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A Commercial Microbial Enhanced Oil Recovery Technology: Evaluation of 322 Projects

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ABSTRACT

This paper discusses a data-base of information collected from 322 projects, all treated with the same Microbial Enhanced Oil Recovery process. An analysis of the data quantifies the effectiveness and economics of this particular process, and is a source of information useful for predicting treatment response in any given reservoir.

INTRODUCTION

During the past ten years, much attention has been focused on the evaluation of individual field applications of a variety of different Microbial Enhanced Oil Recovery ("MEOR") processes. Little, if any, data has been published that reports the results of a single MEOR technology applied across a variety of reservoirs and production strategies. Consequently, oil producers have been resistant to accepting individual, commercial MEOR technologies because they perceive that MEOR has not been subjected to enough extensive, widespread field testing.

This paper will present data illustrating the effectiveness of a single MEOR process that has been successfully applied and results quantified in a large number of commercial projects, representing more than 2,000 producing oil wells in the United States. Since these projects represent such a large number of oil reservoirs, comprising a wide variety of bottomhole conditions, formations, and drive types, it is now possible to provide much needed data to producers that can be used to predict how any given reservoir will respond to this MEOR process.

A data-base, which is believed to be the first of its kind, has been created with data collected from the broad use of this MEOR system. The data has been organized to isolate ranges of individual reservoir characteristics like lithology, porosity, permeability, crude oil gravity, etc. so that they can be compared to the corresponding response in oil production observed after implementing MEOR. Information generated with the data-base can be used by producers as a tool to determine which of their reservoirs may be the best candidates for this process. It also provides oil producers with information they can use to make informed, economic decisions when considering the feasibility of utilizing this MEOR process once a candidate reservoir has been identified.

BACKGROUND

Almost 3 million oil wells have been drilled nationwide within the United States and thus far more than 500 billion barrels ("bbls.") of oil have been discovered. Primary and secondary recovery, using conventional technology, are expected to recover only 33% (~175 billion bbls.) of the 500 billion barrels of original oil in place ("OOIP").[1] Approximately 150 billion (86%) of those 175 billion recoverable barrels have already been extracted by producers, leaving a domestic proved recoverable

References and illustrations at end of paper.

reserve base of ±25 billion barrels.[2] In the past, producers have maintained or increased the recoverable reserve base through drilling. But now, since most of the major oil traps have been discovered, there are fewer and fewer drilling locations available. Therefore, it is now necessary for producers to consider the roughly 325 billion bbls. of oil that remain trapped in reservoirs, after primary and secondary recovery efforts have been exhausted, as a source to maintain or increase the recoverable reserve base. This is the oil that has been targeted by this MEOR technology.

Even as early as 1926, the scientist Beckman recognized that most of the world's oil reserves would remain trapped within their reservoirs and that methods had to be developed to extract them. He hypothesized that microorganisms could be the answer when he wrote..."**Without doubt the world's supply of oil is limited. It is, however, recognized that a large percentage of oil in the earth still remains after an oil well has stopped flowing, probably because the friction of the viscous oil against the sand is too great to permit the flow to continue. Now is it not possible that if a feeding medium inoculated with enzyme-producing bacteria were left in contact with the remaining oil, the enzymes produced might change the viscosity and gravity of the oil and cause a fresh flow?**"[3]

Based on the fact that the potential for MEOR was recognized nearly 70 years ago, one would assume that this technology might be in widespread use today. Unfortunately, however, the general perception is just the opposite. This perception is largely due to inadequate methods for transfer of technology within the oil industry. For example, if one were to rely on oil industry publications as their primary source of information with respect to emerging technology, the following would have been read in a September 1994 article featuring the current use of enhanced oil recovery processes in the United States..."**Microbial EOR has not caught on, although pilot tests have demonstrated that the process is feasible in low temperature, low salinity, shallow reservoirs. Only one respondent indicated having an ongoing project in the U.S.**"[4] The casual reader would probably have derived the following conclusions from this article: 1) that MEOR can only be used in shallow reservoirs with low temperature and low salinity, and 2) that MEOR is not currently being utilized by U.S. producers. Data will be presented to substantiate that the rigorous, commercial field testing of this MEOR process by U.S. producers is extensive and that its use is not as constrained by reservoir conditions as this article implies.

MECHANISMS AND MATERIALS

Existing primary and secondary oil recovery technology will be successful at recovering only 33% of the OOIP because the remaining 67% of oil is either too viscous to flow or because the strength of the bond which exists between the oil and surrounding reservoir rock (surface tension) is too high. Conventional chemicals, like solvents and surface-active agents ("surfactants"), are known to improve the mobility of oil and have been used for EOR purposes. Solvents decrease oil viscosity, making it thinner and more flowable, and surfactants break the bond between oil and rock or oil and water by reducing their surface tension to one another. However, these conventional chemicals can be referred to as "dead" materials because they rely totally on fluid movement through the reservoir as their only means of transport.

In a waterflood, these chemicals are transported through the reservoir by the water injection stream, usually contacting only areas where the oil has already been effectively removed with water; or the chemicals are "spent" before they ever reach those areas where they are most needed.

Results from chemical solvent and surfactant "squeeze" jobs performed on single wells in their primary phase of production, have been short lived because the chemicals simply cannot contact enough of the reservoir rock to have a long term effect. Since most reservoirs are heterogeneous, the chemicals are unevenly distributed vertically, following the paths of least resistance, which are usually the areas that are lowest in residual oil saturation.

It has been known for decades that specialized, naturally-occurring microorganisms are capable of metabolizing hydrocarbons to produce organic solvents, like alcohol's and aldehyde, fatty acid surfactants, and a host of other biochemicals that are known to be effective at encouraging oil mobility. Therefore, it seems only reasonable to assume that if these living, motile, organisms were injected into an oil producing reservoir, they could transport themselves into areas of high residual oil saturation, and mobilize oil previously considered to be immobile and unrecoverable. The process should be effective because the microorganisms continuously produce desirable biochemicals in the areas where they are most needed, the reservoir pore spaces.

Components of the MEOR Process

Although researchers have recognized the potential of MEOR for many years, few have been able to develop a process to overcome the environmental and chemical barriers to its use, which exist in an oil reservoir. However, the MEOR process described here consists of special biological and chemical materials, and application techniques that have been designed and are proved to overcome these reservoir environmental and chemical obstacles to microbial growth.

There are three components of this MEOR process: hydrocarbon-utilizing bacteria, inorganic nutrients, and a proprietary biocatalyst.

The naturally-occurring, hydrocarbon-utilizing bacteria have been collected, over the years, from a broad range of petroleum enriched environments where significant microbial activities have been observed, and those bacteria most efficient at metabolizing hydrocarbons have been isolated for use in this process. These specially selected species are grown, in laboratory conditions, exclusively on a blend of hydrocarbons to produce mixed culture communities. The resulting product, in the form of a dry powder with a concentration of 450 trillion cells per pound, has a minimum viable shelf life of one year.

These MEOR bacteria are simple, single-celled organisms that are a maximum of one micron (0.00004 inches) in length and width. They are comprised of a liquid center, which is 95% water, surrounded by a cell wall made of protein. They have no bony or skeletal structure. These bacteria do not produce hydrogen sulfide gas nor do they produce extra-cellular "slime". Since the cell wall self-destructs when the organism dies, no solid cellular debris remains. Tests by public health laboratories verify that the mixed culture of bacteria is safe to handle and poses no threat to plants, animals, or humans.

Special, granular inorganic nutrients that function as vitamins and minerals to the MEOR bacteria include nitrogen, potassium, phosphorus, and trace elements. These inorganic nutrients are a component of this MEOR process because they enable the bacteria to more efficiently metabolize the hydrocarbon food source.

The biocatalyst is a liquid that closely resembles water. It is a proprietary enzymatic stimulant which enhances microbial activity, increases the bacteria's tolerance to high salinity, and apparently maximizes the microorganisms ability to use oxygen.

Oil Release Mechanism

This MEOR process utilizes an oil release mechanism which may be roughly summarized as follows: the three components of the MEOR process are blended and injected into the target reservoir. In the reservoir, the MEOR bacteria transport themselves through water and congregate in pore spaces at oil/rock and oil/water interfaces where they metabolize a very small amount of oil to produce organic biochemicals like solvents, surfactants, weak acids, and carbon dioxide. These biochemicals reduce oil viscosity, decrease interfacial surface tension between the oil/rock and oil/water surfaces, and may also restore effective permeability by removing paraffin and scale blockage from pore throats. Finally, new microbial cells are produced and the process continues. The net effect of the entire MEOR process causes previously immobile, unrecoverable oil to become mobile so that it is now available to be swept into producing wellbores, causing an incremental improvement in oil production. The effect that each biochemical by-product has on the reservoir is summarized below in Table 1.

Table 1

By-Product	Effect
Solvents	*Dissolves in oil to reduce viscosity *Improves effective permeability by dissolving and removing heavy, long-chain hydrocarbons from pore throats
Surfactants	*Reduces interfacial tension between oil and rock/water surfaces
Acids	*Improves effective permeability by dissolving carbonate precipitates from pore throats *Etch quartz and carbonate surfaces to improve porosity and permeability *Carbon dioxide produced from chemical reaction between acid and carbonate reduces oil viscosity and causes oil droplet to swell.
Gases	*Dissolves in oil to reduce viscosity *Encourages physical displacement of oil droplet by causing it to swell
New Microbial Cells	*Physically displace oil by growing between oil and rock/water surface

It should be mentioned that there are other benefits realized from this MEOR process in addition to a quantitative enhancement in recoverable oil reserves. Generally, it is common to observe a qualitative improvement in the efficiency of oil production. Many operational problems associated with paraffin, emulsion, scale, and corrosion, to name a few, can be controlled with conventional solvent and surfactant based chemicals. Since these MEOR bacteria produce organic solvent and surfactant by-products from metabolizing oil, it is reasonable to expect that these common operational problems may be significantly reduced.

This process has also been qualified for Enhanced Oil Recovery/Improved Oil Recovery tax incentives currently offered by many states in the United States. Producers have successfully used this MEOR process to access these tax incentives. A few of the states currently offering these incentives are Kansas, Louisiana, Mississippi, Montana, New Mexico, Oklahoma, Texas, Utah, and Wyoming.

MEOR TREATMENT PROCEDURE

Over the past seven years, this process has been systematically applied to a large number of projects including MEOR treatment of single wells still in their primary phase of production, and microbial enhancement of existing waterfloods.

All project sites were pre-screened for MEOR compatibility and quality of reservoir and production data. Pre-treatment produced and, when applicable, injection fluid samples were collected and tested for 1) compatibility with the MEOR system and, 2) to establish the base-line population of indigenous hydrocarbon-utilizing bacteria. Pertinent field and reservoir data was collected and studied, so that treatment strategies specific to each project, could be designed.

Tabular, historical oil production data was collected for each project. "Best fit" decline trend curves were computer-generated through the pre-MEOR oil production data and extrapolated to establish the base-line for expected future production without the affects of MEOR.

Single Well Projects

MEOR is applied to single wells in order to stimulate and enhance oil production from 1) only the well which has been treated or, 2) the treated well plus nearby offsets producing from the same reservoir. An MEOR solution is placed into the near-wellbore reservoir with a procedure that closely resembles a matrix-squeeze approach. An MEOR biological treatment volume capable of filling 100% of the reservoir pore space across the entire net perforated height for a given depth into the reservoir is calculated mathematically. The MEOR solution is blended and pumped, by truck, down the casing-tubing annulus of the well, followed by a volume of fluid (usually lease oil or water) adequate to displace the entire biological solution through the perforations and into the target reservoir. The well is then shut-in for a period of time, normally ranging from 24 hours to seven days, before it is returned to production. This treatment procedure, which is repeated once every three to six months, provides the microorganisms the opportunity to migrate deeper into the reservoir so that they can contact more oil. A schematic diagram of a single well MEOR treatment is presented in Figure 1. The MEOR biological treatment volume is determined according to Equation (1).

$$\frac{\pi r^2 h\phi(1.2)}{5.615} \quad \text{................................(1)}$$

Microbial Enhanced Waterflooding

MEOR is applied to existing waterfloods to improve their performance and enhance oil production by treating the entire reservoir. MEOR materials are added, either continuously or periodically, to the water holding tanks at the primary injection stations. The biological materials are then transported into the reservoir with the injection water through the existing water injection system at normal rate and pressure. Little or no modification of the existing water injection equipment is required to accommodate the MEOR process and normal waterflooding operations are not interrupted. A schematic diagram of a waterflood MEOR treatment is presented in Figure 2.

Project Monitoring and Evaluation

After an MEOR project has begun, its status is determined by monitoring MEOR bacteria population and oil production with the passing of time.

The population of hydrocarbon-utilizing bacteria present in produced fluid samples after beginning MEOR is monitored and compared to the base-line population of indigenous hydrocarbon-utilizing bacteria which existed before MEOR was begun. Normally, hydrocarbon-utilizing bacteria population slowly increases with time after beginning MEOR. Monitoring produced fluids for hydrocarbon-utilizing bacteria population is also used to determine the rate and extent of their penetration through the reservoir after injection has begun.

Oil production is monitored and compared to the base-line production volumes projected and defined by the extrapolation of the historical decline trend curve. Positive response (incremental oil production) resulting from MEOR is defined as actual oil production in excess of the volumes projected by the historical decline trend curve extrapolation. The term "incremental production" is defined in Equation (2).

$$I = P2 - P1 \quad \text{................................(2)}$$

Tabular oil production data has been converted to semi-logarithmic line-graph form for each project in the data-base using a Microsoft Excel, Version 4.0 computer software program. These production graphs have been analyzed in order to determine if oil production has been influenced after beginning MEOR treatment. An example of a production graph defining incremental oil production is presented graphically in Figure 3.

THE MEOR DATA-BASE

The MEOR data-base has been created using a Microsoft Excel, Version 4.0 computer software program. Each project has been listed alphabetically by operator name, followed by project lease name, field name, location, recovery classification, and number of wells in the project. Pertinent reservoir data including lithology, porosity, permeability, depth, temperature, and pressure have been entered as well as reservoir fluid properties such as oil gravity, brine salinity, and percent water-cut. Incremental oil production resulting from MEOR has been entered for each project, expressed in barrels and as a percentage.

RESULTS FROM EVALUATION OF DATA-BASE

In order for a project to be considered in this statistical evaluation of the data-base, the following were required:

- A minimum of twelve months of consistent, historical pre-MEOR treatment oil production data.
- A minimum of 12 months of post-MEOR treatment oil production data.
- Documentation that incremental oil production includes only that oil produced as a result of MEOR, and not as a result of a workover, recompletion, increase in water injection rate or pressure, in-field drilling, or any other outside variable.

The information in the data-base was analyzed to determine how many of the projects responded to MEOR with a positive incremental increase in oil production. According to the data, 78% of all projects undertaken have demonstrated arrested or decreased decline rate and production of incremental oil after initiating MEOR. The other 22% of the projects indicated that MEOR had no influence on oil production. No decrease in oil production has ever been observed as a result of this MEOR process. On average, MEOR has caused 36% more oil to be produced than would have otherwise been produced without this process. Normally, there is an indication that MEOR is having a positive effect on oil production within six months of the first treatment, and certainly within 12 months. Figures 4 through 14 are production graphs from actual MEOR projects that illustrate the different responses in oil production which have been observed after implementing this process.

Technological Evaluation

The data-base has been used to determine if any one reservoir characteristic is a dominating factor in determining the applicability of this MEOR process. Bar graphs have been constructed to illustrate the average incremental increase in oil production observed in various lithology, porosity, permeability, oil gravity, formation temperature, and water-cut.

Figure 15 illustrates that approximately 73% of all MEOR projects have been conducted in sandstone reservoirs and that 27% have been conducted in carbonate reservoirs.

Figure 16 suggests that reservoir lithology neither enhances or impedes the effectiveness of MEOR; therefore, it should not necessarily be considered a limiting factor to its use.

Figure 17 indicates that as reservoir porosity increases, the percent incremental increase in oil production which can be expected from MEOR decreases. However, it should be noted that even in the highest porosity range, the average percent incremental increase in oil production has been nearly 20% and should, therefore, not be considered a limiting factor.

Figure 18 illustrates that as reservoir permeability increases, the percent incremental increase in oil production which can be expected from MEOR also increases. This has been generally true with the exception of reservoirs exhibiting average permeability in excess of 501 millidarcies. Since there have been only three recent MEOR projects conducted in reservoirs with permeability in excess of 501 millidarcies, it is possible that the lower average presented in this range is due to a lack of data. As more projects are conducted in this range and as more data is collected from current projects, it is anticipated that the average percent incremental oil increase will rise. The lower average observed in this range may also indicate that, due to the high permeability, a large percentage of the OOIP has already been recovered, leaving little to be recovered with EOR technologies.

Figure 19 suggests that as oil gravity decreases, the percent incremental increase in oil production which can be expected from MEOR increases. Although no MEOR projects have been conducted in reservoirs containing crude oil gravity of less than 20° API, the trend indicates that the best results from this MEOR process can be expected in this range.

Figure 20 indicates that reservoir temperature has not been a limiting factor with respect to MEOR. It appears that microorganisms can survive temperatures present in most oil reservoirs.

Finally, Figure 21 illustrates that the percent of total fluid produced in the form of water neither enhances or impedes the effectiveness of MEOR; therefore, it should not necessarily be considered a limiting factor to its use.

The data indicates that this MEOR technology has been effective in a broad range of reservoir environments. It does not appear there is any single reservoir characteristic that is a dominant factor in determining the applicability of this MEOR process.

Economical Evaluation

An economic section of the data-base calculates the net value of the cumulative incremental oil produced from each project as a result of MEOR according to Equation (3).

NV = bbls. incremental oil x oil price x NRI x tax.............(3)

The net monetary value of the incremental oil produced from each project as a result of MEOR has been divided by the total amount of money invested in each project to determine producers return on investment. Equation (4) has been used to calculate return on investment.

ROI = net Value ÷total investment....................(4)

According to the data, the average return on investment to the producer has been 5:1 after the first 24 months of the MEOR project and the average time to project payback has been six months.

This MEOR process is affordable. The cost of the process ranges from $0.25 to $0.50 per barrel of oil produced at the time MEOR begins and does not go up as oil production increase as a result of MEOR. The cost for each incremental barrel of oil produced as a result of MEOR can be calculated according to Equation (5).

Cost/bbl. = Total Investment ÷bbls. incremental oil.....(5)

According to the data, this MEOR process can cause additional oil to be produced for a cost of only $2.00 per incremental barrel.

CONCLUSIONS

1. This MEOR process has been extensively field tested in 322 commercial projects representing more than 2,000 producing oil wells in the U. S.
2. Statistical analysis of economic and technological data gathered from the broad use of this commercial technology provides producers with a tool to more accurately forecast the risked, economic potential of MEOR in any given reservoir.
3. This MEOR process contacts and mobilizes residual reservoir crude oil that would otherwise remain immobile and unrecoverable.
4. This MEOR process overcomes the environmental and chemical conditions that exist in oil reservoirs that are normally barriers to microbial growth.
5. This MEOR process is safe for the oil field and the environment. It poses no threat to plants, animals, or humans.
6. This MEOR process has been observed to significantly reduce common operational problems associated with paraffin, emulsion, scale, and corrosion.
7. This MEOR process has been qualified for Enhanced Oil Recovery/Improved Oil Recovery tax incentives currently offered by many states in the U.S. and has been used successfully by producers to access these tax incentives.
8. MEOR treatment of single producing wells still in their primary phase of production and microbially enhanced waterflooding is economically and technologically feasible.
9. MEOR is easily applied, usually requiring little or no modification of existing production/injection equipment to accommodate it.
10. The status of MEOR can be easily monitored.
11. This MEOR process has been effective at incrementally improving oil production. 78% of all projects undertaken have demonstrated a positive incremental increase in oil production after initiating this process.
12. On average, this MEOR process causes 36% more oil to be produced than would have otherwise been produced without this process.
13. No decrease in oil production has ever been observed as a result of this MEOR process.
14. This MEOR process can function effectively in most oil reservoir environments.
15. This MEOR process produces quick results. The producers average return on investment from MEOR has been 5:1 within the first 24 months of MEOR and the average time to project payback has been six months.
16. This MEOR technology is affordable. The cost of the process ranges from $0.25 to $0.50 per barrel of oil produced at the time MEOR begins and does not go up as oil production increases. The cost for incremental oil produced from MEOR is only about $2.00 per barrel.

NOMENCLATURE

π = 3.14
r = radius (desired depth of penetration into reservoir)
h = height (reservoir thickness)
ϕ = average reservoir porosity
I = incremental oil production
P1 = the cumulative projected post-MEOR production of oil defined by the extrapolation of the historical decline trend curve (expressed in bbls.)
P2 = the cumulative actual post-MEOR production of oil (expressed in bbls.)
NV = net value of incremental oil
NRI= producers net revenue interest in a project

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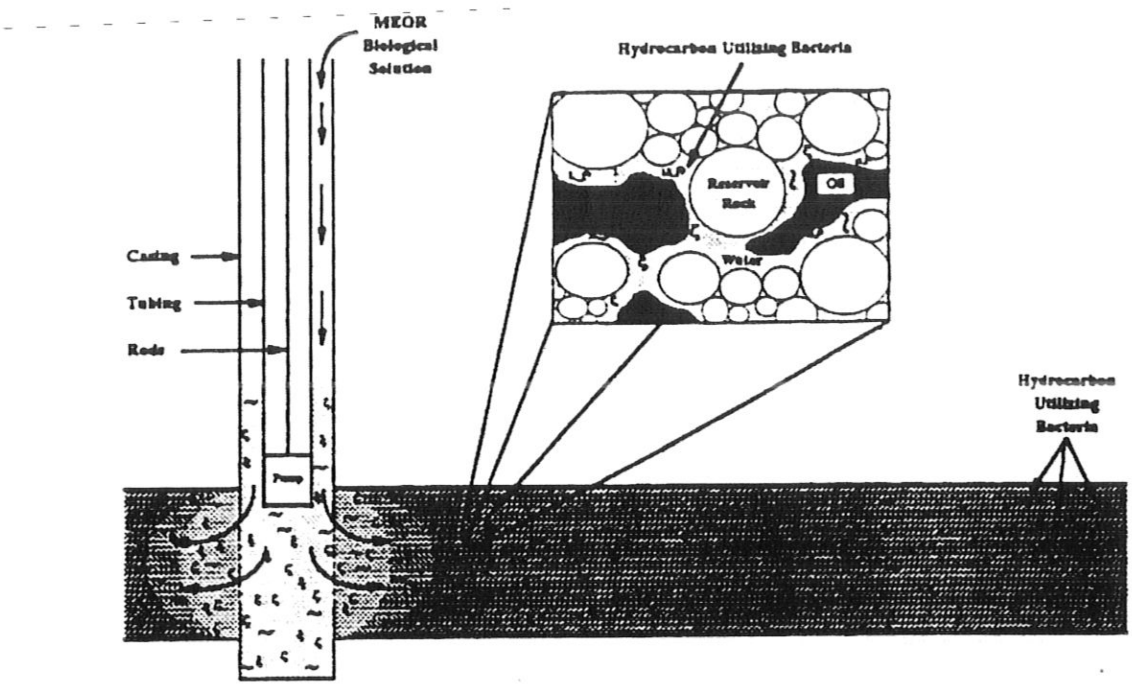


Figure 1 - MEOR Treatment of Single Producing Well

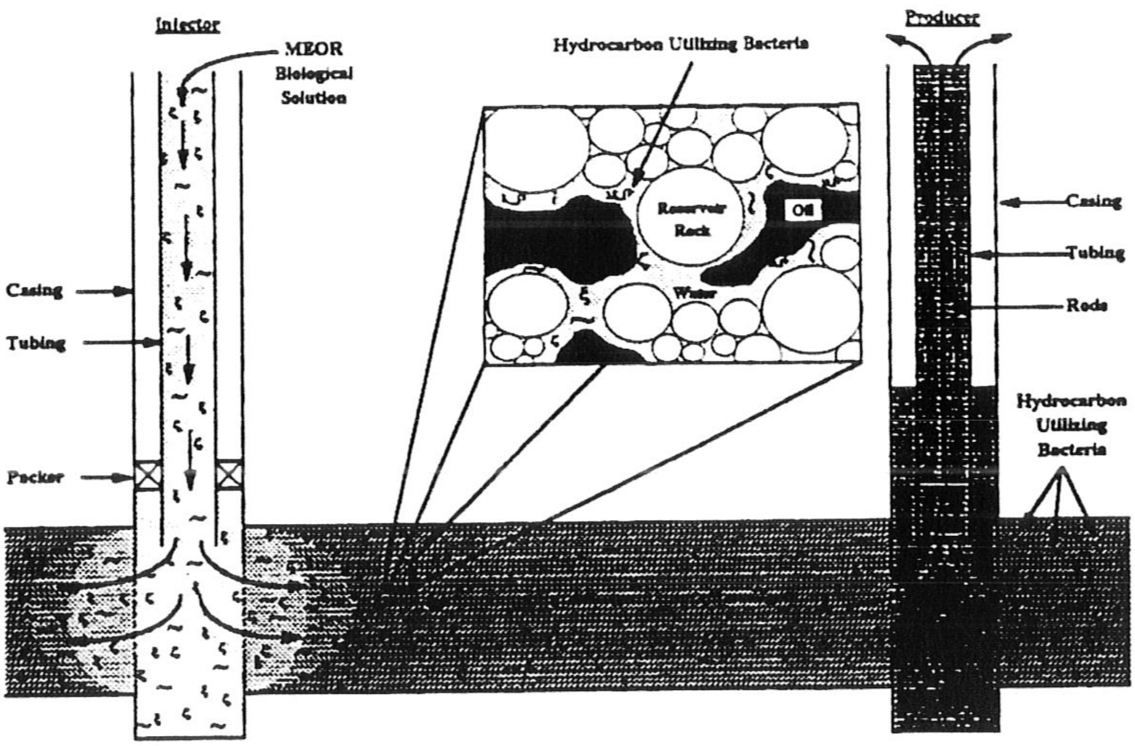
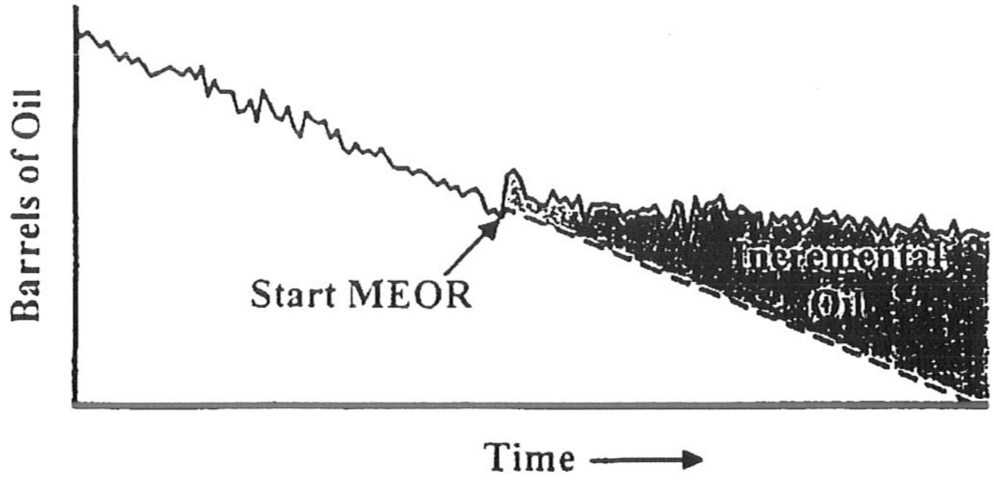


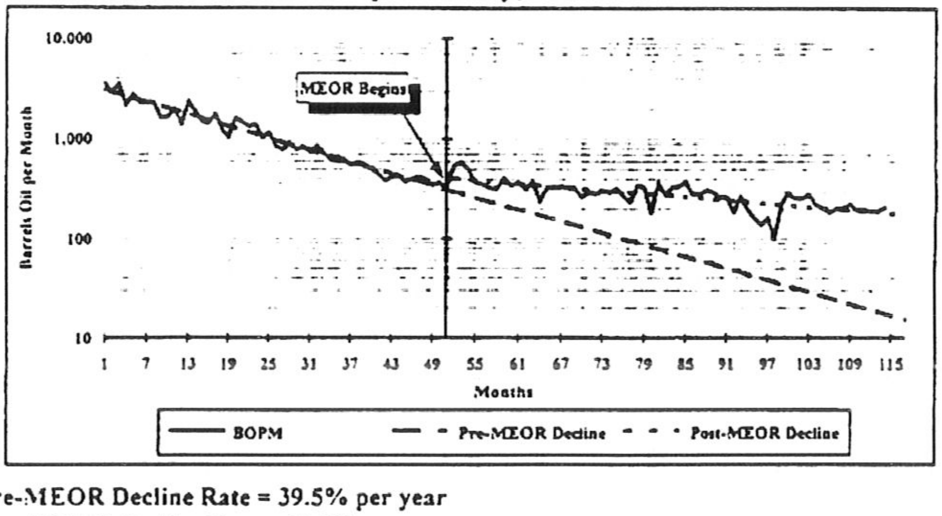
Figure 2 - MEOR Treatment in Waterflood



Incremental Oil = Actual Oil - Projected Oil

Figure 3 - Graphical Representation of Incremental Oil

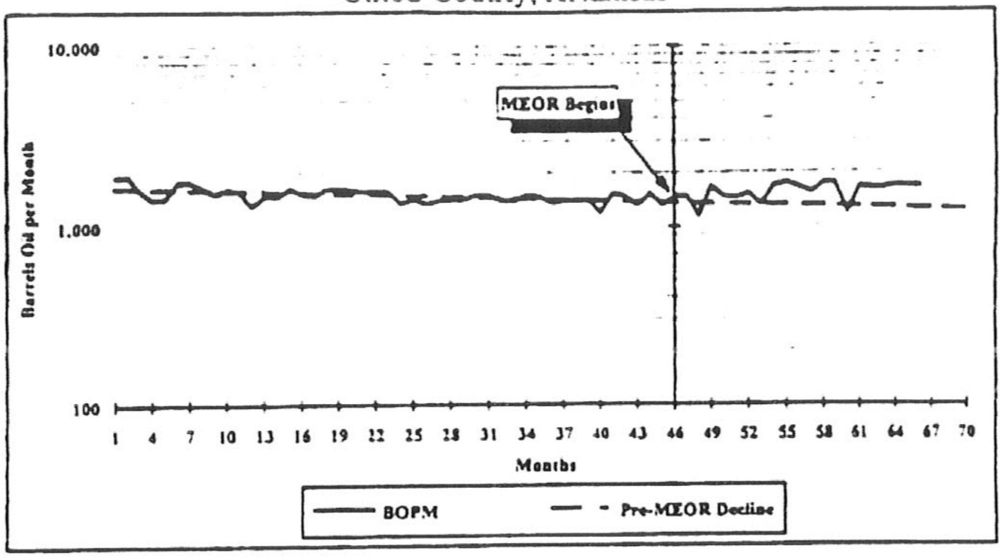
Microbial Enhanced Waterflood Project
2 Injection Wells/7 Producing Wells
Aux Vases Sandstone Formation
Wayne County, Illinois



Pre-MEOR Decline Rate = 39.5% per year
Post-MEOR Decline Rate = 12.9% per year
Project Months = 63
Cumulative Incremental Oil = +11,730 bbls. (+186.5%)
Return on Investment = 4.5:1

Figure 4

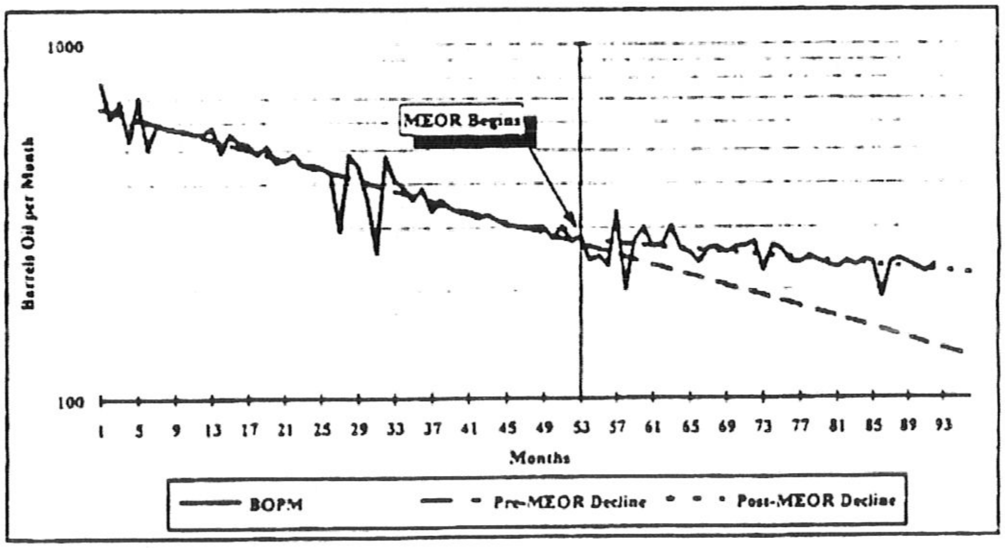
Microbial Enhanced Waterflood Project
5 Injection Wells/19 Producing Wells
Blossom Sandstone Formation
Union County, Arkansas



Project Months = 20
Cumulative Incremental Oil = +5,076 bbls. (+19.5%)
Return on Investment = 4.2:1

Figure 5

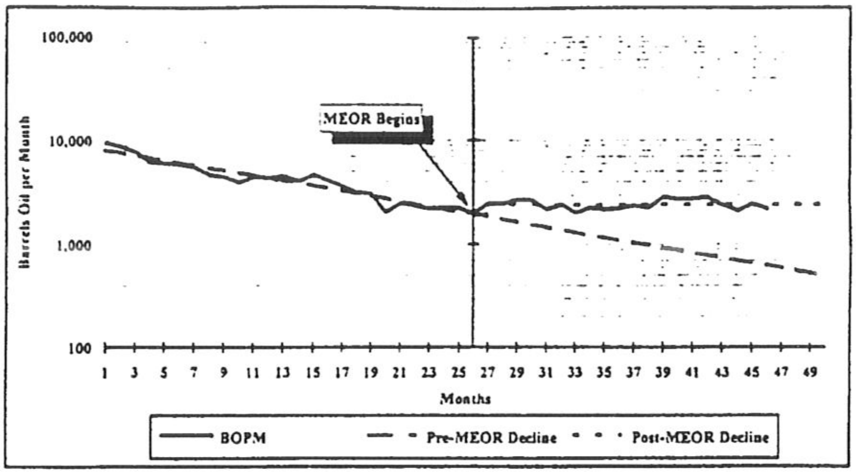
Single Well Microbial Enhanced Oil Recovery Project
Marchand Sandstone Formation
Caddo County, Oklahoma



Pre-MEOR Decline Rate = 17.2% per year
Post-MEOR Decline Rate = 5.6%
Project Months = 44
Cumulative Incremental Oil = +2,140 bbls. (+28.0%)
Return on Investment = 3.6:1

Figure 6

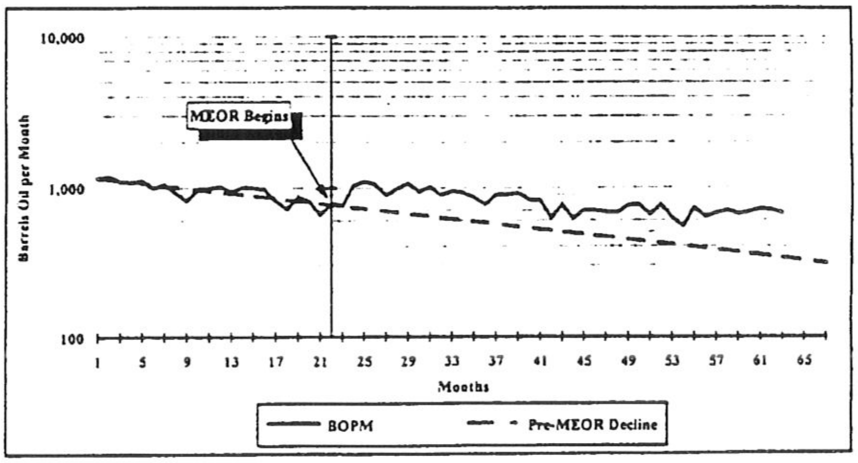
Single Well Microbial Enhanced Oil Recovery Project
Morrow Sandstone Formation
Cheyenne County, Colorado



Pre-MEOR Decline Rate = 46.5% per year
Post-MEOR Decline Rate = 0.3% per year
Project Months = 20
Cumulative Incremental Oil = +25,916 bbls. (+114.6%)
Return on Investment = 17:1

Figure 7

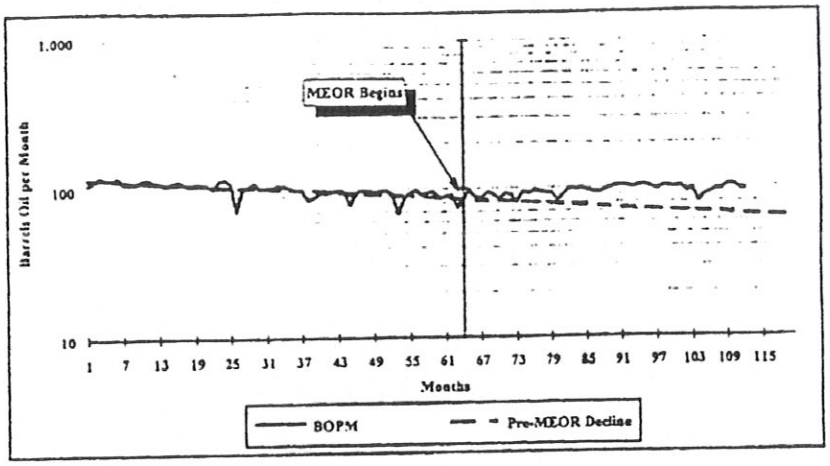
Single Well Microbial Enhanced Oil Recovery Project
Oswego Sandstone Formation
Woodward County, Oklahoma



Project Months = 41
Cumulative Incremental Oil = +11,476 bbls. (+54.2%)
Return on Investment = 8.5:1

Figure 8

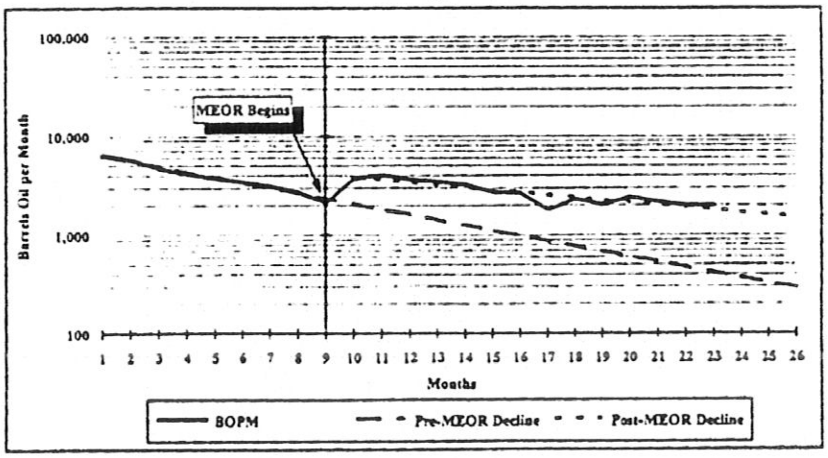
Single Well Microbial Enhanced Oil Recovery Project
Deese Sandstone Formation
Carter County, Oklahoma



Project Months = 41
Cumulative Incremental Oil = +990 bbls. (+27.6%)
Return on Investment = 2.2:1

Figure 9

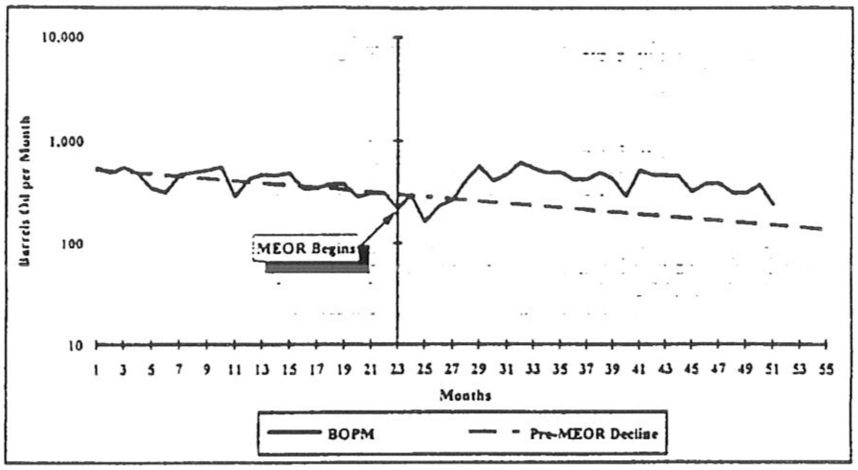
Single Well Microbial Enhanced Oil Recovery Project
Chester Limestone Formation
Grant County, Kansas



Pre-MEOR Decline Rate = 73.8% per year
Post-MEOR Decline Rate = 46.9% per year
Project Months = 14
Cumulative Incremental Oil = +23,136 bbls. (+116.9%)
Return on Investment = 20:1

Figure 10

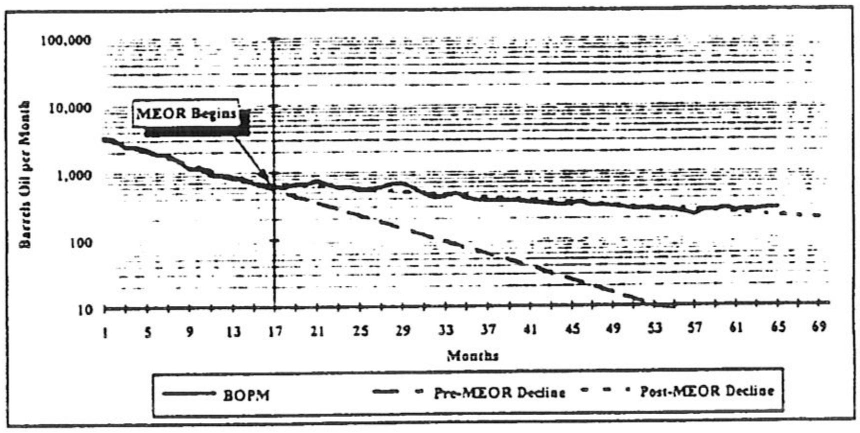
Single Well Microbial Enhanced Oil Recovery Project
Lansing Limestone Formation
Haskell County, Kansas



Project Months = 28
Cumulative Incremental Oil = +5,363 bbls. (+88.5%)
Return on Investment = 14:1

Figure 11

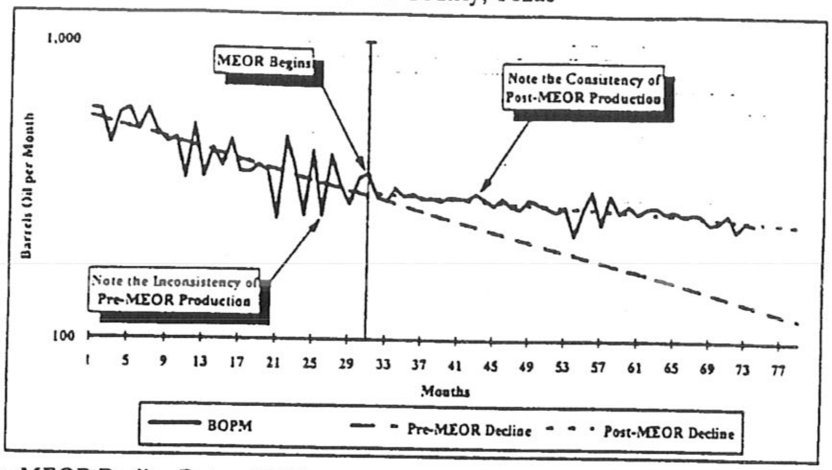
Single Well Microbial Enhanced Oil Recovery Project
Medrano Sandstone Formation
Grady County, Oklahoma



Pre-MEOR Decline Rate = 70.6% per year
Post-MEOR Decline Rate = 23.1% per year
Project Months = 48
Cumulative Incremental Oil = +14,869 bbls. (+320.0%)
Return on Investment = 12:1

Figure 12

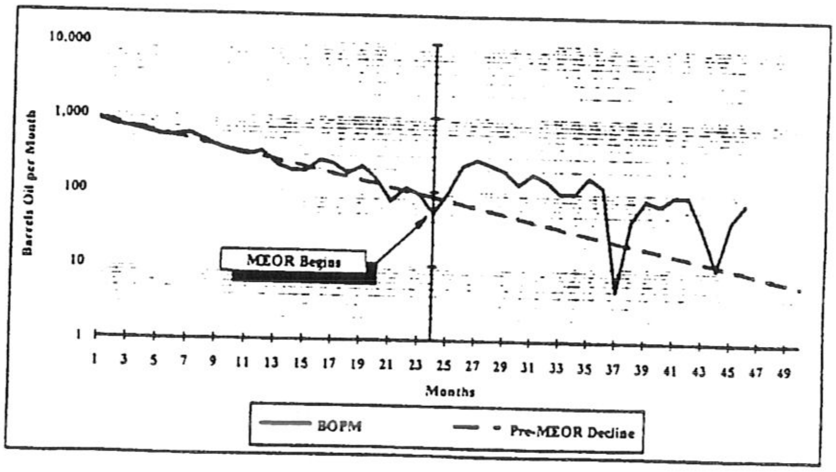
Single Well Microbial Enhanced Oil Recovery Project
Cleveland Sandstone Formation
Ochiltree County, Texas



Pre-MEOR Decline Rate = 19.5% per year
Post-MEOR Decline Rate = 5.3% per year
Project Months = 43
Cumulative Incremental Oil = +3,377 bbls. (+38.2%)
Return on Investment = 6:1

Figure 13

Single Well Microbial Enhanced Oil Recovery Project
Lansing Limestone Formation
Baca County, Colorado



Project Months = 22
Cumulative Incremental Oil = +1,814 bbls. (+254.9%)
Return on Investment = 8:1

Figure 14

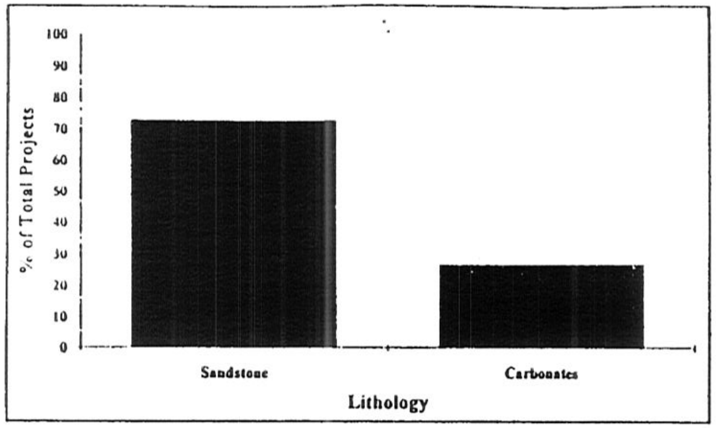


Figure 15 - Percent of Total Projects vs. Lithology

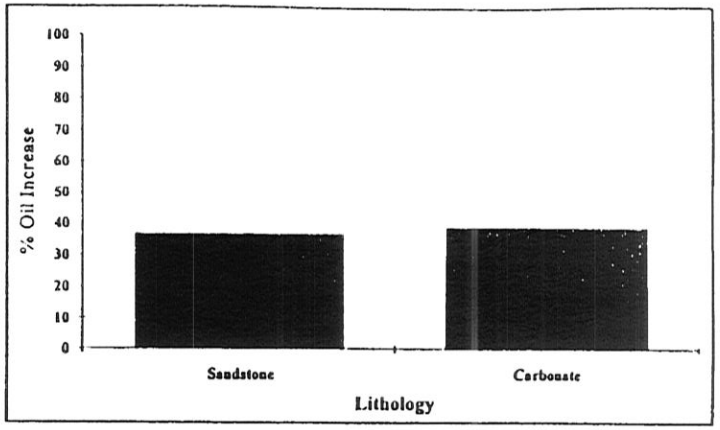


Figure 16 - Percent Oil Increase vs. Lithology

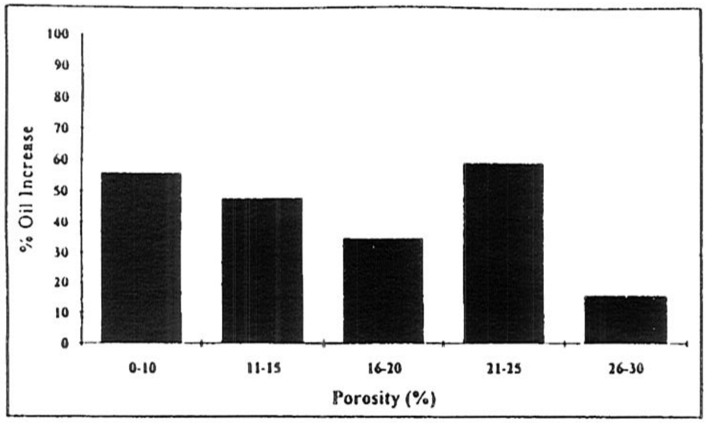


Figure 17 - Percent Oil Increase vs. Porosity

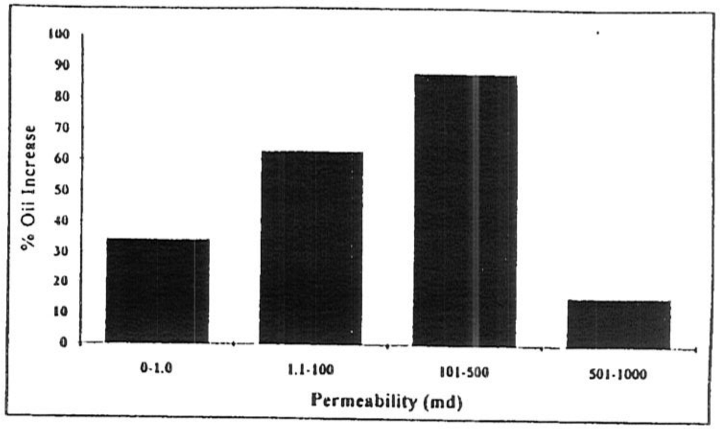


Figure 18 - Percent Oil Increase vs. Permeability

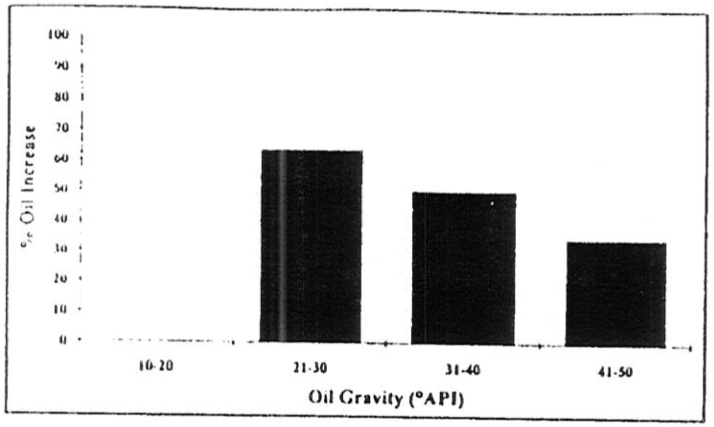


Figure 19 - Percent Oil Increase vs. Oil Gravity

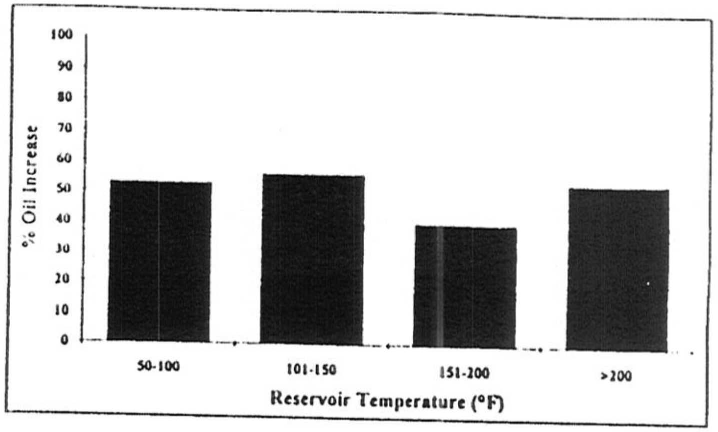


Figure 20 - Percent Oil Increase vs. Reservoir Temperature

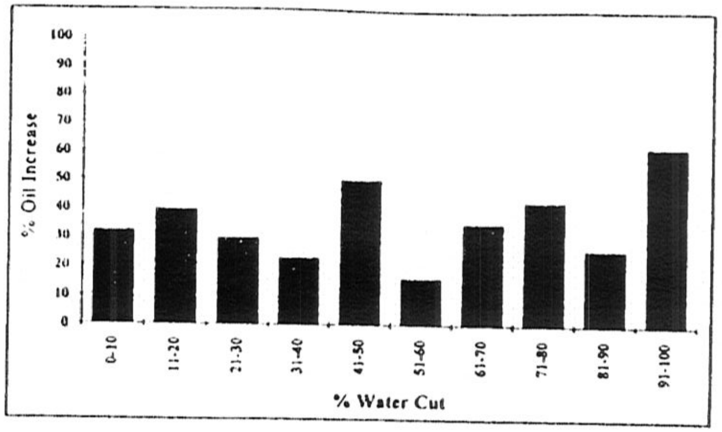


Figure 21 - Percent Oil Increase vs. Percent Water Cut