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Innovative MIOR Process Utilizing Indigenous Reservoir Constituents

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ABSTRACT

This research program is directed at improving the knowledge of reservoir ecology and developing practical microbial solutions for improving oil production. The goal is to identify indigenous microbial populations which can produce beneficial metabolic products and develop a methodology to stimulate those select microbes with inorganic nutrient amendments to increase oil recovery. This microbial technology has the capability of producing multiple oil-releasing agents. The potential of the system will be illustrated and demonstrated by the example of biopolymer production on oil recovery.

Research has begun on the program and experimental laboratory work is underway. Polymer-producing cultures have been isolated from produced water samples and initially characterized. Concurrently, a microcosm scale sand-packed column has been designed and developed for testing cultures of interest, including polymer-producing strains. Coreflood experiments have begun and comparative experiments demonstrating in situ polymer production have been conducted. Comparative laboratory studies demonstrating in situ production of microbial products as oil recovery agents were conducted in sand packs with synthetic and natural field waters with cultures and conditions representative of oil reservoirs.

EXECUTIVE SUMMARY

This project is an experimental laboratory study aimed to improve the understanding of reservoir ecology, and establishing methods of manipulating indigenous microorganisms to utilize naturally occurring water soluble organic acids to produce beneficial oil recovery agents. The objectives of this research program are to demonstrate in-situ production of oil recovery agents in reservoir waters by indigenous microbial populations, and to enhance and control the content and concentration of the bioproducts by the selective addition of low concentrations of inorganic salts as an alternate electron system.

The research program has been divided into a series of seven tasks that are designed to determine feasibility of developing a practical and cost effective in-situ microbial system for increasing the effectiveness of oil-recovery agents in oil reservoirs. Research in this program will focus on stimulating in situ polymer production to reduce permeability of porous zones and alter fluid flow patterns in heterogeneous formations. Experimental work on the project begins in Task 1 with selection of suitable microbial strains and development of test procedures for subsequent studies. Research in Task 2 will begin to develop physical models which can be used to quantify fluid diversion in different types of porous media. The objective of Task 3 is to demonstrate that nutrient amendments can be used to selectively stimulate polymer-producing microbes to modify matrix permeability and cause changes in flow patterns. Results from Tasks 1 through 3, will be applied in Task 4 into an increased oil recovery system. This task will be incorporated in conjunction with the preceding flooding tests. Task 4 tests may involve a significant portion of the test program and will involve demonstrating and optimizing the effectiveness of the oil recovery biosystem. Data from experimental work will be correlated and integrated for the effects of the biosystems on oil recovery in Task 5, and reported in a form which could be offered for technology transfer to the oil industry for commercial applications. As results are obtained from the laboratory investigations and are made available to field operations through technology transfer, work in Task 6 will be directed toward applying the new technology to field studies, situations, and operations. This approach allows rapid introduction and evaluation of any system and/or product which is developed by this program, and will provide directly comparable data to be collected. Technical reports will be prepared and offered to industry under Task 7 to complete the project.

The described research project was designed as a three-year experimental study. Work on the project commenced on October 1, 1999 and research projects were initiated as planned at that time. Active experimental projects are now in progress in all Tasks. Samples of produced water have been obtained from actively producing fields and enriched for polymer-producing microorganisms. Several promising strains of microbes have been isolated and are currently being used for experimental work. Microcosm scale sand-packed columns were designed and tested for developing selected cultures by nutrient stimulation. Experimental design of flooding regimes is in progress to test the effects of nutrient stimulation on flow behavior in physical models. No problems have been encountered in the project to date.

CHAPTER 1
Introduction

It is known that microorganisms can survive and multiply in and under reservoir conditions, and have the capability to significantly influence oil practices and production (credited to Beckman, 1926). Using such data, it has been proposed that microorganisms can also exert and have a positive effect on oil production (1, 2). Areas being actively studied include the production of biopolymers and biosurfactants by microorganisms, and the injection of these products for viscosity and surface tension modifications. In addition, microorganisms have been tested for their ability to grow in oil reservoirs and by their growth in-situ cause the increased mobilization of oil through various mechanisms and/or products such as CO_2 and other gases, surfactants, organic acids and solvents. Successful field tests employing Microbial Improved Oil Recovery (MIOR) technologies have been reported and more field tests are now in progress (3).

More recently it has been shown that the presence of inorganic nutrients can control reservoir ecology, and adding inorganic nutrients as alternate electron acceptors can stimulate distinct groups of bacteria (4). Several discoveries resulting from this understanding of reservoir ecology are of key importance for the present research project:

- Low concentrations of selected nitrogen salts stimulate populations of indigenous denitrifying microbes,
- Such denitrifying populations are heterotrophs known to produce copious amounts of biopolymers (and biosurfactants) at reservoir conditions,
- Beneficial polymer-producing populations can be established and maintained within the reservoir by supplying low-cost nitrogen salts.

This line of investigation has been expanded in the present research program to develop an understanding of a methodology to use low-cost inorganic nutrient amendments that stimulate indigenous microflora to utilize natural reservoir constituents to produce beneficial products. The three-year research project began in October 1999. This report describes month ten through month fifteen of the project. Chapter 2 describes the selection of suitable microbial strains, isolation of cultures from oil field brines and other sources, and nutrient studies. Design and development of physical models for studying fluid flow and diversion is detailed in Chapter 3, as well as sand pack flood results. Physical models were used in Chapter 4 to test the concepts of controlled microbial ecology for creating a fluid diversion system. Several sand pack floods were completed. Most of the research effort is now concentrated on oil recovery tests, described in Chapter 5.

Chapter 6 introduces the beginning of data correlation and interpretation. Chapter 7 gives a brief introduction of the field evaluation of new technology/products. Chapter 8 describes the work thus far on reports and technology transfer.

CHAPTER 2
Laboratory Procedures

Introduction

Oil reservoirs contain diverse microbial populations, including species introduced during drilling and production activities, and species native to the reservoir environment. Except in cases of extreme biological constraint (i.e., temperature, salt, etc.), oil reservoirs establish indigenous microbial communities which adapt to the prevailing reservoir conditions. These complex microbial communities demonstrate they contain the metabolic capabilities to produce known oil recovery agents such as biosurfactants and biopolymers. The indigenous communities are in dynamic equilibrium with their environment, and must be restructured in a directed way to favor production of beneficial products. The presence of inorganic nutrients can control reservoir ecology, and adding inorganic nutrients as alternate electron acceptors can stimulate distinct groups of bacteria. However, to understand how these groups contribute to the process, we must first assess their individual contributions.

This research program focuses on developing an understanding of a methodology to use low-cost inorganic nutrient amendments that stimulate indigenous microflora to utilize natural reservoir constituents to produce beneficial products. In order to assess effects that the distinct physiological groups have on oil mobilization, it is necessary to develop procedures to measure the multiciplicity of effects. Experimental work on the project began with selection of suitable microbial strains and development of test procedures for subsequent studies.

Background

Previous investigations of oilfield waters have endowed us with an extensive culture collection of oilfield microflora. Numerous cultures have been isolated from a wide range of field waters and facilities, including primary production wells and waterflooded fields, ranging from fresh waters to highly saline formation waters, and at various reservoir temperatures. The cultures have been isolated on varied media, and in particular the standard API acetate-lactate SRB (sulfate reducing bacteria) medium used widely by the oil industry. The collection has been supplemented with isolates from several other environmental sources including activated sewage sludge, polluted marine waters and sediments, naturally attenuated remediation sites, and historically contaminated production sites. Selected cultures from the collection were used as a primary source of inocula for enrichments.

Experimental

The objective of the culture studies is to select cultures from natural microbial consortia that will utilize natural reservoir constituents to produce beneficial products for oil mobilization. Strains isolated from produced water samples as described in the January 2000 Semi-Annual report (5) were tested with various nutrient combinations. The nutrient amounts are shown in Table 1.

Table 1. Nutrient components.

Component	g/L	ppm
$C_2H_3NaO_2$	1.64	1180 acetate
$NaNO_3$	1.70	1240 nitrate
Na_2HPO_4	0.75	1050 phosphate
KH_2PO_4	1.50	1050 phosphate
$MgCl_2 \cdot 6H_2O$	0.10	12 magnesium
$NaNO_2$	1.70	1140 nitrite

Eight different nutrient combinations were used, and named Nutrient 1 through Nutrient 8, as shown in Table 2.

Table 2. Nutrient compositions.

Component	1	2	3	4	5	6	7	8
$C_2H_3NaO_2$	X	X	X	X	X	X	X	X
$NaNO_3$	X	X	X	X	X	X	X	X
Na_2HPO_4	X	X	X		X			X
KH_2PO_4	X	X		X		X		X
$MgCl_2 \cdot 6H_2O$	X		X	X			X	X
$NaNO_2$								X

Brines and oils were obtained from several oil field sites in Oklahoma. The leases were designated as Hominy, Shidler, and the Naval Reserve. The brines were analyzed for sulfate, TDS (total dissolved solids), iron, and acetate. The brines were also checked for microbial activity, and to determine whether microbes from our collection would grow in them.

Samples were obtained from a wastewater treatment plant to attempt to isolate denitrifying bacteria and other bacteria which may be suitable for this project.

Results and Discussion

Good microbial growth was observed in Nutrients 1, 2, 3, 5, and 7, as shown in Table 3. Variations based on these nutrients will be used for future studies, reducing the concentrations to determine the minimum amounts needed for growth and production of desired microbial products.

Table 3. Growth results.

Nutrient #	First series	Second series
Nutrient 1	slightly turbid, tiny white particles, lots of rods	slightly turbid, no particles, lots of rods
Nutrient 2	slightly turbid, tiny white particles, lots of rods	slightly turbid, precipitate, small white particles, lots of rods
Nutrient 3	slightly turbid, small white particles, no bacteria	precipitate, small white particles, lots of rods
Nutrient 4	clump of biomass? no bacteria	precipitate, small white particles, no bacteria
Nutrient 5	slightly turbid, small white particles, lots of rods	precipitate, small white particles, lots of rods
Nutrient 6	not turbid, no particles, no bacteria	precipitate, small white particles, no bacteria
Nutrient 7	slightly turbid, lots of rods	precipitate, some small white particles, some rods, not as many as the other nutrients
Nutrient 8	not turbid, no bacteria	precipitate, small white particles, no bacteria

Results of analysis of oil field brines are shown in Table 4.

Table 4. Analysis of oil field brines.

Brine sample	Sulfate (ppm)	Iron (ppm)	TDS (%)	Acetate (ppm)
Hominy	0	12	18.2	7
Naval Reserve	0	11	18.0	10
Shidler	0	10	8.0	3

Some bacteria were found in the Shidler brine, but not in the other two brines. When the brines were enriched with added acetate and nitrate and inoculated with some cultures from our collection, growth was observed in the Hominy brine, also. Further work will be done with these brines as well as brines from other sites to determine if they would be good candidates for field tests.

Conclusions

- Low-cost inorganic nutrients can be used to stimulate growth of indigenous bacteria.
- Samples were obtained from oil fields and a wastewater treatment plant to isolate bacteria suitable for use in this project.

CHAPTER 3
Flooding Test Procedures, Flooding Apparatus

Introduction

The research project focuses on stimulating in situ polymer production to reduce permeability of porous zones and alter fluid flow patterns in heterogeneous formations. Experimental designs and protocols for examining cultures in porous media and conducting flooding experiments in sand-packed columns and Berea cores were needed. Because of the versatility for examining different porous media, and multiple cores in series or parallel, the sand-packed column system was chosen for preliminary testing. Sand-packed column systems have been previously developed and used extensively for studying sequential effects of nitrate-based stimulation systems. However, the need to screen a large number of cultures required modifications of the traditional sand packed columns.

Research in the flooding test procedures and flooding apparatuses began with the development of a microcosm-scale physical model that can be used to examine enrichment cultures and isolates for growth characteristics and polymer production. The microcosm model was tested in a preliminary screening of isolates and mixed cultures.

Background

A large number of waterflood operations use seawater as the injection and drive fluid. A seawater-based medium was chosen for the initial column growth studies as the representative flood water. This seawater base medium was fortified with sodium acetate at levels that have been measured and reported in many major oil reservoirs such as the Alaska North Slope and North Sea. The combination of the choice and the selection of cultures, together with the known composition of the base growth fluids which were easily amended to realistic fluid water compositions allowed the preliminary test protocol to be established and controlled.

Experimental

Many sand pack flooding experiments were conducted to determine the effects of various nutrients and flooding regimes on oil recovery. All experiments were conducted at 40° C unless otherwise noted. The sand pack columns were made of glass, and were 1.27 cm in diameter. Mill Creek sand was used for the sand packs. The packs were saturated with Instant Ocean synthetic brine.

After brine saturation, the packs were inoculated using gravity feed with one pore volume (PV) of a mixed culture grown in DNB (denitrifying bacteria) broth. The composition of DNB broth is described in the January 2000 Semi-Annual Report (5). The packs were then flooded with reduced synthetic brine with 1.64 g/l sodium acetate (1180 ppm acetate) added (RAB) to wash out the broth. The packs were incubated for three days. The packs were then saturated with Skiatook-11 crude oil. PI-8a was inoculated after oil saturation. Details for each pack are reported in Table 5.

Table 5. Sand packs PI-1 through PI-8a.

Sand pack #	Length (cm)	PV (ml)	OOIP (ml)
PI-1	25.5	13.1	9.0
PI-3	26.5	12.4	10.3
PI-4	25.5	12.4	13.0
PI-5	25.5	13.2	10.6
PI-7	25.4	12.9	11.2
PI-8	25.4	13.4	10.9
PI-8a	25.6	13.9	12.0

The packs were flooded with RAB to residual oil saturation. Nutrient treatments were then started by adding sodium nitrate and/or sodium acetate to the brine. The packs were flooded continuously over a period of several days and were not shut in.

Results and Discussion

Table 6 shows the oil recovery results. In this experiment, no additional oil was produced without the addition of nitrate and acetate, demonstrating that these nutrients are essential for oil recovery in this system.

Table 6. Sand packs PI-1 through PI-8a oil recovery results.

Sand pack #	Waterflood Recovery (%)	Treatment Type	Treatment Recovery (%)	Final Recovery (%)
PI-1	104.4	0 ppm acetate 0 ppm nitrate	0.0	104.4
PI-3	67.0	500 ppm acetate 0 ppm nitrate	0.0	67.0
PI-4	45.4	1000 ppm acetate 0 ppm nitrate	0.0	45.4
PI-5	85.8	0 ppm acetate 100 ppm nitrate	0.0	85.8
PI-7	67.0	500 ppm acetate 100 ppm nitrate	18.7	85.7
PI-8	96.3	1000 ppm acetate 100 ppm nitrate	9.2	105.5
PI-8a	69.2	1000 ppm acetate 100 ppm nitrate	7.5	76.7

Conclusions

- In these experiments, acetate and nitrate are necessary for additional oil recovery.

CHAPTER 4
Flooding Regimes and Protocols

Introduction

Biogeochemical properties of an oil reservoir are dominant factors which govern the composition and action of reservoir microflora. It can be expected that the indigenous microbial community will be in a dynamic equilibrium at reservoir conditions. Alterations of the reservoir environment will cause a selective shift in both the numbers of microbes present, and the metabolic activities of the community. Thus, an understanding of the interactions of the geochemical factors and the biological response will influence the uses and capabilities of such natural indigenous microbial populations in oil recovery systems.

Nutrient amendments in reservoir waters have been shown to modify reservoir ecology and stimulate distinct groups of microorganisms. Of key importance are the nitrate-reducing, polymer producing bacteria. Through controlled addition of nitrogen compounds into reservoir waters, reservoir ecology can be manipulated and restructured to stimulate denitrifying bacteria. The onset of polymer production by this distinct group of microbes can be induced by certain chemical and physical conditions, and is often triggered by availability of specific nitrogen compounds. There is evidence to indicate that the introduction of selected and low levels of nitrogen containing salts, such as nitrate, combined with an appreciation of the natural reservoir ecology, can lead to the ability to produce biopolymers in-situ in areas deep within the formation where such viscosity increases would have the greatest and most effective impact.

The research objective is to demonstrate that amendments of certain nitrogen containing salts to reservoir waters can be used to selectively stimulate polymer-producing microbes to modify matrix permeability and cause changes in flow patterns. To establish an understanding of conditions that stimulate polymer production, comparative tests will be conducted with a variety of nitrogen containing salts. Effects of these directed nutrient manipulations on fluid flow properties will be measured in artificial and natural brine floods of the physical models.

Background

Preliminary data suggest that it is possible and that the technology has the potential to be able to manipulate and modify the production of biopolymer by changing the form of the inorganic salts (nitrate). This ability, which is in addition to effects caused by changes in concentration of the salts, will have an important effect on the production of microbial products. This new and important development which complements the use of the VFA and indigenous microflora offers uniqueness to the proposed system that previously has not been considered. Thus, in addition to studies which measure effects of nitrate/nitrite on polymer production, the systems would be studied in regard to the effects of adding various sodium, calcium, or ammonium forms of such salts. This increases the effectiveness of the process. For example, using the ammonium form of nitrate would have an added effect on the types and numbers of the microbial species that are established. The resultant polymer production can be increased. Previous work with different nitrate salts added for sulfide control have shown that biomass/polymer production will be influenced and it is usually observed that lower concentrations of nitrogen will increase biopolymer production. This ability to modify biopolymer composition/concentration by minor

modifications of the added nitrogen sources is being investigated. This directed and controlled addition of the nitrogen compounds can be expected to provide additional advantages for the selective development of a unique in-situ polymer generating system.

Experimental

Sand pack flooding experiments to demonstrate production of polymer in-situ were conducted using synthetic brine (0.75% NaCl). The sand pack flooding schematic was depicted in the July 2000 Semi-Annual Report (5). These experiments were conducted at ambient temperature. The sand pack columns were made of glass, and were 1.27 cm in diameter. Mill Creek sand was used to pack the columns. After brine saturation, the packs were inoculated using gravity feed with four PV inoculum. Pack P-4 was inoculated with culture A1 grown in DNB broth. Pack P-6 was inoculated with culture 1 grown in DNB broth. These cultures were isolated from oilfield brines. The packs were then flooded with fresh DNB media, shut in, and incubated at ambient temperature. Pack P-4 was incubated for 10 days. Pack P-6 was incubated for 13 days. After incubation, the post-treatment permeability was measured.

Results and Discussion

The permeability of both packs was reduced substantially by in-situ polymer production by the injected microbial cultures, as shown in Table 7. The permeability in P-4 was reduced by 42%, and the permeability in P-6 was reduced by 38%. It is postulated that the nitrate in the DNB media stimulated polymer production.

Table 7. Permeability reduction.

Sand pack #	Length (cm)	PV (ml)	Original Permeability (D)	Final Permeability (D)
P-4	12.5	4.5	3.94	2.30
P-6	12.5	5.8	6.58	4.06

Conclusions

- Indigenous oilfield bacteria can be stimulated to produce polymer and cause a decrease in permeability using a nitrate/acetate-based nutrient.

CHAPTER 5
Oil Recovery Tests

Introduction

Protocols and regimes developed in the other Tasks will be used to identify the conditions and parameters that would demonstrate the effective increase of polymer production by the biosystem operations. Such tests will also identify the limitations of the biosystem and lead to the development of alternate treating and flooding schemes to overcome such limitations. This exploratory study approach will allow many variables to be determined rapidly and provide the information needed to conduct more effective tests that measure oil increase. This approach is based on the known observation and data which demonstrated that biopolymer production causes viscosity increase which will have an impact on profile modification, flow patterns, etc. As the system is optimized and treatment procedures and techniques are developed, the flooding tests will include similar systems that contain oil.

It is proposed to introduce oil into the flooding systems as rapidly as possible to develop data on increased oil recovery. This task is being incorporated in conjunction and simultaneously with the preceding flooding tests. The same analytical procedures and testing program will be followed and will be expanded to include all factors and test measurements that concern the oil phase, content, and characteristics. These oil flooding tests could involve a significant portion of the test program and will involve demonstrating and optimizing the effectiveness of the oil recovery biosystem.

Background

The role of VFA as a key component which leads to the biogenic formation of sulfide in reservoirs was pioneered at GMT. These investigations lead to the discovery of a novel technology which used the naturally occurring VFA in a beneficial role to prevent and remove sulfide in the reservoir. This patented technology causes the replacement of the detrimental SRB with a beneficial microbial population by the addition of a proprietary mixture of inorganic salts which act as an alternate electron acceptor. The technology which has been termed "Biocompetitive Exclusion" is based on the presence of VFA in the reservoir and its preferential use and removal by an indigenous microflora and therefore requires no addition of organisms. The growth of those anaerobic denitrifying microorganisms has the added potential of increasing oil recovery by the production of their metabolic products which can include gases (CO_2 and N_2), biosurfactants, biopolymers, and acids.

This past work which has identified VFA in oil field brines and which has shown its impact on reservoir souring and corrosion has lead to the development of technologies which incorporate the VFA in a positive role. These previous experiments, field data, and results can be incorporated directly into this research effort. This research provides strong background information on VFA in reservoir fluids, and will be coupled with the ongoing studies of VFA in oil reservoirs to offer a unique information base for the successful completion of the program.

Experimental

Many sand pack flooding experiments were conducted to determine the effects of various nutrients and flooding regimes on oil recovery. All experiments were conducted at 40° C unless otherwise noted. The sand pack columns were made of glass, and were 1.27 cm in diameter. Mill Creek sand was used for the sand packs. The packs were saturated with synthetic brine based on the composition of Velma rural water, which was used for a previous field test. Brine composition is shown in Table 8.

Table 8. Composition of Velma synthetic brine.

Component	g/L
NaCl	20.000
$CaCl_2 \cdot 2H_2O$	0.35
$MgCl_2 \cdot 6H_2O$	0.25
Na_2SO_4	0.20
$NaHCO_3$	0.075

After brine saturation, the packs were inoculated using gravity feed with one pore volume of a microbial culture named A1 grown in DNB broth. The packs were then flooded with reduced synthetic brine with 1.64 g/l sodium acetate (1180 ppm acetate) added (RAB) to wash out the broth. The packs were re-inoculated to ensure good transport of the bacteria, then flooded again with RAB. The packs were saturated with Skiatook-11 crude oil. Details for each pack are reported in Table 9.

Table 9. Sand packs PB-8 and PB-9.

Sand pack #	Length (cm)	PV (ml)	K (D)	OOIP (ml)
PB-8	24.7	11.1	9.1	10.6
PB-9	16.8	12.7	9.9	9.8

The packs were flooded with RAB to residual oil saturation. Nitrate treatment was then started by adding sodium nitrate (1240 ppm nitrate) to the RAB. This treatment is referred to as RANB. The packs were flooded over a period of several days, and were shut in each night.
Sand packs PB-10 through PB-14 were prepared using the same procedure as PB-8 and 9, except the packs were inoculated with bacteria only once. Details for each pack are shown in Table 10.

Table 10. Sand packs PB-10 through PB-14.

Sand pack #	Length (cm)	PV (ml)	K (D)	OOIP (ml)
PB-10	26.4	12.2	9.8	9.6
PB-11	25.0	12.9	10.6	9.6
PB-12	24.5	12.7	9.9	10.5
PB-13	25.6	12.3	11.0	9.6
PB-14	25.7	12.7	11.5	9.6

The packs were flooded with RAB to residual oil saturation. Nutrient treatments were then started by adding sodium nitrate alone or sodium nitrate and sodium phosphate to the brine. The packs were flooded continuously over a period of several days and were not shut in.

Sand packs PI-17 through PI-24 were prepared using the same procedure as PB-10 through 14 except that Instant Ocean synthetic brine was used. The inoculum was suspended in brine and injected rather than being injected with DNB broth. A roller pump was used instead of gravity feed to maintain a more constant flow rate. Details for each pack are shown in Table 11.

Table 11. Sand packs PI-17 through PI-24.

Sand pack #	Length (cm)	PV (ml)	OOIP (ml)
PI-17	25.2	14.0	10.0
PI-18	26.4	13.9	10.6
PI-19	24.6	13.7	10.8
PI-20	25.1	14.4	10.8
PI-21	25.4	13.8	10.6
PI-22	26.3	14.2	10.9
PI-23	25.6	13.9	10.8
PI-24	25.3	13.7	11.2

Sand packs PH-1 and PH-2 were prepared using the same procedure as PI-17 through PI-24 except that Hominy field brine and oil were used. Details for each pack are shown in Table 12. Both packs were inoculated with culture A1 combined with bacteria isolated from Hominy brine. PH-1 was a control, with no nutrient added. PH-2 was treated with Maxwell Waterflood Treatment, a proprietary nutrient formula containing 20 ppm nitrate.

Table 12. Sand packs PH-1 and PH-2.

Sand pack #	Length (cm)	PV (ml)	OOIP (ml)
PH-1	24.7	15.6	11.4
PH-2	24.6	16.2	12.2

Results and Discussion

PB-8 produced an additional 3 ml of oil, for a final oil recovery of 94.3%. PB-9 produced an additional 1.65 ml of oil, for a final oil recovery of 98.5%. Results are shown in Table 13 and in Figures 1 and 2. This experiment demonstrates that the addition of nitrate stimulated the bacteria to produce additional oil.

Table 13. Sand packs PB-8 and PB-9 oil recovery results.

Core #	Waterflood Recovery (%)	Treatment Type	Treatment Recovery (%)	Final Recovery (%)
PB-8	75.5	1180 ppm acetate 1240 ppm nitrate	18.8	94.3
PB-9	81.6	1180 ppm acetate 1240 ppm nitrate	16.9	98.5

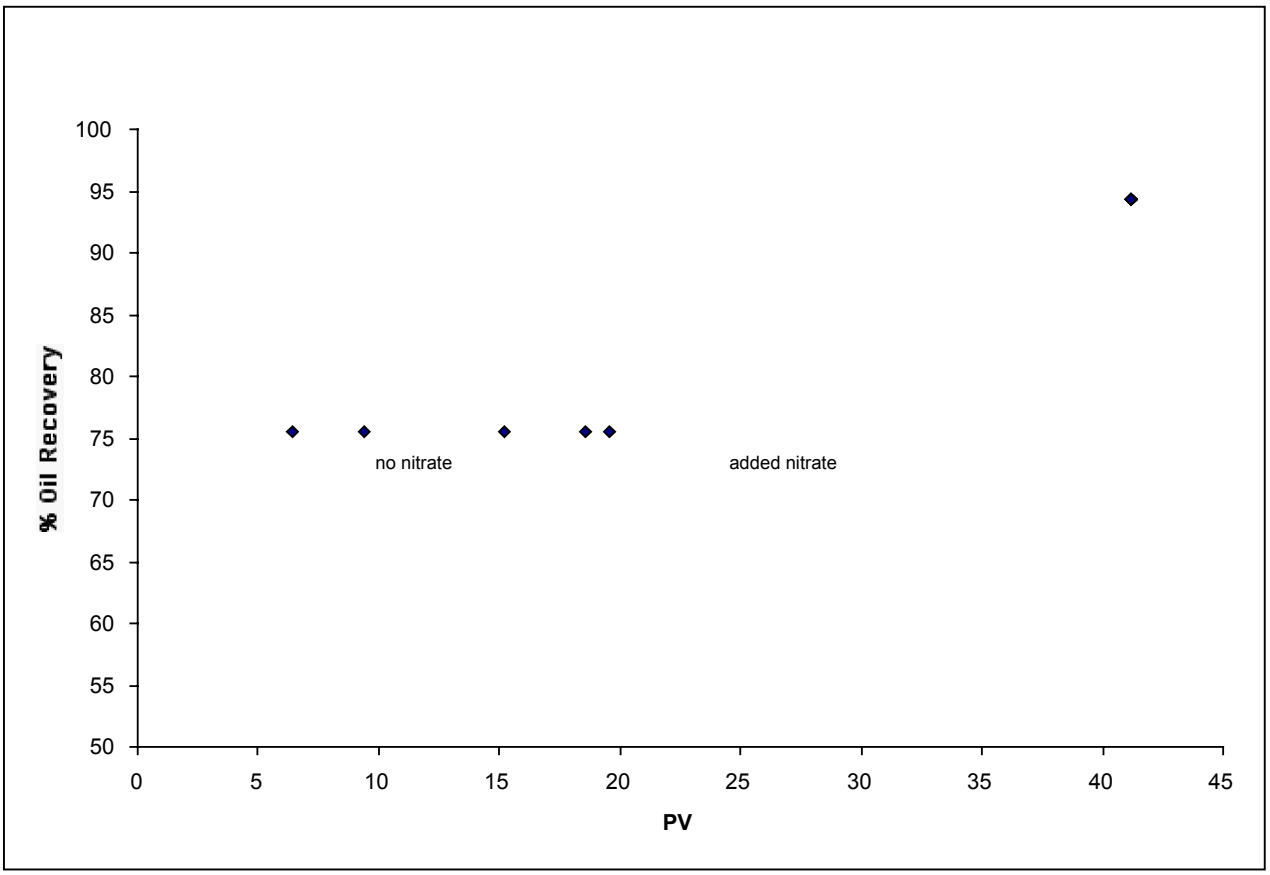

Figure 1. Sand pack PB-8 treated with nitrate.

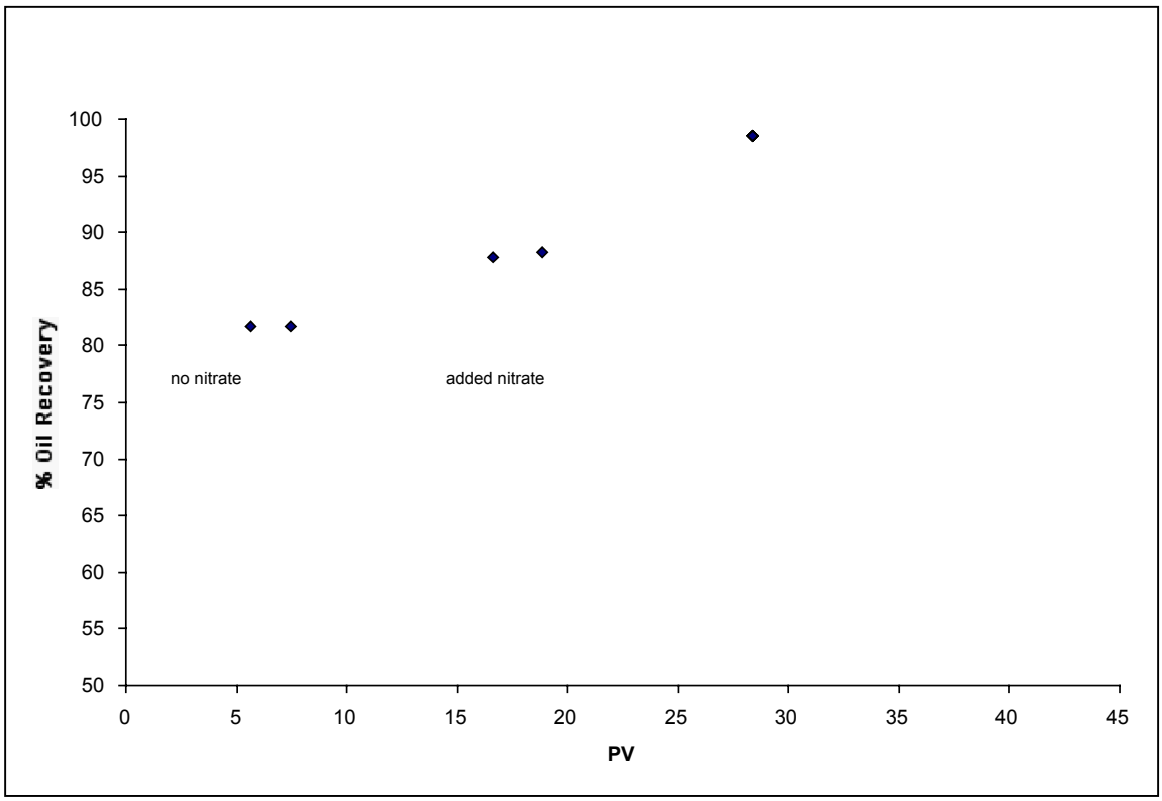

Figure 2. Sand pack PB-9 treated with nitrate.

Table 14 and Figure 3 show the oil recovery results for PB-10 through PB-14. In this experiment, no additional oil was produced without the addition of nitrate. The addition of phosphate along with nitrate stimulated the bacteria to produce additional oil.

Table 14. Sand packs PB-10 through PB-14 oil recovery results.

Sand pack #	Waterflood Recovery (%)	Treatment Type	Treatment Recovery (%)	Final Recovery (%)
PB-10	85.9	1180 ppm acetate	0.0	85.9
PB-11	66.1	1180 ppm acetate 100 ppm nitrate 100 ppm phosphate	14.6	80.7
PB-12	61.0	1180 ppm acetate 1000 ppm nitrate 100 ppm phosphate	19.0	80.0
PB-13	75.0	1180 ppm acetate 100 ppm nitrate	0.0	75.0
PB-14	62.5	1180 ppm acetate 1000 ppm nitrate	1.0	63.5

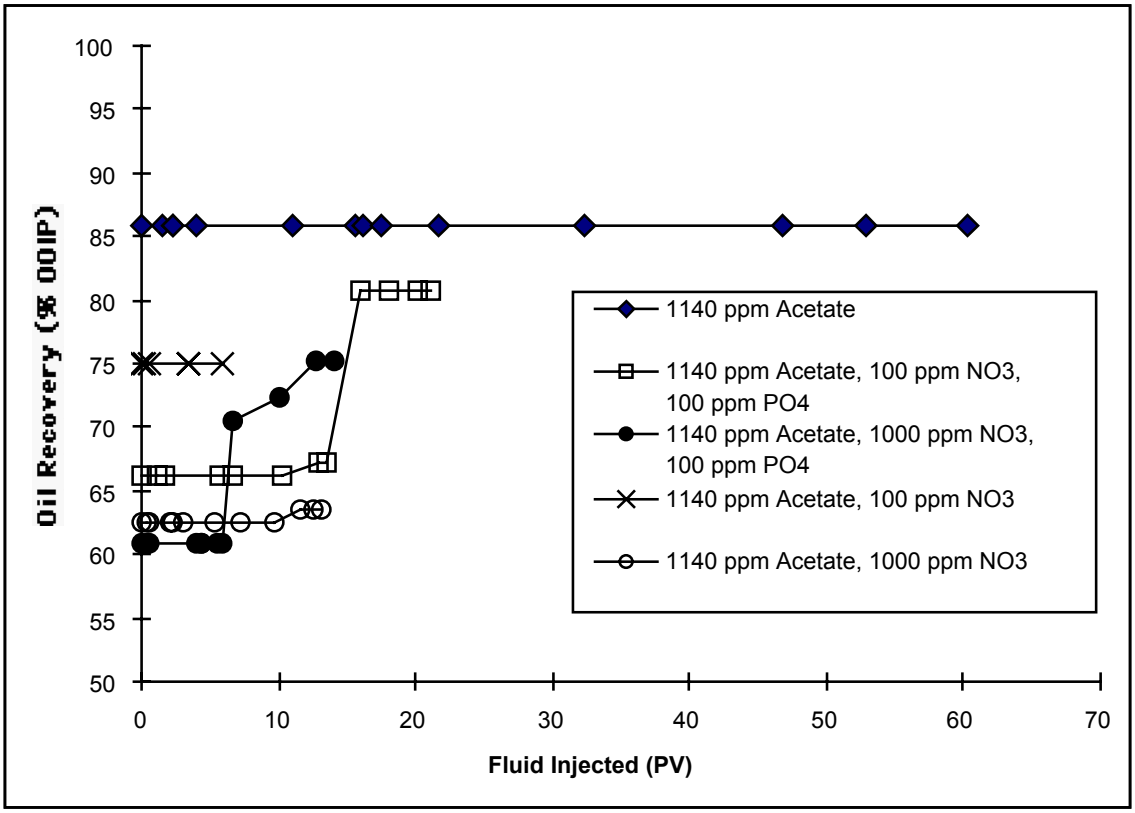

Figure 3. Sand packs PB-10 through 14 oil recovery results.

Results for PI-17 through PI-24 are shown in Table 15. Oil recovery is not as high with this inoculation strategy as it was when DNB broth was used. This set of packs did not give consistent results. Further study is needed to determine the optimum flooding protocol.

Table 15. Sand packs PI-17 through PI-24 oil recovery results.

Sand pack #	Waterflood Recovery (%)	Treatment Type	Treatment Recovery (%)	Final Recovery (%)
PI-17	81.6	0 ppm acetate 0 ppm nitrate 100 ppm phosphate	0.5	82.1
PI-18	66.2	100 ppm acetate 0 ppm nitrate 100 ppm phosphate	4.7	70.9
PI-19	65.0	500 ppm acetate 0 ppm nitrate 100 ppm phosphate	0.5	65.5
PI-20	68.1	1000 ppm acetate 0 ppm nitrate 100 ppm phosphate	4.6	72.7
PI-21	67.9	0 ppm acetate 1000 ppm nitrate 100 ppm phosphate	0.0	67.9
PI-22	73.2	100 ppm acetate 1000 ppm nitrate 100 ppm phosphate	2.3	75.5
PI-23	68.5	500 ppm acetate 1000 ppm nitrate 100 ppm phosphate	5.6	74.1
PI-24	67.6	1000 ppm acetate 1000 ppm nitrate 100 ppm phosphate	2.7	70.3

Figure 4 shows the oil recovery results for PH-1 and PH-2. The flood with Maxwell Waterflood Treatment increased the oil production by 2.3%, even with the very low nitrate concentration.

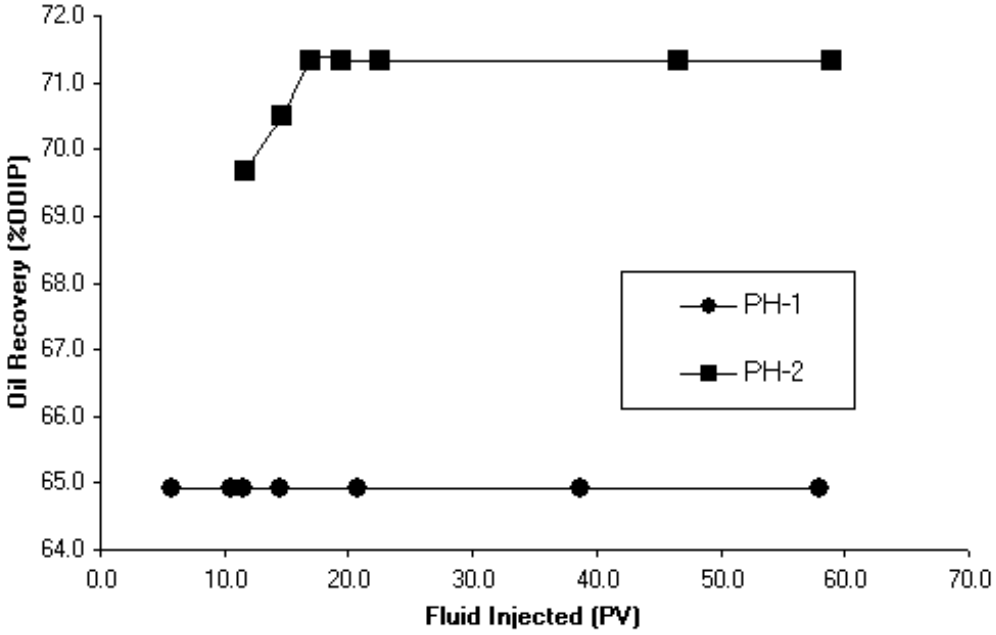

Figure 4. Sand packs PH-1 and 2 oil recovery results.

In most of the floods that were conducted, the addition of acetate and nitrate is necessary to stimulate microbial activity and increase oil production. Some results were inconsistent, and further study is needed to determine optimum nutrient concentrations and injection protocol.

Conclusions

- In most cases, the addition of both nitrate and acetate was necessary for increased oil production.
- Further work is needed to optimize the system.

CHAPTER 6
Data Correlation and Interpretation

Introduction

The program will develop extensive data on the microbiology, geochemistry, polymer production, profile modification, etc. of flooding systems. These data will be correlated and integrated for the effects of the biosystems on oil recovery. All results will be examined and correlated for identifying conditions and treatments that maximize the polymer production. The interactions of the results from the various test conditions and parameters will be integrated to present a composite evaluation of the biosystem actions on oil recovery. These results will be reported in a form that could be offered for technology transfer to the oil industry for commercial applications.

CHAPTER 7
Field Evaluation of New Technology/Products

Introduction

As results are obtained from the laboratory investigations and are made available to field operations through technology transfer, it is anticipated that the findings would be offered and applied to field studies, situations, and operations. As the laboratory results are incorporated into pilot field projects, these field operations would be closely followed and monitored. The identifications of such fields and participation of the operators would provide additional feedback data from such projects. These pilot field evaluations would be conducted in conjunction with ongoing projects whenever possible. By utilizing such ongoing projects, the requirements for collection of baseline data, flood responses, field operations, etc. would be minimized and a pilot study could rapidly be implemented with operator assistance. This approach would allow rapid introduction and evaluation of any system/product that was developed by this program and would provide directly comparable data to be collected. This method of field testing offers a low cost and easily approved and operated system to introduce the technology/products which will be developed in this research program.

Discussions have been held with representatives from several oilfields concerning possible field testing. This is still in the preliminary stage.

CHAPTER 8
Reports and Technology Transfer

Introduction

The data will be presented in the form of tables, graphs and reports. Such data will be offered in a form most suitable for technology transfer to industry. Reports will be issued semiannually, and as a final comprehensive report. Reports will be issued and offered to industry.

The second Semi-Annual report was delivered on schedule.

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