorphal and Penshorn leases

Alpha Environmental's MEOR solution was introduced into the formation through the annulus of well #7 by gravity feed. Immediately before injection, the well was pumped for 24 hours to remove fluids from the casing. During the treatment all other producing wells were pumped on their established schedule.

Well #7 was continuously treated for five days, shut-in for five days and then put back on production. The tight formation allowed only a 1BBL/hr injection rate. Microbial populations were monitored in the surrounding wells.

Little to no increase in microbial population and activity was observed in the wells that were down dip from the treatment well. Significant increases in microbial population were observed in the wells to the North East of the treatment well (Vorphal# 1A, 9, and Penshorn Lease wells). The wells to the northeast lie updip from the treated well and along the trend of the underlying Luling Fault Zone. Fractures parallel to the northeast trending Luling Fault Zone may be present in the Navarro, but are not documented in this field.

Oil production for the Vorphal lease before and after treatment is presented in Figure 5. Population levels of hydrocarbon degrading microorganisms from samples collected before and after treatment of the Vorphal lease on a well

by well basis are presented in Figure 6. Tabular data supporting Figures 5 and 6 are presented in the appendix.

**PENSHORN LEASE**

An unexpected increase in oil production on the Penshorn lease to the northeast of the Vorphal lease led to sampling of up-dip wells for microbial activity. Sporadic high populations of bacteria were found in the Penshorn lease wells. the Penshorn lease was not included in the original observation program and therefore no pre-treatment analyses of well samples were made for the presence of indigenous hydrocarbon degrading microbes. Oil production in the wells to the North East increased within three weeks of the Vorphal treatment. Figure 7 shows oil production from the Penshorn lease before and after the treatment of the Vorphal well #7. It appears that the treatment of the Vorphal #7 well stimulated oil production in the nearby Penshorn Lease. The reservoir in the LaVernia Field dips down to the south- southeast. Microbial activity and increased oil production appeared up-dip from the treatment well in the producing formation.

**WISEMAN LEASE**

To test the theory that the microbes migrated up-dip from the injection well, the Wiseman lease, which abuts the Vorphal to the west, was studied and treated.

Four wells on the Wiseman Lease (wells 16-19, on the left of Figure 3) are located directly updip from well #20, which is the deepest completion and furthest down-dip well on the lease. Well # 20 was treated in December, 1986 and wells 19-16 observed for signs of microbial activity and changes in oil production. Production history for the Wiseman lease before and after injection is reported in Figure 8. Substantial increases in microbial population were observed in all the wells for a period of six months (Figure 9). This lease was not monitored beyond June, 1987

**Results**

The results for the leases in the LaVernia Field show a cycle of microbial population through time. Microbial population was high in the treated wells immediately after application of microoganisms, population levels gradually tapered off through time. In wells up-dip from the treatment sites, microbial populations started low and gradually

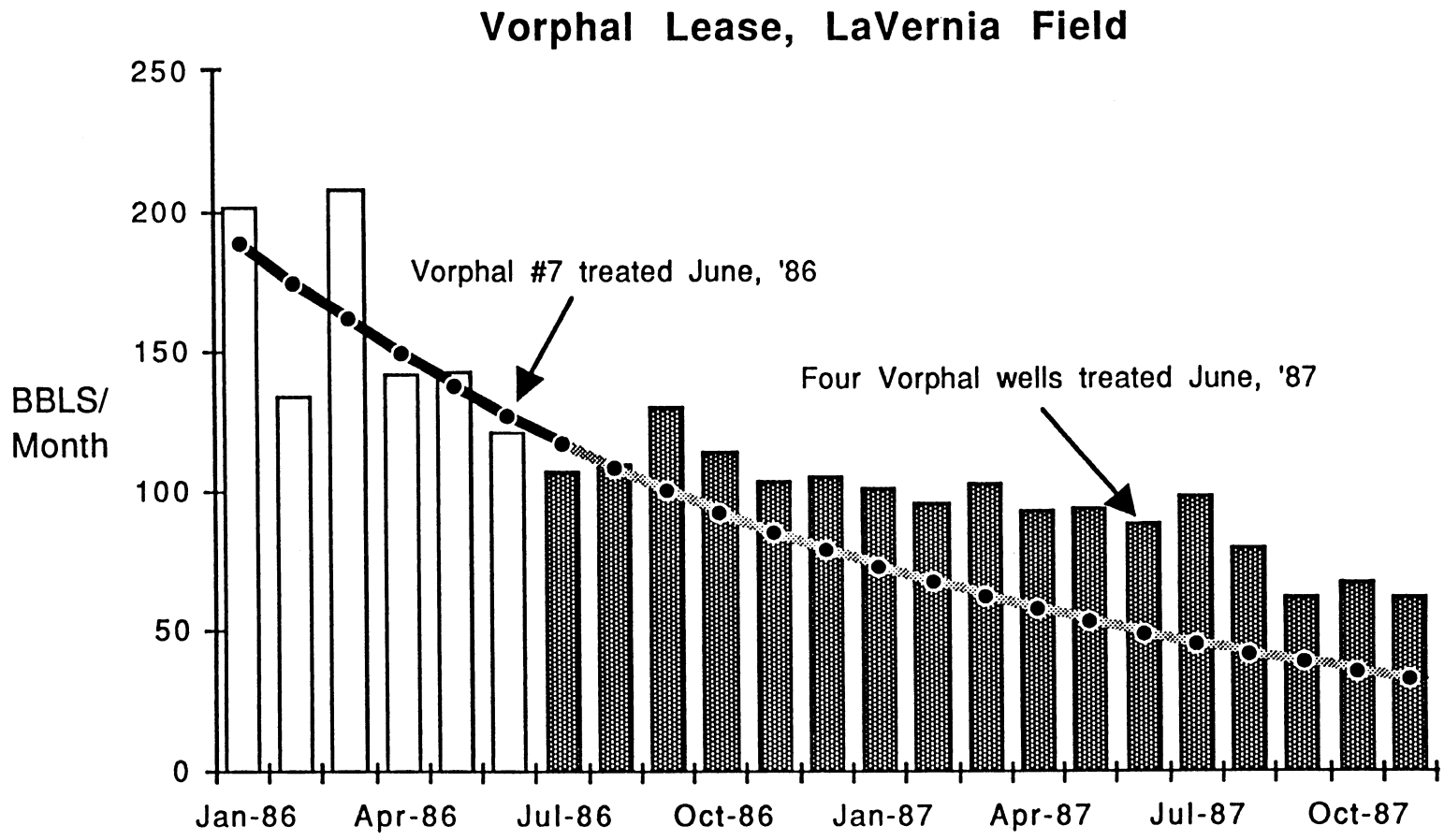



**Figure 5. Pre- and post-treatment oil production with actual and extrapolated decline curve for five wells drilled in January, 1986 on the Vorphal lease, LaVernia Field, Texas.** White bars = pre-treatment production, shaded bars = post-treatment production. The actual decline curve, indicated by the solid line, was calculated from the six months of pre-treatment oil production. This curve was extrapolated into the future as a basis for post-treatment oil production comparison and is indicated by the stippled portion of the curve.

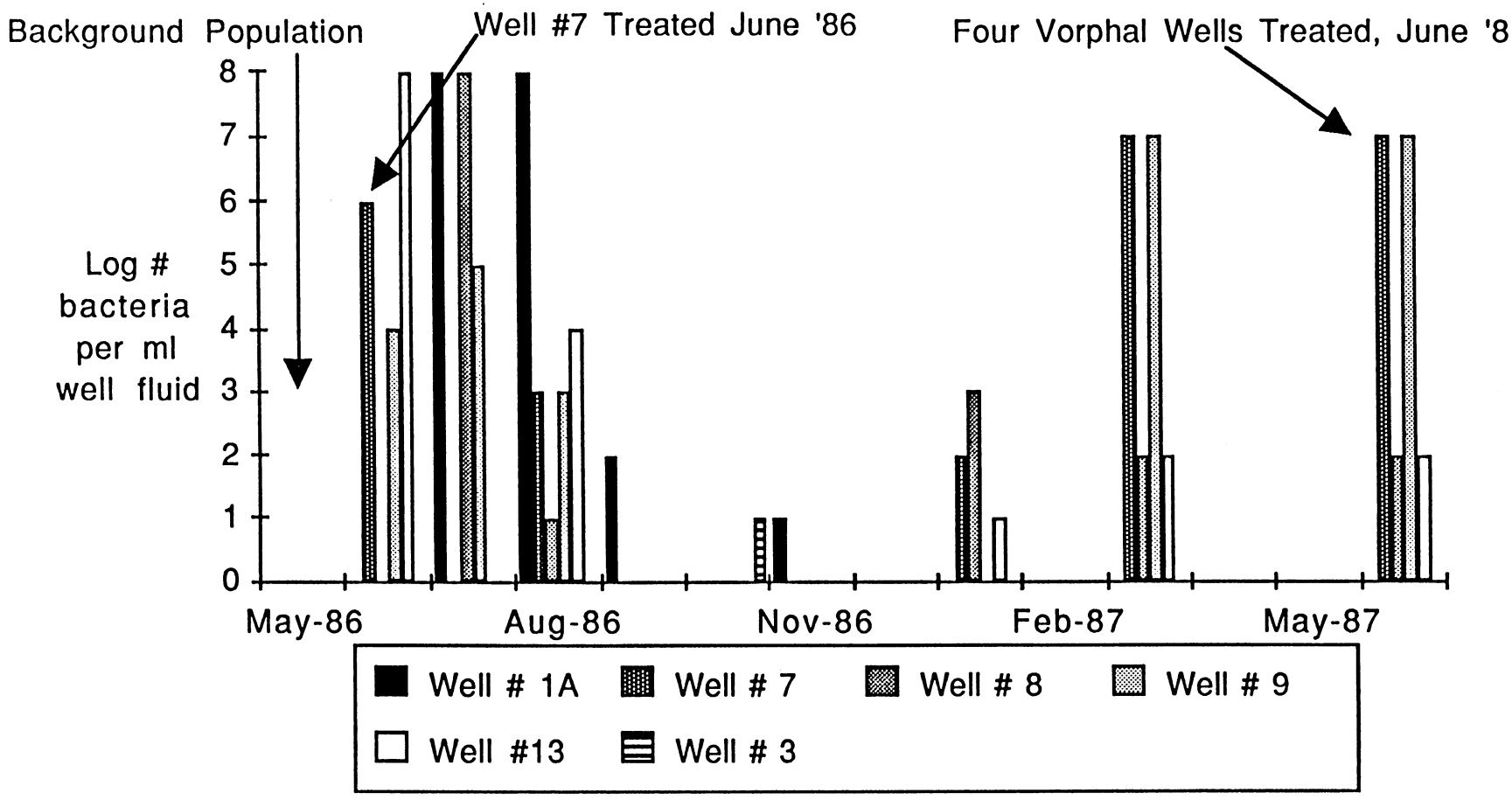



**Figure 6. Population of hydrocarbon degrading bacteria in six wells of the Vorphal lease, LaVernia Field, Texas.** Well fluid was sampled from each "observation well" through time and the population of hydrocarbon degraders was determined by serial dilution enumeration as explained in the Materials and Methods section.

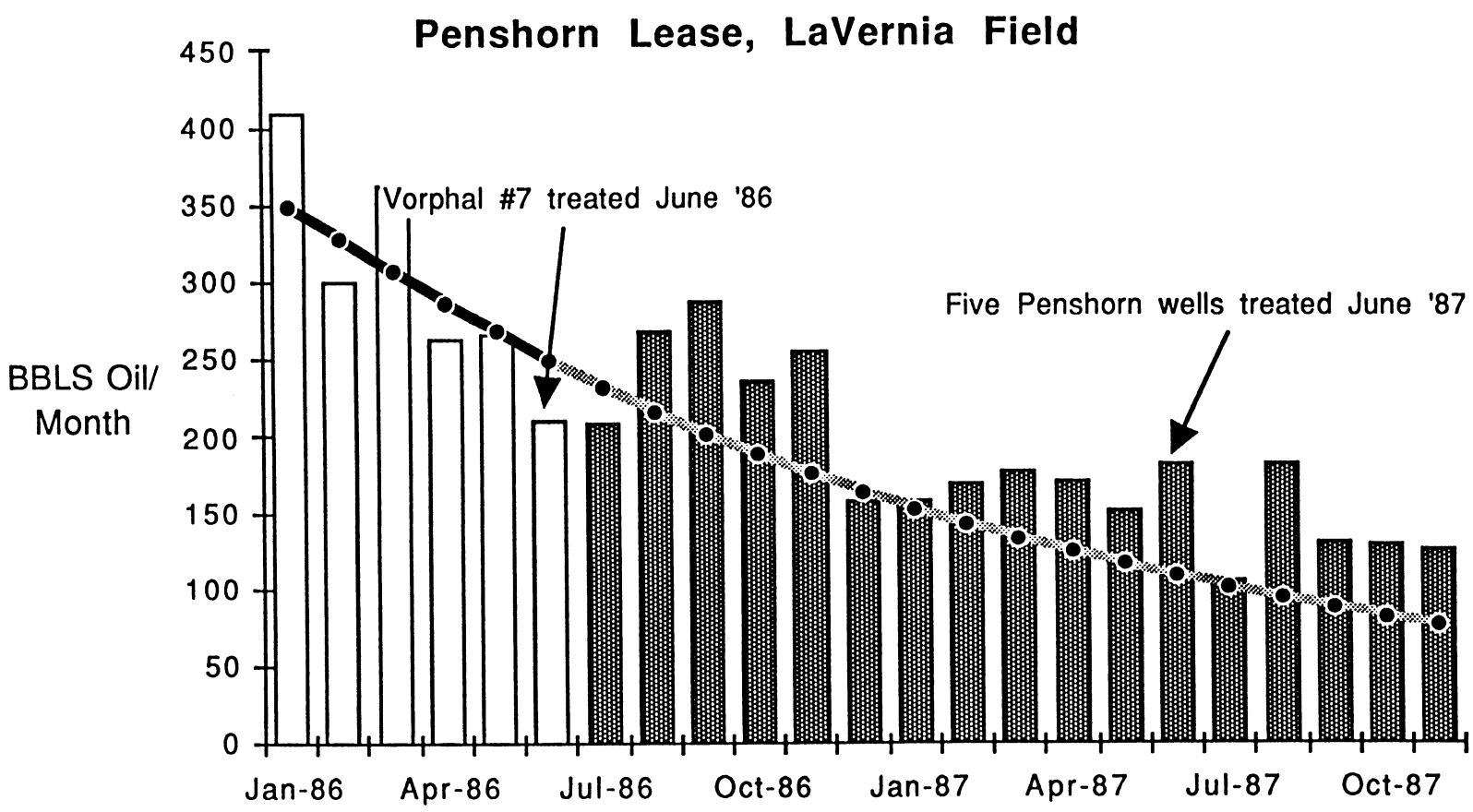



**Figure 7. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Penshorn Lease, LaVernia Field, Texas.** White bars = pre-treatment production, shaded bars = post-treatment production. The actual decline curve, indicated by the solid line, was calculated from the six months of pre-treatment oil production. This curve was extrapolated into the future as a basis for post-treatment oil production comparison and is indicated by the stippled portion of the curve.

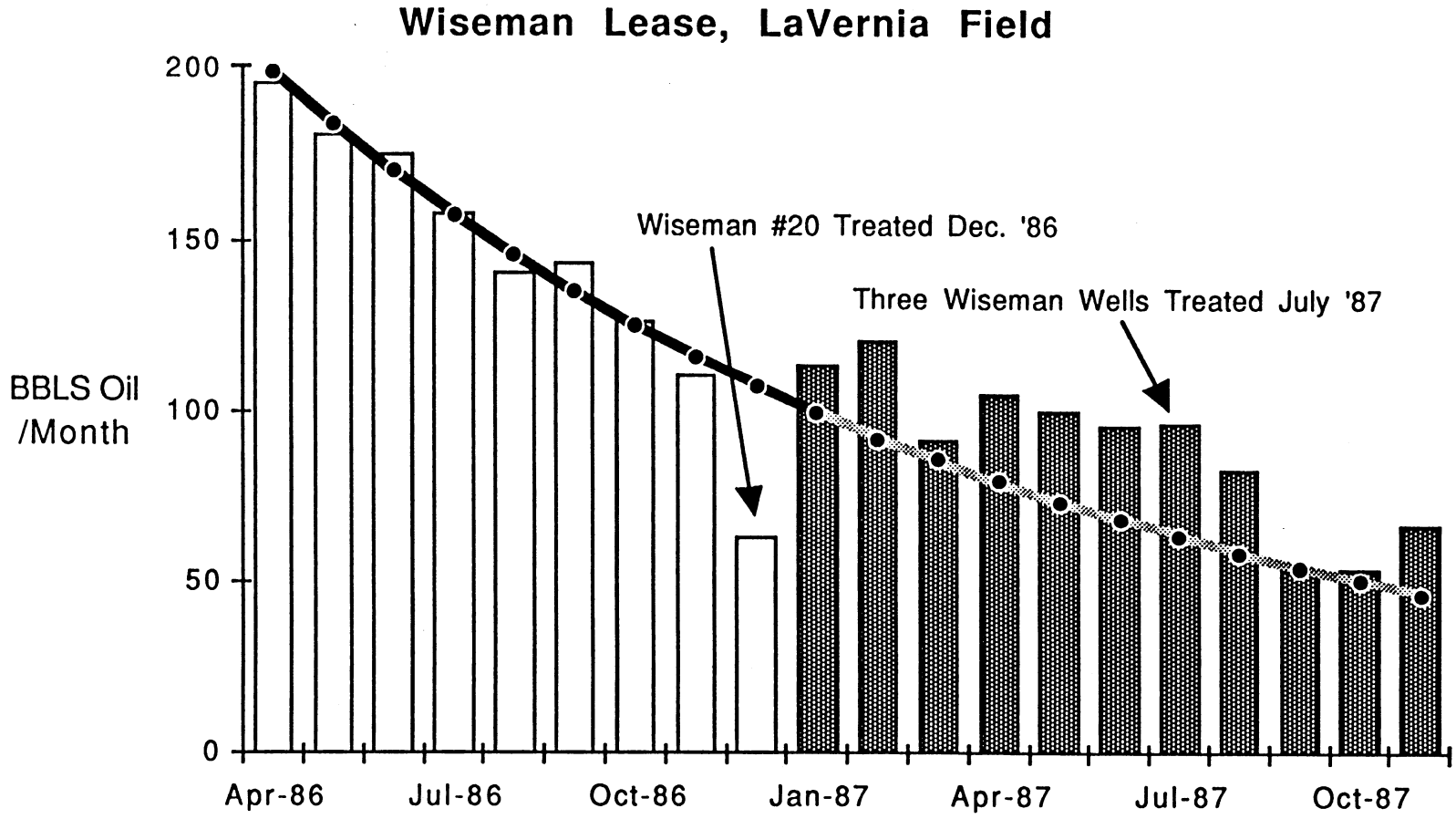



**Figure 8. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Wiseman Lease, LaVernia Field, Texas.** White bars = pre-treatment production, shaded bars = post-treatment production. The decline curve, indicated by the solid line, was calculated from the nine months of pre-treatment oil production. This curve was extrapolated into the future as a basis for post-treatment oil production comparison and is indicated by the stippled portion of the curve.

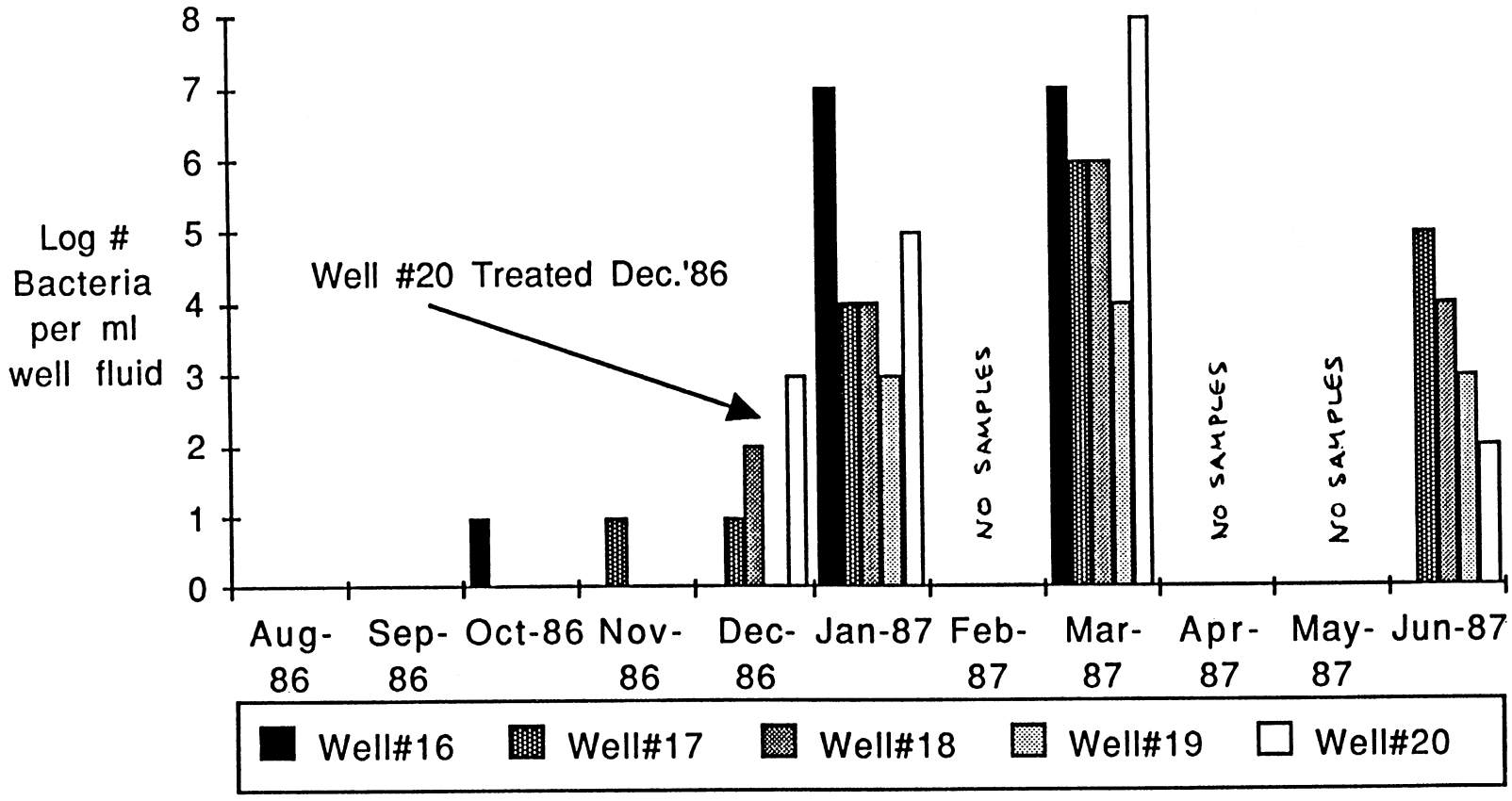



**Figure 9. Population of hydrocarbon degrading bacteria in the five wells of the Wiseman lease, LaVernia Field, Texas.** August - November data represent pre-treatment background populations. Samples were not collected during the months of February, April, and May. Bacteria were counted by serial dilution enumeration technique as described in the Materials and Methods section.

increased to a peak and then gradually also tapered off. This suggests that bacteria moved through the formation, and experienced a population growth and decline cycle similar to that observed in any closed environmental system where a limited nutrient or growth component can cause the population to reach a peak and then decline. Sequential first arrival times of microorganisms in oil producing wells were not correlated with distance from the treatment well, perhaps due to geological heterogeneities in the reservoir. The increased microbial population and activity count measured at observation wells near the treatment well is a typical response to the treatment.

In addition to oil production increase, the lease operators observed several other changes that may be attributable to the activity of hydrocarbon degrading microorganisms. Paraffin buildup at the wellhead was reduced as was equipment maintenance resulting from paraffin problems. The API gravity of the produced oil, as determined by the company collecting the crude oil, was increased. Quantitative procedures are being developed to accurately measure these parameters in subsequent field operations. The organic chemistry of crude oil before and after biodegradation is currently being studied as a part of the continuation and expansion of work reported here.

As the natural, in-situ microbial population in the subsurface formation may be assumed to have been in static equilibrium before MEOR treatment, the rapid increase in numbers of microorganisms in observation wells may be explained by the movement of the injected organisms through the field. Comparing the distance between the observation wells and injection well with the time of first arrival of the microorganisms at the observation wells suggests microbial migration rates of up to several hundred feet per day. This transport rate is substantially higher than commonly accepted for particle transport through porous media. Alpha reports this data as a field observation. We are currently designing laboratory experiments in cooperation with the Department of Petroleum Engineering at the University of Texas at Austin to study bacterial transport phenomena in both homogeneous and fractured reservoir rock.

**LONGWOOD FIELD**

A lease producing from the Goodland Limestone in the Longwood Field of east Texas was selected as an example of a carbonate reservoir. Longwood field is situated on the west flank of the Sabine Uplift, a structural high that separates this area from the giant East Texas Field. The reservoir and brine chemistry features of the Goodland Limestone, a member of the lower Cretaceous Fredericksburg formation, are summarized in Tables 3 and 4. The Goodland lime is known to be a depletion type reservoir with a high connate water content. The wells produce water but there is no effective water drive. The average recovery factor of the reservoir is estimated to be 14%.

**BOYNTON HEIRS LEASE**

The Boynton Heirs lease lies in the Longwood Field, which is located along the Texas /Louisiana border in Harrison County, Texas just west of Shreveport and about eight miles east of Leigh, Texas. Average permeability is 25 millidarcies, average porosity is 25 percent. Average residual oil saturation is 17.0 percent, average total water saturation is 69 percent (data from Core Labs analysis of nearby Goodland Lime wells, 1/16/76). The average net productive interval is 20 to 30 feet. The wells on the Boynton Heirs Lease produce from the interval of -2080 to -2120 feet subsea. Often several zones within the Goodland produce oil but the Boynton Heirs lease produces from only the topmost portion of the formation. The Boynton Heirs Lease is located on the flank of a broad structural high but shows no distinct closure. The upper Cretaceous Tokio Shales truncate the Goodland lime and form a stratigraphic trap for hydrocarbons.

The typical well on the Boynton Heirs lease produces between .5 and 1.0 BBLS oil ( 38-40 API gravity), 5-10 BBLS brine and 10-15 MCF gas per day (vented) from the Goodland Limestone. The Boynton Heirs Lease has 13 working wells all producing from the Goodland Lime. The wells produce through one central gun barrel and into two storage tanks. Salt water produced from the 13 wells on the Boynton Heirs Lease is injected into the overlying Nacatoch Sands, a brine aquifer at a depth of -989 to -1081 ft.

The Boynton Heirs Lease was treated in July, 1986 with essentially the same procedure as the LaVernia leases. Two

| | |
|---|---|
| **FIELD NAME** | Longwood |
| **LOCATION** | Harrison County,Texas, east of Shreveport, LA. |
| **FORMATION** | Goodland Lime, Lower Cret. |
| **PERMEABILITY** | 0-180 md, average = 25 md. |
| **POROSITY** | Average = 25 % |
| **RESERVOIR DEPTH** | 2080 - 2120 ft. sub sea |
| **GROSS PAY THICKNESS** | 30 feet |
| **LITHOLOGY** | chalky limestone |
| **TRAP** | flank of structural high |
| **OIL** | API gravity: 39-40 |
| **WELL STIMULATION** | Acid treated with 5000 gals. HCL |
| **WELL SERVICE** | Wells chemically treated bi-weekly for paraffin and gypsum |
| **NUMBER OF WELLS** | 13 on one lease |
| **WELL SPACING** | 20 acre spacing |
| **PREVIOUS EOR** | none |

**Table 3. Reservoir data for the Boynton Heirs Lease Harrison County , TX.**

| | |
|---|---|
| Specific Gravity | 1.03 |
| Surface tension | 31.8 dynes/cm |
| Density | 8.56 lbs/gal |
| pH | 7.28 |
| Total dissolved Solids | 37,700 mg/L |
| Ca | 1300.00 |
| Mg | 330.00 |
| Chlorides | 27,250 mg/L |
| Sulfates | 0.00 |
| HCO3 | 293 mg/L |
| Na | 15663 (by calculation) |
| K | 0.00 |
| Ba | 95 mg/L |
| Fe (total) | 0.89 mg/L |
| Fe (ferrous) | 0.53 mg/L |

Analysis by Halliburton Division Laboratory, Bossier City, LA.

**Table 4. Chemistry of formation water from the Boynton Heirs Lease, TX**

wells were selected as treatment sites on a lease of thirteen producing wells. The observation wells for each treatment well were chosen based upon proximity and structural position in the reservoir relative to the treatment well. Expected microbial transport was to the south and east of each treatment well. For treatment well #11, observation wells 3, 7, and 10 were predicted to be most affected by the MEOR treatment. Wells # 6, 8 and 12 were identified as those with potential to be affected by treatment well #11. For treatment well # 1, wells 14 and 16 were predicted as those that would be most affected, and wells 5 and 15 as those with potential to be affected. Since well 13 was located at a considerable distance and downdip from either treatment well, no microbial activity was predicted.

**Boynton Heirs Results**

The population level of hydrocarbon degrading bacteria was observed to gradually increase in each observation well as it became microbially active. Lease-wide, wells became microbially active at least during one sample date during September-November. Lease-wide microbial population peaked in October and appeared to begin a decline in November.

Treatment well #1 became immediately microbially active and continued to increase in population density through the test period, peaking in November. Moderate to high bacterial populations were observed in wells 6, 14, and 16 from September through November. Moderate levels of microbial population were recorded in well #15 (over three thousand feet from the treatment well) in October and November. A very high population level was recorded in well #5 in November.

The microbial population in treatment well #11 did not establish itself as well as in Treatment well #1. The population count was low and stable from the treatment date through October, then rose slightly in November. Some of the surrounding observation wells recorded higher microbial populations than did the treatment well. Wells # 7 and 10, updip and within approximately 1500 ft of the treatment well recorded moderate population levels through November. Wells # 6 and 8, located between the two treatment wells, responded most positively in regards to increasing microbial population of all observation wells, sustaining a moderate population through September and October and showing

a very high population in November. Well #12 recorded a moderate population throughout the test period. Well # 13, in which no activity was predicted, recorded a moderate population level in September.

Oil production results based upon monthly records for the entire lease indicate little-to-no significant oil production increase during the test period. Early results based upon analysis of daily production records indicated a promising increase and an upward change in the decline of oil production (Oppenheimer and Hiebert, 1987). The data base for analysis of this lease was changed from daily measurements provided by the operator to monthly records collected by the Texas Railroad Commission (TRC) as the quality of reports from the operator deteriorated. All data for pre- and post-treatment oil production, and the calculation of the decline curve are from TRC records. Oil production data for pre- and post- treatment are reported in Figure 10, microbial population levels by well.are reported in Figure 11. Tabular data supporting Figures 10 and 11 are reported in the Appendix.

**WEST GEFF FIELD**

The West Geff Field in Wayne County Illinois was selected as the final reservoir to investigate during this project. The West Geff Field is a small isolated structural trap. The small size of the field provided the opportunity to study the effects of MEOR on a field-wide basis.

The Aux Vases Sandstone is the uppermost unit in the Valmeyeran Series of the Mississippian System in Illinois. The Aux Vases marks a transition from carbonate to clastic deposition. Of the three facies observed in the Aux Vases (carbonate, tidal clastics, thick sandstones) the Pennington/Stevenson lease is located at the transition of thick and tidal sandstones. Sedimentary structures found in Aux Vases cores include thinly laminated low-angle crossbedding,and herring-bone crossbedding. Primary intergranular porosity is usually high. The minerals of the Aux Vases Sandstone include quartz, plagioclase, orthoclase, smectite, illite, chlorite, calcite, and dolomite. (Seyler, 1986)

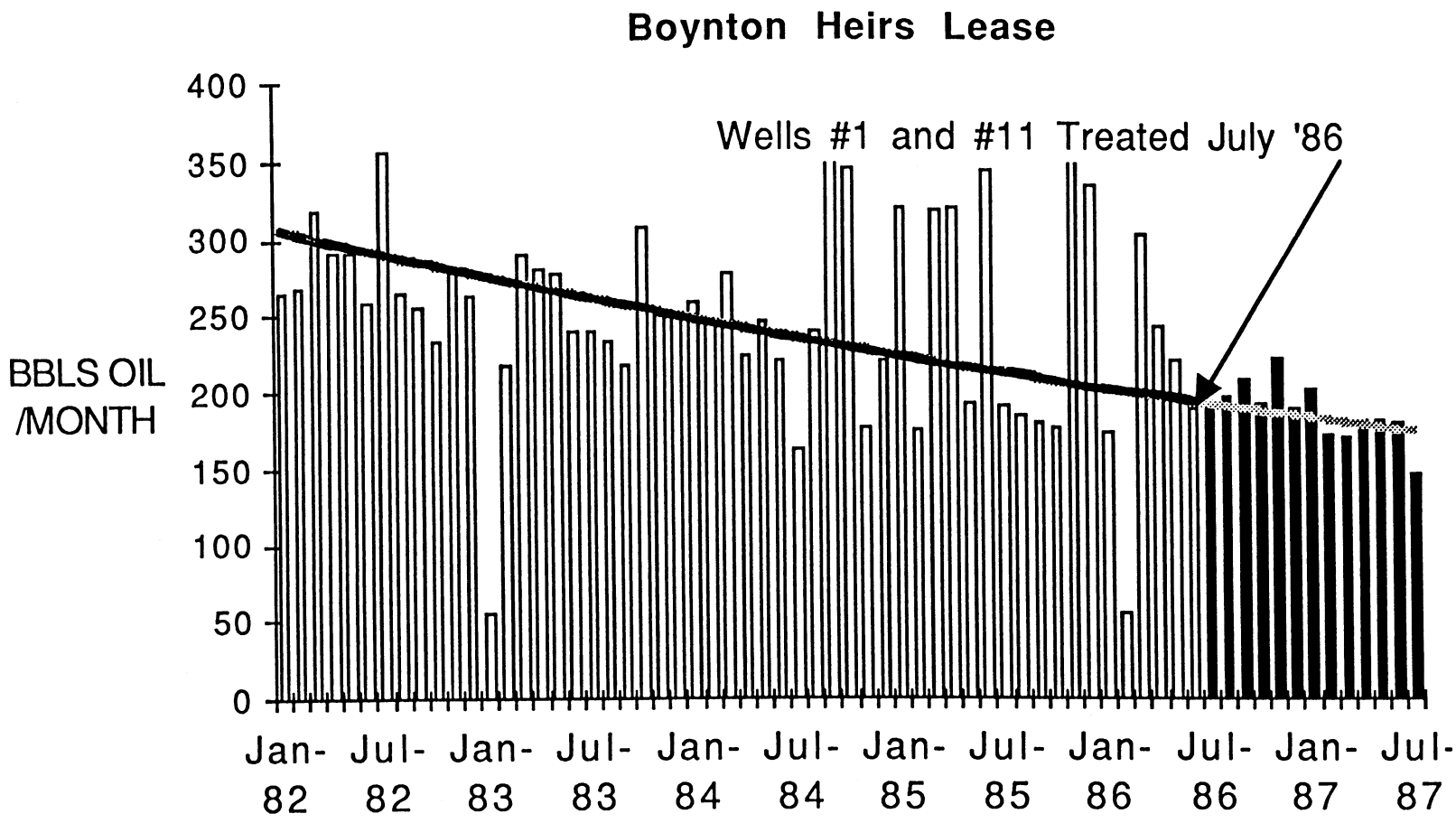



**Figure 10. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Boynton Heirs Lease, Longwood Field, Texas.** White bars = pre-treatment production, shaded bars = post-treatment production. The decline curve, indicated by the solid line, was calculated from 14 years of monthly pre-treatment oil production data. This curve was extrapolated into the future as a basis for post-treatment oil production comparison and is indicated by the stippled portion of the curve.

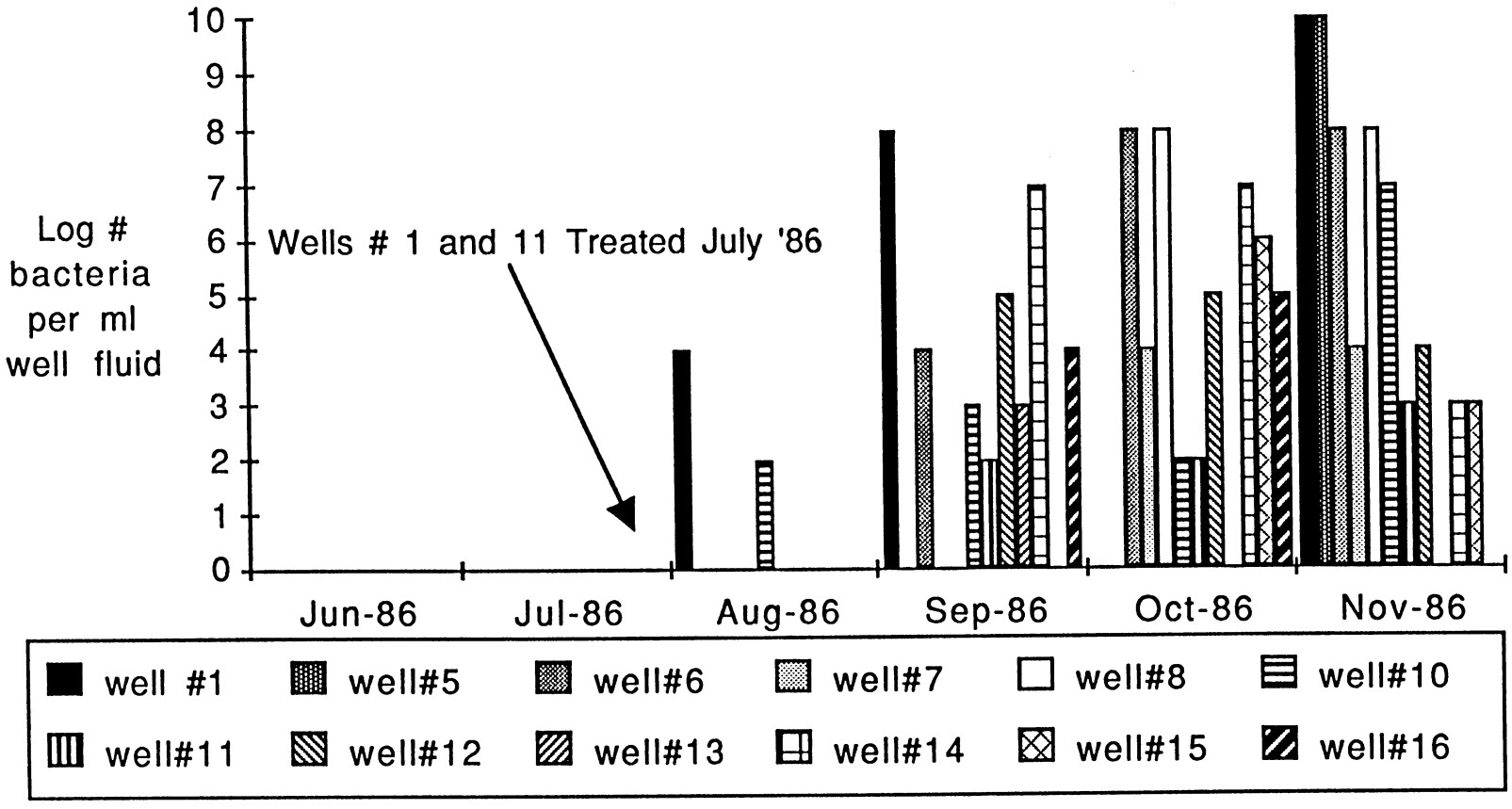



**Figure 11. Population of hydrocarbon degrading bacteria in twelve wells of the Boynton Heirs Lease, Longwood Field, Texas.** Well fluid was sampled from each "observation well" through time and the population of hydrocarbon degraders was determined by serial dilution enumeration as explained in the Materials and Methods section.

**PENNINGTON/STEVENSON LEASE**

The entire West Geff field consists of seven producing wells and two water injection wells. The MEOR system was applied through the two water injection wells. One lease covers two thirds of the entire structure and has the only production for this small field (Figure 12). The field has been producing oil for ten years, exhibiting a steady decline. Field-wide water production ranges between 60 to 100 bbls/day. Two water injection wells, which are located at the edge of the structural high of the oil producers, dispose of produced formation water back into the oil formation. All equipment is new or in good condition. Wells are located approximately 620 feet apart. Oil is collected in three separate batteries from seven producing wells. Well depths range from -2600 to -2618 ft. sub sea. Maximum downhole temperature is 110 degrees F. Wells are drilled through the sand body but completed only in the top 6-8 feet of the formation. This field is not treated with any chemicals. There is a minor paraffin problem. Reservoir data are summarized in Table 5.

**Treatment Procedure**

The MEOR system was injected in daily aliquotes for ten days in the following procedure:

1. Fill brine storage tank with 100 bbls ( 42 gal/bbl) of uncontaminated formation water.
2. Add nutrient and catalyst to formation water.
3. Mix bacteria in formation water until all bacteria are in suspension.
4. Add bacterial solution to mixture in tank and agitate until entire solution is consistent and all solids in suspension.
5. Sample injection mixture for lab analysis
6. Flow complete mixture into injection well.
7. Time rate of flow into well.

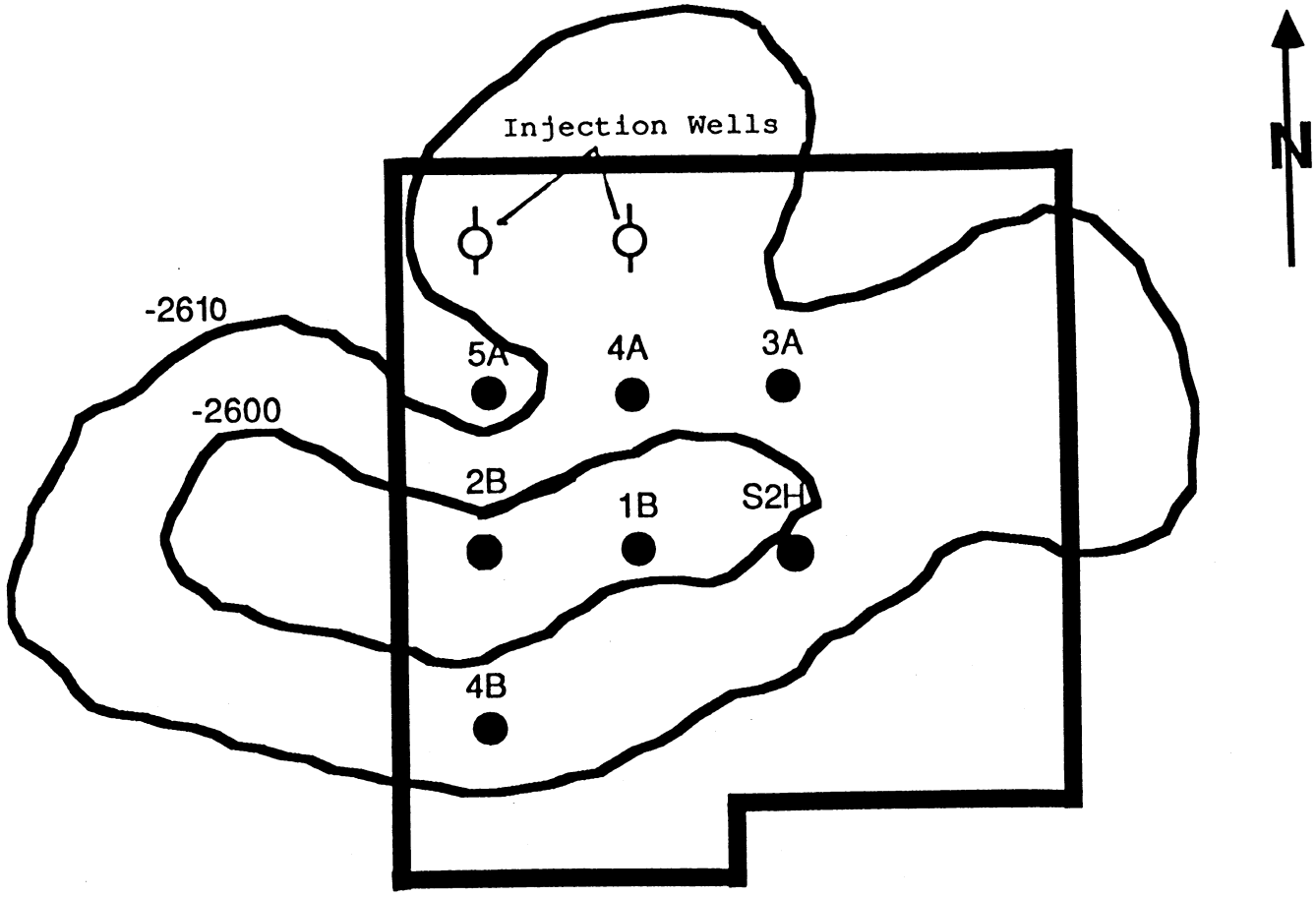
While this report was in review data from the Pennington/Stevenson lease continued to be collected and is reported with the data collected during the contract period. Pre- and post treatment production for the

Pennington/Stevenson lease is reported in Figure 13. Population levels of hydrocarbon degrading microorganisms from samples taken from the Pennington/Stevenson lease are reported on a well by well basis in Figure 14. Tabular data supporting Figures 13 and 14 are presented in the appendix.

The Pennington/Stevenson lease treatment was the last treatment program during the reported project and has proved to be the most successful in both terms of oil production and in quantity and quality of test data. The quality of background data for this reservoir is much better than that available for the previous treatment leases. Microbial transport patterns in the Pennington/Stevenson lease were unexpected, but not anomalous. Two production wells, 4B and 2B, located furthest from the injection wells, were the first to experience an increase in microbial population, within two weeks of treatment. Wells 5A, 4A and 3A, all adjacent to the injection wells, did not show increased microbial activity for up to a month after treatment. Again, the movement of microbes seems to be controlled, at least indirectly, by reservoir structure. The microbes apparently have been transported along the oil/water contact below the portion of the reservoir from which the wells completed in the crest of the dome produce. Within six weeks of treatment, however, all wells in the field showed a moderate level of microbial population increase. The increase in field-wide microbial population correlated well with a substantial oil production increase during the first four months. A decline in oil production during December 1987, and January, 1988 correlates with a decline in bacterial population across the field. It should be noted however, that three of the seven producing wells were down during December and January with power supply problems. Oil production has been stable at a rate of about 12 to 13 bbls/day for the last ten months, effectively defining a new decline curve for the field.

| | |
|---|---|
| **FIELD NAME** | West Geff |
| **LOCATION** | Wayne County, IL |
| **FORMATION** | Aux Vases Sandstone, L. Mississippian |
| **PERMEABILITY** | 5 - 165 md |
| **POROSITY** | 13-24 % |
| **RESERVOIR DEPTH** | 2600 - 2620 ft. sub sea |
| **GROSS PAY THICKNESS** | 10 - 20 ft. |
| **LITHOLOGY** | clay-rich, calcareous sandstone |
| **TRAP** | small isolated elongate dome |
| **OIL** | 36-38 API gravity |
| **WELL STIMULATION** | Sand frac with low volume HCL treatment |
| **WELL SERVICE** | No regular chemical treatments |
| **NUMBER OF WELLS** | 7 wells on one lease |
| **WELL SPACING** | 10 acre spacing |
| **PREVIOUS EOR** | none |

**Table 5. Reservoir data for the Pennington/Stevenson Lease, IL.**




Pennington/Stevenson Lease
Scale: 1" = 800'
Contour Interval = 10 ft.

**Figure 12. Structure-contour map on the base of the Lower Renault formation, Pennington/Stevenson Lease, West Geff Field, Illinois.** Injection wells are labeled. Observation wells = 3A, 4A, 5A, 1B, 2B, 4B, and S2H.

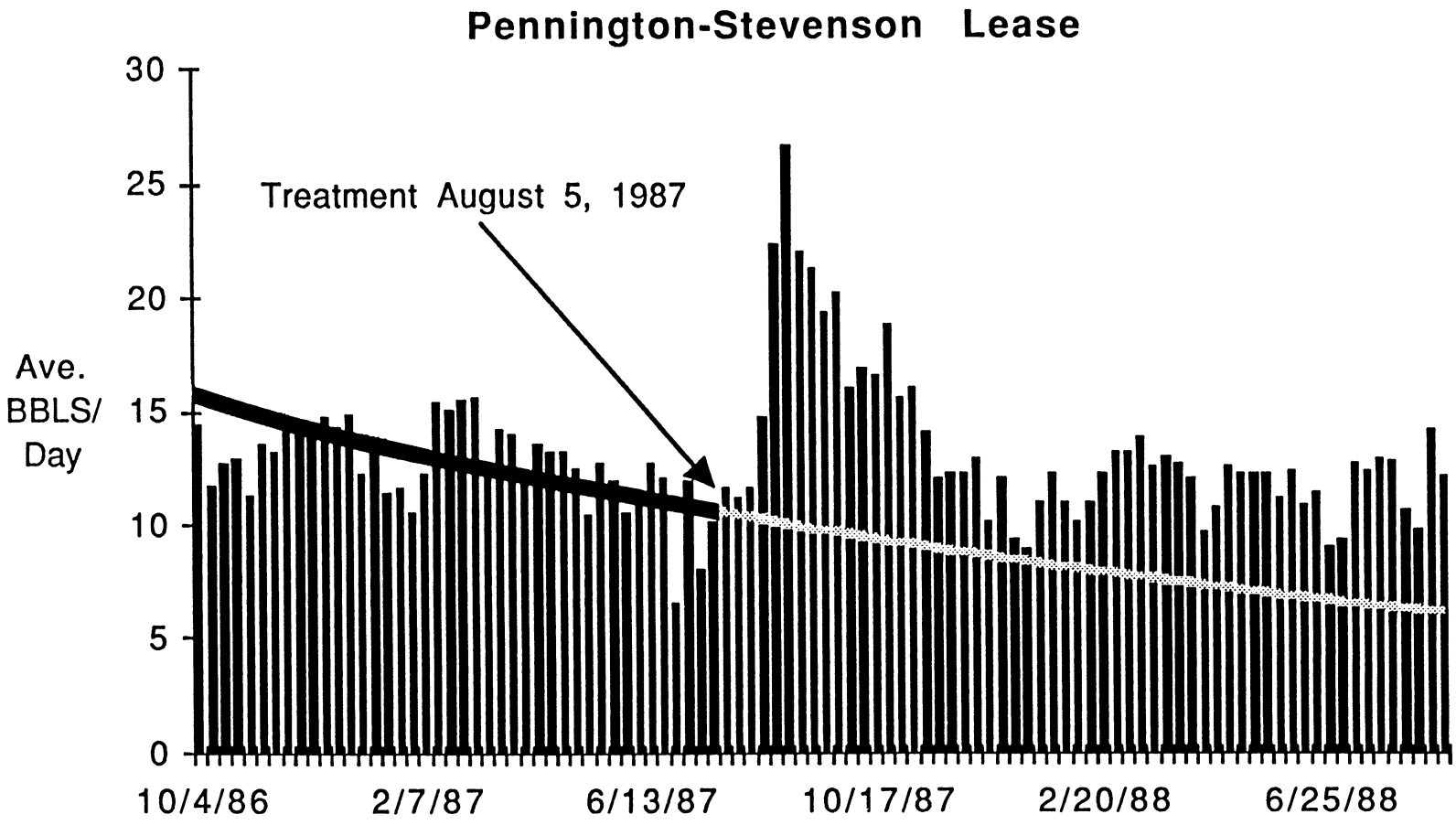



**Figure 13. Pre- and post-treatment oil production with actual and extrapolated decline curve for the Pennington/Stevenson Lease, West Geff Field, Illinois.** Each bar represents the average barrels of oil/day produced from the entire field for a given week. The decline curve, indicated by the solid line, was calculated from seventy-five weeks of pre-treatment oil production data. This curve was extrapolated into the future as a basis for post-treatment oil production comparison and is indicated by the stippled portion of the curve.

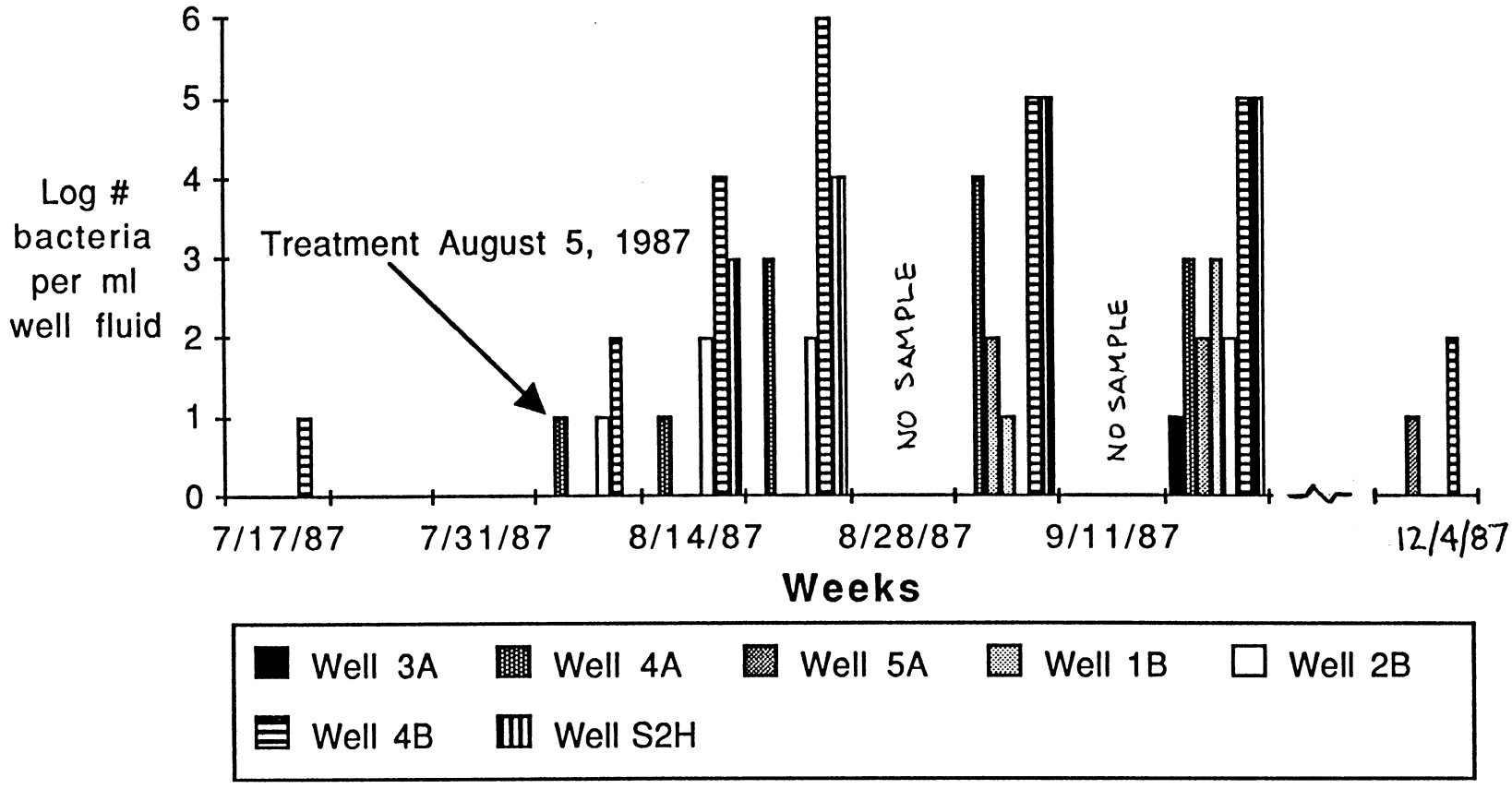



**Figure 14. Population of hydrocarbon degrading bacteria in seven wells of the Pennington/Stevenson Lease, West Geff Field, Illinois.** Well fluid was sampled weekly from each "observation well" and the population of hydrocarbon degraders was determined by serial dilution enumeration as explained in the Materials and Methods section. Tabular data supporting this graph is presented in the appendix.

# CHAPTER THREE.

## SUMMARY OF RESULTS, DISCUSSION AND CONCLUSIONS

This report contains the results of a series of field experiments demonstrating that the application of an MEOR system consisting of a mixture of aerobic hydrocarbon-oxidizing microorganisms and a biocatalyst, enhanced oil recovery in stripper reservoirs.

The primary objective of this project, to stimulate increased incremental oil production, was achieved in four of the five treated leases. Several other economic benefits, besides increased oil production, that could be indirectly related to the MEOR process, were reported by the field operators, but not quantitatively measured in the research program of this project. The operator of the LaVernia Field reported a decrease in the BS&W in the oil collection tanks and an increase of API gravity of the produced oil (three API points, as reported by Tesoro Oil Company, the oil buyer). These observations could have important financial implications for independent oil producers.

The results of the MEOR treatment in terms of incremental oil produced and of percent change from pre-treatment levels is summarized in Table 6.

The first of the series of tests was made in the Vorphal Lease well #7, in the LaVernia Field. The first significant finding was that oil production increased following treatment. Wells to the North-East of the treatment location showed substantial increases in microbial population. The increase in microorganisms was confined to wells up-dip from the treatment well. The increased oil production correlated with an increase in microbial population in the observed wells. The second significant observation was that the microorganisms moved at a very rapid rate through the formation. This represents an anomaly in the current theoretical paradigm of material transport in porous media and warrants further investigation. The third observation was that one treatment increased oil production for at least 15 months.

**Vorphal Lease Test Period = June, 1986-November, 1987**

| | |
|---|---|
| Total | 1743 BBLS OIL |
| -Expected | 1269 |
| Incremental | 474 |
| % Increase | 27 (plus or minus 3) |

**Wiseman Lease Test Period = January, 1987 - November, 1987**

| | |
|---|---|
| Total | 983 |
| -Expected | 770 |
| Incremental | 213 |
| % Increase | 22 (plus or minus 3) |

**Penshorn Lease Test Period = July, 1986 - November, 1987**

| | |
|---|---|
| Total | 1743 |
| -Expected | 1269 |
| Incremental | 474 |
| % Increase | 27 (plus or minus 3) |

**Boynton Heirs Lease Test Period = July, 1986 - July, 1987**

| | |
|---|---|
| Total | 2451 |
| -Expected | 2366 |
| Incremental | 85 |
| % Change | 3.5 (plus or minus 2) |

**Pennington/Stevenson Lease Test Period = July, 1986 - July, 1987**

| | |
|---|---|
| Total | 5439 |
| -Expected | 3227 |
| Incremental | 2212 |
| % Increase | 41 (plus or minus 0.1) |

**Table 6. Oil volumes produced and percent incremental oil increase by lease.**

The Boynton Heirs lease in east Texas was the second location for the MEOR treatment. This field was selected as an example of a carbonate reservoir. Observations of microbial transport rates and distances in the Vorphal lease were incorporated into the design of the Boynton Heirs test. In this substantially larger field, one well was selected down dip and one up-dip as the treatment wells. The results of microbial transport and population growth were generally similar to the LaVernia findings. However, the field did not significantly increase in oil production. The field operator again noted a small increase in API gravity as reported by the oil buyer. Pump maintenance as a result of paraffin buildup was reduced, but no quantitative measurements were taken.

The second field test further suggested that the orientation of the reservoir structure was an important controlling parameter of microbial transport.. To further test this hypothesis, a second test well on the Wiseman Lease was injected in the LaVernia Field. The treatment well was located at the lowest elevation in the formation. Microbial population and oil production both increased in the up-dip direction from the treatment well. The first arrival of microoganisms did not correlate with a sequential pattern of increasing distance of observation wells from the treatment well however. This may be attributed to reservoir heterogeneities or to characteristics of the reservoir we do not currently understand.

The results of the first two fields to be treated suggested that microorganisms could rapidly move through oil formations. As the microorganisms moved through the formation, oil production increased. The proper application of microorganisms can effectively change the productivity and value of the oil reservoir.

The combined results were then applied in designing an MEOR treatment for a small reservoir in the West Geff field in Central Illinois. This field produced a larger volume of water than the Texas fields and had in place a modified water flood in which the produced water was injected back to the lower part of the producing formation. The microorganisms and catalyst were added to the injected water. The results indicated a substantial increase in production with the associated movement of the microorganisms through the field. After about four months of increased production the yield of the field returned to its base decline

curve. During the following ten months oil production increased and maintained a steady 12-13 bbls/d, well above the expected oil production volume for this field. This has occurred without further treatment.

The results from the combined field tests supported the original concept of the action of the microorganisms in the release of oil from oil reservoirs. We tested two types of oil fields: clastic and carbonate reservoirs . The results were not similar: in the clastic reservoirs the microoganisms spread rapidly and their population increase was correlated with increased oil production. In the carbonate reservoir, the microbes spread rapidly, and populations increased in observation wells, but no significant production increase occurred. In the cases in which the MEOR treatment correlated with increased oil production, it is likely that oil release was associated with the activity of the microorganisms aided by the effects of the biocatalyst to overcome the inhibiting effects of high salinity and low oxygen levels in the reservoir. We believe that the mechanisms proposed originally in developing the process, including the microbial production of detergents and organic fatty acids from the degradation of the hydrocarbons, resulted in oil release. In addition, the microorganism numbers increased and persisted during the test period, supporting the view that they did grow in situ and that there may be a physical displacement of the oil by the bacteria.

## Suggestions for Improving Future Field Studies

Selection of the injection wells is a critical part of the success of the MEOR process. To determine the correct injection well, a thorough knowledge of the geological geometry and lithology of the producing reservoir is required. An analysis of structural, fluid flow, and lithologic trends allows the MEOR planner to choose the most appropriate treatment wells and to more accurately predict the transport direction and effect of the MEOR treatment.

Quantitative methods of measuring paraffin and BS&W reduction should be developed and incorporated into future field evaluations of MEOR processes.

The increase in API gravity reported by the oil buyer indicated that either the microorganisms were chemically

changing the oil or that the microorganisms were instrumental in releasing trapped primary oil that was similar to the original gravity of initial production oil. This observation should be tested under controlled conditions in by organic chemical analysis.and in future field tests.

Future research must measure oil production, bacterial population and transport on a well by well basis, instead of a lease-wide basis. Crucial information on the correlation of microbial activity in a specific well and increased oil production is lost without well by well control.

**Financial Viability of the Alpha MEOR Process in Commercialization**

Marginal oil fields with stripper-well production rates will soon become un-economic to operate if an inexpensive and effective EOR technology does not become available soon. Once shut-in, these wells will never be economic to reopen and will effectively be lost. On a regional scale, lost production from these wells hurts the energy economy, especially independent producers. On the national scale, lost stripper well reserves reduces the United States' flexibility in ensuring energy security.

MEOR stands as an economically attractive EOR technique to oil producers since the initial investment and cost of treatment are low, and the treatment appears to induce long term production effects. The cost of MEOR materials (bacteria, inorganic nutrients, formation brine, and biocatalyst) is relatively low and will continue to decline as production processes are refined, commercialized, and economies of scale are realized in the production of the components. The use of hydrocarbon degrading bacteria eliminates the expense of supplying carbon-based nutrients in the reservoir. The cost of application and investment in EOR equipment for the field operator can be held low. The treatment protocol can be designed to utilize existing equipment and application technology is simple, as illustrated in this report. Finally, the field results in this report indicate that a single MEOR treatment can have a long-term effect.

An objective of this project was to develop a treatment methodology that cost substantially less than the value of the incremental oil produced. Each field treatment was designed to utilize simple procedure, low labor requirements, in-place equipment and inexpensive materials.

The costs of treating the wells in this demonstration and research project are not equivalent to the costs of a mature commercial program. The volume of incremental oil produced in four of the five leases treated in this project suggest that a financially viable treatment cost could be achieved in a commercial framework. The information from these field tests is being used as the basis for developing an injection methodology that sets a goal of ten percent of incremental oil increase as the cost target on a fully commercialized basis.

## CONCLUSION

The Alpha MEOR process was proven effective in several field tests. The MEOR system increased oil production, perhaps reduced associated paraffin problems, and produced crude oil of a higher than expected API gravity. Field operators reported qualitative reduction of paraffin buildup in flow lines and reduction of BS&W in oil holding tanks. In the LaVernia and West Geff field tests, the cost of the MEOR application was less than the value of the incremental oil produced.

The field results supported preliminary laboratory findings that the microorganisms were stimulated by the catalyst, that the microorganisms were able to grow and be active in reservoir brines, and that the low oxygen levels in the oil reservoir environment was not a limiting factor of microbial activity. The results indicate that a properly designed MEOR program and careful selection of treatment wells can enhance oil production.

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# APPENDIX

Oil production data for all the leases treated and studied in this project are list in the following appendices.

Vorphal Monthly Total Oil Production from April 1986 to Nov. 1987

| Date | BBLS/M | Decline | |
|---|---|---|---|
| Jan-86 | 202 | 189 | Five new wells drilled, Dec'85,Jan'86 |
| Feb-86 | 134 | 174 | |
| Mar-86 | 208 | 162 | |
| Apr-86 | 142 | 149 | |
| May-86 | 143 | 138 | |
| Jun-86 | 122 | 127 | Alpha treated well #7 |
| Jul-86 | 108 | 118 | |
| Aug-86 | 110 | 109 | |
| Sep-86 | 131 | 100 | |
| Oct-86 | 115 | 93 | |
| Nov-86 | 104 | 85 | |
| Dec-86 | 106 | 79 | |
| Jan-87 | 101 | 73 | |
| Feb-87 | 96 | 67 | |
| Mar-87 | 103 | 62 | |
| Apr-87 | 93 | 58 | |
| May-87 | 94 | 53 | |
| Jun-87 | 89 | 49 | Treated five wells |
| Jul-87 | 99 | 45 | |
| Aug-87 | 80 | 42 | |
| Sep-87 | 62 | 39 | |
| Oct-87 | 68 | 36 | |
| Nov-87 | 62 | 33 | |
| Dec-87 | | 31 | |

Penshorn Total Monthly Production from April 1986 to November 1987

| Date | BBLS/M | Decline | Notes |
|---|---|---|---|
| Jan-86 | 410 | 349 | Five new wells drilled. |
| Feb-86 | 301 | 328 | |
| Mar-86 | 364 | 307 | |
| Apr-86 | 265 | 287 | |
| May-86 | 268 | 269 | |
| Jun-86 | 212 | 249 | Vorphal #7 Alpha treated |
| Jul-86 | 209 | 233 | |
| Aug-86 | 269 | 217 | |
| Sep-86 | 289 | 202 | |
| Oct-86 | 237 | 189 | |
| Nov-86 | 256 | 176 | |
| Dec-86 | 159 | 164 | Wiseman #20 treated |
| Jan-87 | 159 | 153 | |
| Feb-87 | 169 | 142 | |
| Mar-87 | 178 | 133 | |
| Apr-87 | 172 | 124 | |
| May-87 | 152 | 116 | |
| Jun-87 | 182 | 108 | Five Penshorn Wells treated |
| Jul-87 | 105 | 101 | |
| Aug-87 | 183 | 94 | |
| Sep-87 | 132 | 87 | |
| Oct-87 | 130 | 82 | |
| Nov-87 | 126 | 76 | |

**Wiseman Total Monthly Production from April 1986 to November 1987**

| Date | BBLS/M | Decline | Notes |
|---|---|---|---|
| Apr-86 | 196 | 199 | |
| May-86 | 181 | 184 | |
| Jun-86 | 175 | 170 | |
| Jul-86 | 158 | 158 | |
| Aug-86 | 141 | 146 | |
| Sep-86 | 144 | 135 | |
| Oct-86 | 127 | 125 | |
| Nov-86 | 111 | 116 | |
| Dec-86 | 63 | 108 | Alpha Treated well #20 |
| Jan-87 | 114 | 99 | |
| Feb-87 | 121 | 92 | |
| Mar-87 | 92 | 86 | |
| Apr-87 | 105 | 79 | |
| May-87 | 100 | 74 | |
| Jun-87 | 96 | 68 | |
| Jul-87 | 97 | 63 | Alpha Treated three Wiseman wells |
| Aug-87 | 83 | 58 | |
| Sep-87 | 54 | 54 | |
| Oct-87 | 54 | 50 | |
| Nov-87 | 67 | 46 | |

Boynton Heirs Lease, Longwood Field Monthly Production from January 1985 to June 1987

| Date | BBLS/M | Decline | Notes |
|---|---|---|---|
| Jan-85 | 321 | 265 | |
| Feb-85 | 176 | 260 | |
| Mar-85 | 320 | 254 | |
| Apr-85 | 321 | 249 | |
| May-85 | 193 | 243 | |
| Jun-85 | 345 | 238 | |
| Jul-85 | 192 | 233 | |
| Aug-85 | 185 | 228 | |
| Sep-85 | 180 | 224 | |
| Oct-85 | 178 | 219 | |
| Nov-85 | 352 | 214 | |
| Dec-85 | 335 | 210 | |
| Jan-86 | 175 | 205 | |
| Feb-86 | 57 | 201 | |
| Mar-86 | 303 | 197 | |
| Apr-86 | 243 | 192 | |
| May-86 | 221 | 188 | |
| Jun-86 | 190 | 184 | |
| Jul-86 | 193 | 180 | Wells #1 and #11 treated July 28-Aug 1 |
| Aug-86 | 198 | 176 | |
| Sep-86 | 210 | 172 | |
| Oct-86 | 194 | 169 | |
| Nov-86 | 223 | 165 | |
| Dec-86 | 191 | 162 | |
| Jan-87 | 203 | 158 | |
| Feb-87 | 173 | 155 | |
| Mar-87 | 171 | 152 | |
| Apr-87 | 183 | 148 | |
| May-87 | 183 | 145 | |
| Jun-87 | 181 | 142 | |
| Jul-87 | | 139 | |
| Aug-87 | | 136 | |

**Pennington/Stevenson Lease, Average Daily Production by Week**

| date | A wells (3) | B wells (3) | S 2H (1) | Total (7) | Decline |
|---|---|---|---|---|---|
| 1/4/86 | 7.3 | 16.4 | 0.0 | 23.8 | 22.7 |
| 1/11/86 | 7.6 | 15.0 | 0.3 | 23.0 | 22.4 |
| 1/18/86 | 7.8 | 15.3 | 1.3 | 24.4 | 22.2 |
| 1/25/86 | 7.6 | 15.3 | 0.3 | 23.3 | 22.0 |
| 2/1/86 | 8.3 | 12.8 | 0.2 | 21.3 | 21.8 |
| 2/8/86 | 8.5 | 15.6 | 0.8 | 24.9 | 21.6 |
| 2/15/86 | 8.1 | 13.0 | 0.0 | 21.1 | 21.4 |
| 2/22/86 | 7.6 | 15.5 | 0.0 | 23.1 | 21.2 |
| 3/1/86 | 6.8 | 16.0 | 0.0 | 22.8 | 21.0 |
| 3/8/86 | 5.8 | 9.8 | 0.0 | 15.6 | 20.8 |
| 3/15/86 | 6.7 | 12.9 | 0.0 | 19.6 | 20.6 |
| 3/22/86 | 7.6 | 13.0 | 0.0 | 20.6 | 20.4 |
| 3/29/86 | 7.5 | 12.8 | 0.0 | 20.3 | 20.2 |
| 4/5/86 | 7.1 | 13.1 | 0.0 | 20.3 | 20.0 |
| 4/12/86 | 7.0 | 13.0 | 0.0 | 20.0 | 19.8 |
| 4/19/86 | 6.6 | 13.0 | 0.0 | 19.6 | 19.6 |
| 4/26/86 | 7.1 | 14.9 | 0.2 | 22.2 | 19.5 |
| 5/3/86 | 6.3 | 12.0 | 0.3 | 18.6 | 19.3 |
| 5/10/86 | 5.8 | 12.0 | 0.2 | 18.0 | 19.1 |
| 5/17/86 | 5.6 | 12.8 | 0.2 | 18.6 | 18.9 |
| 5/24/86 | 5.7 | 11.6 | 0.2 | 17.5 | 18.7 |
| 5/31/86 | 5.8 | 12.3 | 0.5 | 18.6 | 18.6 |
| 6/7/86 | 7.1 | 12.7 | 0.2 | 20.0 | 18.4 |
| 6/14/86 | 7.6 | 12.5 | 0.3 | 20.4 | 18.2 |
| 6/21/86 | 7.9 | 12.4 | 0.5 | 20.8 | 18.0 |
| 6/28/86 | 7.1 | 12.5 | 0.3 | 19.9 | 17.9 |
| 7/5/86 | 7.6 | 11.1 | 0.3 | 19.1 | 17.7 |
| 7/12/86 | 7.1 | 11.3 | 0.3 | 18.8 | 17.5 |
| 7/19/86 | 6.8 | 9.0 | 0.3 | 16.2 | 17.4 |
| 7/26/86 | 7.0 | 10.1 | 0.3 | 17.5 | 17.2 |
| 8/2/86 | 6.2 | 11.6 | 0.3 | 18.1 | 17.0 |
| 8/9/86 | 6.3 | 8.3 | 0.3 | 14.9 | 16.9 |
| 8/16/86 | 9.8 | 7.0 | 0.3 | 17.1 | 16.7 |
| 8/23/86 | 9.3 | 8.6 | 0.3 | 18.3 | 16.6 |
| 8/30/86 | 8.5 | 8.3 | 0.2 | 17.0 | 16.4 |
| 9/6/86 | 7.6 | 7.8 | 0.2 | 15.6 | 16.2 |
| 9/13/86 | 7.1 | 8.0 | 0.0 | 15.1 | 16.1 |
| 9/20/86 | 4.7 | 8.5 | 0.0 | 13.2 | 15.9 |
| 9/27/86 | 7.8 | 8.6 | 0.0 | 16.5 | 15.8 |
| 10/4/86 | 6.5 | 8.0 | 0.0 | 14.5 | 15.6 |
| 10/11/86 | 5.7 | 6.2 | 0.0 | 11.8 | 15.5 |
| 10/18/86 | 5.8 | 7.0 | 0.0 | 12.8 | 15.3 |
| 10/25/86 | 5.5 | 7.5 | 0.0 | 13.0 | 15.2 |
| 11/1/86 | 4.7 | 6.7 | 0.0 | 11.4 | 15.0 |
| 11/8/86 | 5.3 | 8.3 | 0.0 | 13.6 | 14.9 |
| 11/15/86 | 5.3 | 8.0 | 0.0 | 13.3 | 14.8 |
| 11/22/86 | 5.7 | 8.6 | 0.0 | 14.4 | 14.6 |

| | | | | | |
|---|---|---|---|---|---|
| 11/29/86 | 5.6 | 8.6 | 0.0 | 14.3 | 14.5 |
| 12/6/86 | 6.2 | 8.2 | 0.0 | 14.3 | 14.3 |
| 12/13/86 | 6.3 | 8.5 | 0.0 | 14.8 | 14.2 |
| 12/20/86 | 6.2 | 8.2 | 0.0 | 14.4 | 14.1 |
| 12/27/86 | 6.0 | 9.0 | 0.0 | 15.0 | 13.9 |
| 1/3/87 | 5.8 | 6.5 | 0.0 | 12.3 | 13.8 |
| 1/10/87 | 5.7 | 7.8 | 0.0 | 13.5 | 13.7 |
| 1/17/87 | 4.7 | 6.8 | 0.0 | 11.5 | 13.6 |
| 1/24/87 | 4.2 | 7.5 | 0.0 | 11.6 | 13.4 |
| 1/31/87 | 4.8 | 5.8 | 0.0 | 10.6 | 13.3 |
| 2/7/87 | 4.0 | 8.3 | 0.0 | 12.3 | 13.2 |
| 2/14/87 | 7.2 | 8.3 | 0.0 | 15.5 | 13.0 |
| 2/21/87 | 6.5 | 8.5 | 0.2 | 15.1 | 12.9 |
| 2/28/87 | 6.7 | 8.3 | 0.5 | 15.5 | 12.8 |
| 3/7/87 | 6.3 | 8.2 | 1.2 | 15.6 | 12.7 |
| 3/14/87 | 6.0 | 6.2 | 0.3 | 12.6 | 12.6 |
| 3/21/87 | 6.3 | 7.5 | 0.5 | 14.3 | 12.4 |
| 3/28/87 | 6.2 | 7.5 | 0.4 | 14.0 | 12.3 |
| 4/4/87 | 5.7 | 6.7 | 0.2 | 12.5 | 12.2 |
| 4/11/87 | 6.3 | 6.8 | 0.5 | 13.6 | 12.1 |
| 4/18/87 | 6.2 | 6.7 | 0.5 | 13.3 | 12.0 |
| 4/25/87 | 6.3 | 6.5 | 0.5 | 13.3 | 11.9 |
| 5/2/87 | 5.5 | 6.6 | 0.5 | 12.6 | 11.7 |
| 5/9/87 | 3.5 | 6.7 | 0.3 | 10.5 | 11.6 |
| 5/16/87 | 6.2 | 6.3 | 0.3 | 12.8 | 11.5 |
| 5/23/87 | 5.0 | 6.5 | 0.5 | 12.0 | 11.4 |
| 5/30/87 | 4.0 | 6.3 | 0.3 | 10.6 | 11.3 |
| 6/6/87 | 5.3 | 6.0 | 0.2 | 11.5 | 11.2 |
| 6/13/87 | 6.3 | 6.2 | 0.3 | 12.8 | 11.1 |
| 6/20/87 | 6.0 | 5.8 | 0.3 | 12.1 | 11.0 |
| 6/27/87 | 0.0 | 6.3 | 0.3 | 6.7 | 10.9 |
| 7/4/87 | 5.7 | 6.0 | 0.3 | 12.0 | 10.8 |
| 7/11/87 | 1.8 | 6.0 | 0.3 | 8.1 | 10.7 |
| 7/18/87 | 4.3 | 5.5 | 0.3 | 10.1 | 10.6 |
| 7/25/87 | 5.7 | 6.0 | 0.0 | 11.6 | 10.5 |
| 8/1/87 | 5.7 | 5.6 | 0.0 | 11.3 | 10.4 |
| 8/8/87 | 5.5 | 6.0 | 0.2 | 11.6 | 10.3 |
| 8/15/87 | 8.1 | 6.5 | 0.2 | 14.8 | 10.2 |
| 8/22/87 | 10.3 | 12.0 | 0.2 | 22.4 | 10.1 |
| 8/29/87 | 7.3 | 19.3 | 0.2 | 26.7 | 10.0 |
| 9/5/87 | 5.2 | 16.6 | 0.3 | 22.1 | 9.9 |
| 9/12/87 | 6.8 | 14.3 | 0.3 | 21.4 | 9.8 |
| 9/19/87 | 6.5 | 12.8 | 0.2 | 19.4 | 9.7 |
| 9/26/87 | 7.1 | 12.8 | 0.3 | 20.3 | 9.6 |
| 10/3/87 | 3.8 | 12.0 | 0.3 | 16.1 | 9.5 |
| 10/10/87 | 5.3 | 11.3 | 0.3 | 16.9 | 9.4 |
| 10/17/87 | 5.5 | 10.8 | 0.3 | 16.6 | 9.3 |
| 10/24/87 | 8.3 | 10.4 | 0.2 | 18.9 | 9.3 |
| 10/31/87 | 5.2 | 10.0 | 0.5 | 15.7 | 9.2 |

| | | | | | |
|---|---|---|---|---|---|
| 11/7/87 | 5.7 | 10.0 | 0.5 | 16.1 | 9.1 |
| 11/14/87 | 4.6 | 9.3 | 0.2 | 14.1 | 9.0 |
| 11/21/87 | 2.8 | 8.8 | 0.5 | 12.1 | 8.9 |
| 11/28/87 | 4.0 | 8.3 | 0.0 | 12.3 | 8.8 |
| 12/5/87 | 4.8 | 7.5 | 0.0 | 12.3 | 8.7 |
| 12/12/87 | 3.8 | 8.8 | 0.3 | 12.9 | 8.7 |
| 12/19/87 | 3.2 | 7.0 | 0.0 | 10.1 | 8.6 |
| 12/26/87 | 4.2 | 8.0 | 0.0 | 12.1 | 8.5 |
| 1/2/88 | 2.5 | 7.0 | 0.0 | 9.5 | 8.4 |
| 1/9/88 | 2.7 | 6.3 | 0.0 | 9.0 | 8.3 |
| 1/16/88 | 3.5 | 7.6 | 0.0 | 11.0 | 8.3 |
| 1/23/88 | 3.3 | 8.5 | 0.5 | 12.3 | 8.2 |
| 1/30/88 | 4.0 | 6.8 | 0.2 | 11.0 | 8.1 |
| 2/6/88 | 3.0 | 6.6 | 0.5 | 10.1 | 8.0 |
| 2/13/88 | 3.7 | 7.1 | 0.2 | 11.0 | 8.0 |
| 2/20/88 | 3.3 | 8.8 | 0.2 | 12.3 | 7.9 |
| 2/27/88 | 4.8 | 8.1 | 0.3 | 13.3 | 7.8 |
| 3/5/88 | 5.0 | 8.0 | 0.3 | 13.3 | 7.7 |
| 3/12/88 | 5.0 | 8.7 | 0.3 | 14.0 | 7.7 |
| 3/19/88 | 4.7 | 7.8 | 0.2 | 12.6 | 7.6 |
| 3/26/88 | 4.7 | 8.0 | 0.5 | 13.1 | 7.5 |
| 4/2/88 | 4.8 | 8.0 | 0.0 | 12.8 | 7.4 |
| 4/9/88 | 4.3 | 7.8 | 0.0 | 12.1 | 7.4 |
| 4/16/88 | 2.7 | 7.0 | 0.0 | 9.7 | 7.3 |
| 4/23/88 | 4.3 | 6.5 | 0.0 | 10.8 | 7.2 |
| 4/30/88 | 4.8 | 7.6 | 0.2 | 12.6 | 7.2 |
| 5/7/88 | 5.0 | 7.3 | 0.0 | 12.3 | 7.1 |
| 5/14/88 | 5.3 | 7.0 | 0.0 | 12.3 | 7.0 |
| 5/21/88 | 5.3 | 7.0 | 0.0 | 12.3 | 7.0 |
| 5/28/88 | 4.2 | 7.1 | 0.0 | 11.3 | 6.9 |
| 6/4/88 | 5.0 | 7.5 | 0.0 | 12.5 | 6.8 |
| 6/11/88 | 4.3 | 6.6 | 0.0 | 11.0 | 6.8 |
| 6/18/88 | 3.8 | 7.2 | 0.5 | 11.5 | 6.7 |
| 6/25/88 | 2.5 | 6.1 | 0.5 | 9.1 | 6.6 |
| 7/2/88 | 3.3 | 5.8 | 0.3 | 9.4 | 6.6 |
| 7/9/88 | 5.2 | 7.3 | 0.3 | 12.8 | 6.5 |
| 7/16/88 | 5.2 | 7.0 | 0.3 | 12.4 | 6.5 |
| 7/23/88 | 5.5 | 7.2 | 0.3 | 12.9 | 6.4 |
| 7/30/88 | 5.3 | 7.3 | 0.3 | 12.9 | 6.3 |
| 8/6/88 | 3.8 | 6.7 | 0.3 | 10.8 | 6.3 |
| 8/13/88 | 5.2 | 4.7 | 0.0 | 9.8 | 6.2 |
| 8/20/88 | 7.2 | 7.2 | 0.0 | 14.3 | 6.2 |
| 8/27/88 | 4.7 | 7.3 | 0.3 | 12.3 | 6.1 |
| 9/3/88 | 4.7 | 5.0 | 0.3 | 10.0 | 6.1 |
| 9/10/88 | 4.8 | 6.5 | 0.3 | 11.6 | 6.1 |

Martin Vorphal lease, La Vernia field, La Vernia Texas
Population of bacteria reported as the log number of bacteria per ml formation water

| Date | Well # 1A | Well # 7 | Well # 8 | Well # 9 | Well #13 | Well # 3 | |
|---|---|---|---|---|---|---|---|
| May-86 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Jun-86 | 0 | 6 | 0 | 4 | 8 | 0 | Well #7 treated |
| Jul-86 | 8 | 0 | 8 | 5 | 0 | 0 | |
| Aug-86 | 8 | 3 | 1 | 3 | 4 | 0 | |
| Sep-86 | 2 | 0 | 0 | 0 | 0 | 0 | |
| Oct-86 | 0 | 0 | 0 | 0 | 0 | 1 | |
| Nov-86 | 1 | 0 | 0 | 0 | 0 | 0 | |
| Dec-86 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Jan-87 | 0 | 2 | 3 | 0 | 1 | 0 | |
| Feb-87 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Mar-87 | 0 | 7 | 2 | 7 | 2 | 0 | |
| Apr-87 | 0 | 0 | 0 | 0 | 0 | 0 | |
| May-87 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Jun-87 | 0 | 7 | 2 | 7 | 2 | 0 | 4 wells treated |

Wiseman Lease, La Vernia Field, Tx
Population of hydrocarbon degrading bacteria in five wells

| Date | Well#16 | Well#17 | Well#18 | Well#19 | Well#20 | |
|---|---|---|---|---|---|---|
| Aug-86 | 0 | 0 | 0 | 0 | 0 | |
| Sep-86 | | | | | | |
| Oct-86 | 1 | 0 | 0 | 0 | 0 | |
| Nov-86 | 0 | 1 | 0 | 0 | 0 | Injection on 11.19.86 |
| Dec-86 | | 1 | 2 | 0 | 3 | |
| Jan-87 | 7 | 4 | 4 | 3 | 5 | |
| Feb-87 | | | | | | |
| Mar-87 | 7 | 6 | 6 | 4 | 8 | |
| Apr-87 | | | | | | |
| May-87 | | | | | | |
| Jun-87 | 0 | 5 | 4 | 3 | 2 | |

Boynton Heirs Lease, Population of Hydrocarbon degrading bacteria in 12 wells
Population reported in log number of bacteria per ml of reservoir fluid.
Data from Alpha Environmental, Austin, Texas.

| Date | Treatment Wells | Observation Wells | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 11 | 5 | 6 | 7 | 8 | 10 | 12 | 13 | 14 | 15 | 16 |
| June | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| July | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| August | 4 | nd | 0 | 0 | 0 | nd | 2 | 0 | nd | 0 | nd | 0 |
| Sept | 6 | 2 | nd | 4 | 0 | 0 | 3 | 5 | 3 | 7 | 0 | 4 |
| Oct | nd | 2 | nd | 8 | 4 | 8 | 2 | 5 | 0 | 7 | 6 | 5 |
| Nov | 9 | 3 | 9 | 8 | 4 | 8 | 7 | 4 | 0 | 3 | 3 | 0 |

Pennington/Stevenson Lease, Wayne County, IL

Population of hydrocarbon degrading bacteria in seven wells, reported in log number of bacteria per ml reservoir flui

| Date | Well 3A | Well 4A | Well 5A | Well 1B | Well 2B | Well 4B | Well S2H | |
|---|---|---|---|---|---|---|---|---|
| 7/17/87 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | |
| 7/24/87 | | | | | | | | |
| 7/31/87 | | | | | | | | Treatment 8/5/87 |
| 8/7/87 | 0 | 1 | 0 | 0 | 1 | 2 | 0 | |
| 8/14/87 | 0 | 1 | 0 | 0 | 2 | 4 | 3 | |
| 8/21/87 | 0 | 3 | 0 | 0 | 2 | 6 | 4 | |
| 8/28/87 | | | | | | | | |
| 9/4/87 | 0 | 4 | 2 | 1 | 0 | 5 | 5 | |
| 9/11/87 | | | | | | | | |
| 9/18/87 | 1 | 3 | 2 | 3 | 2 | 5 | 5 | |
| 11/27/87 | | | | | | | | |
| 12/4/87 | 0 | 0 | 1 | 0 | | 2 | 0 | |



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