DOE/BC/15214-3
(OSTI ID: 807689)

Innovative MIOR Process Utilizing Indigenous Reservoir Constituents

By
D. O. Hitzman
A. K. Stepp
D. M. Dennis
L. R. Graumann

October 2001
Semi-Annual Report

Work Performed Under Contract DE-AC26-99BC15214

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

Virginia Weyland, Project Manager
National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by:
Geo-Microbial Technologies, Inc.
East Main Street
Ochelata, Oklahoma 74051

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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.

Research has begun on the program and experimental laboratory work is underway. Microbial 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. Sand pack flooding 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. Two field pilot studies are now underway.

EXECUTIVE SUMMARY

This project is an experimental laboratory study designed to improve the understanding of reservoir ecology, and to establish methods of manipulating indigenous microorganisms that 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 the 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 to Task 4 for inclusion 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 provides rapid introduction and evaluation of any system and/or product which is developed by this program, and will allow 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 microbial 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 thirteen through month twenty-four of the project. Chapter 2 describes the laboratory experiments, including 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 also detailed, as well as sand pack flood results. Physical models were used 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.

Chapter 3 details the two field pilot tests currently underway. Chapter 4 describes the work thus far on reports and technology transfer.

CHAPTER 2
Laboratory Experiments

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

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 multiplicity 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.

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 floodwater. 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 that were easily amended to realistic field water compositions allowed the preliminary test protocol to be established and controlled.

The role of VFA as a key component which leads to the biogenic formation of sulfide in reservoirs was pioneered at GMT. These investigations led 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 led 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

Nutrient Studies

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

Flooding Tests

Sand pack flooding experiments were conducted to determine the effects of various nutrients and flooding regimes. The sand pack columns were made of glass, and were in lengths ranging from 24 to 28 cm, and were 1.27 cm in diameter. Mill Creek sand was used for the sand packs.

A parallel sand pack flood was conducted to measure flow rate reduction due to biopolymer production. The experiment was conducted at room temperature. Sand packs PI-29 and PI-32 were saturated with Instant Ocean synthetic seawater brine. PI-29 was inoculated with a bacterial solution and an acetate/nitrate nutrient broth. Both packs were shut in for nine days. Flooding was then started with Instant Ocean amended with nitrate and acetate. Flow rates were measured periodically.

Oil Recovery Tests

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.

After brine saturation with Instant Ocean synthetic brine, oil saturation with Skiatook-11 crude oil obtained from an Oklahoma oil field, and waterflooding to residual oil saturation, packs PI-26 through PI-30 and PI-39 through PI-42 were inoculated using gravity feed with one pore volume (PV) of a mixed microbial consortium. The packs were shut in overnight. Flooding was then begun with Instant Ocean brine amended with acetate and/or nitrate. Details for each pack are reported in Table 3.

Table 3. Sand packs PI-26 through PI-30 and PI-39 through PI-42.

Sand pack #	Length (cm)	PV (ml)	OOIP (ml)
PI-26	25.4	14.0	10.8
PI-27	24.5	14.1	11.2
PI-28	27.1	12.2	9.2
PI-29	24.5	14.4	12.0
PI-30	25.0	14.2	11.2
PI-39	26.7	12.6	10.0
PI-40	24.4	13.3	10.9
PI-41	25.7	13.6	11.0
PI-42	26.0	13.6	11.4

Sand packs PH-1 and PH-2 were prepared using the same procedure as PI-26 through PI-30 except that Hominy field brine and oil (obtained from an Oklahoma oil field) were used. Details for each pack are shown in Table 4. Both packs were inoculated with microbial culture A1 combined with bacteria isolated from Hominy brine. PH-1 was a control, with no nutrient added. PH-2 was treated with Max-Well Waterflood Treatment, a proprietary nutrient formula.

Table 4. 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

A sand pack flood was conducted in a 10-foot long plastic tube with an inner diameter of 1.5 inches. The tube was packed with Mill Creek sand and saturated with Aera Belridge produced water (from a California field). The pack was then saturated with Skiatook-11 crude oil, and waterflooded to residual oil saturation. The test was conducted at 37° C. After waterflooding, the pack was inoculated with a microbial consortium and treated with Max-Well 2000 Waterflood Nutrient.

Results and Discussion

Nutrient Studies

Good microbial growth was observed in Nutrients 1, 2, 3, 5, and 7, as shown in Table 5. 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 5. Growth results.

	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

Flooding Tests

Results for the parallel sand pack flood are shown in Figure 1. The flow rate for the treated pack, PI-29, was substantially reduced due to polymer production by the injected bacteria.

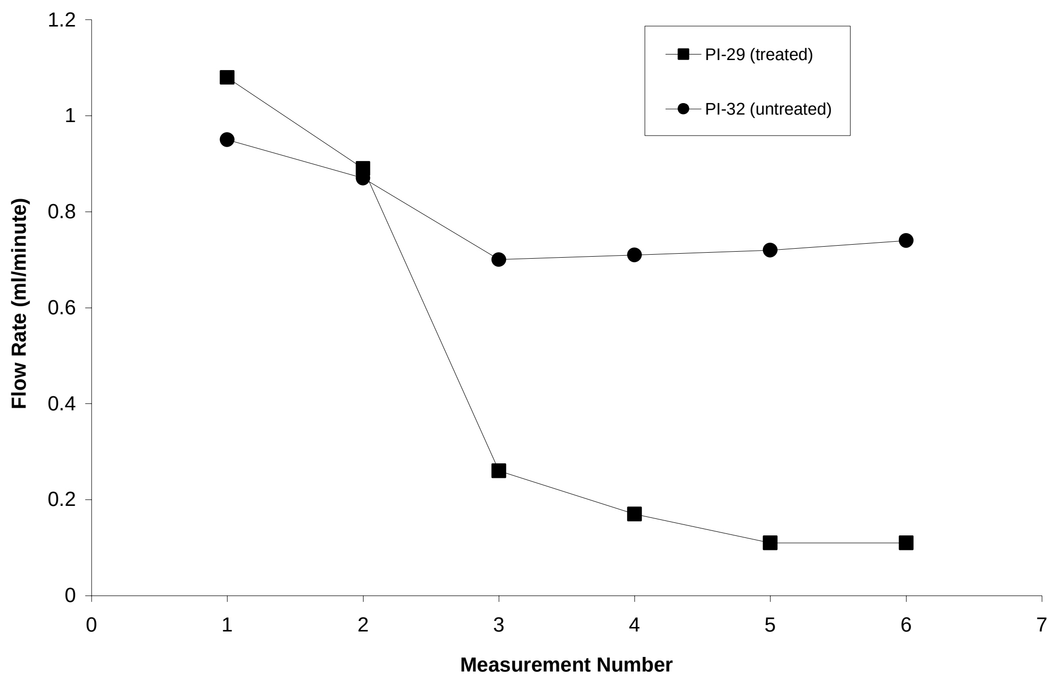

Figure 1. Flow rate reduction due to biopolymer production

Oil Recovery Tests

Sand packs PI-26 through 30 and PI-39 through 42 were shut in overnight, then waterflooded with Instant Ocean mixed with the nutrients listed in Table 6, which shows the oil recovery results for the sand packs. Results for PI-39 through 42 are also shown in Figure 2.

Table 6. Sand packs PI-26 through 30 and PI-39 through 42 oil recovery results.

Sand pack #	Waterflood Recovery (%)	Treatment Type	Treatment Recovery (%)	Final Recovery (%)
PI-26	66.2	0 nitrate, 100 acetate	5.6	71.8
PI-27	63.4	100 nitrate, 0 acetate	0.9	64.3
PI-28	71.7	100 nitrate, 100 acetate	1.1	72.8
PI-29	65.8	100 nitrate, 500 acetate	1.7	67.5
PI-30	58.0	100 nitrate, 1000 acetate	0.9	58.9
PI-39	70.0	0 nitrate, 0 acetate	2.0	72.0
PI-40	66.1	1000 nitrate, 0 acetate	4.6	70.7
PI-41	70.0	0 nitrate, 1000 acetate	0.9	70.9
PI-42	64.0	1000 nitrate, 1000 acetate	14.5	78.5

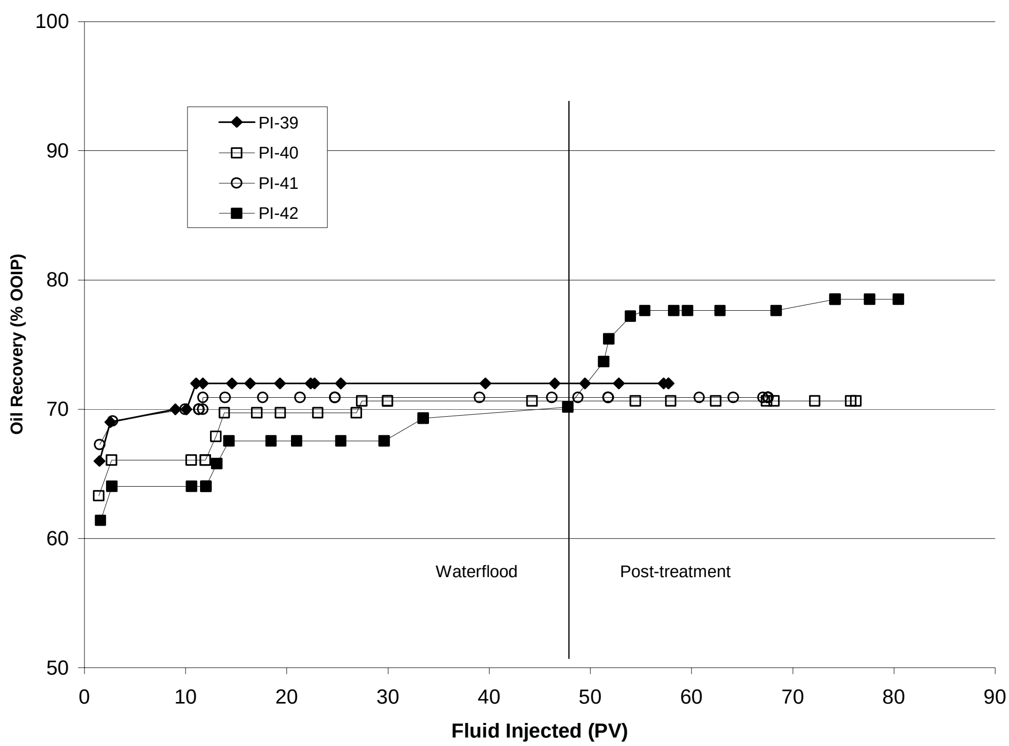

Figure 2. Oil recovery results for PI-39 through PI-42.

Figure 3 shows the oil recovery results for PH-1 and PH-2. The flood with Max-Well Waterflood Treatment increased the oil production by 2.3%.

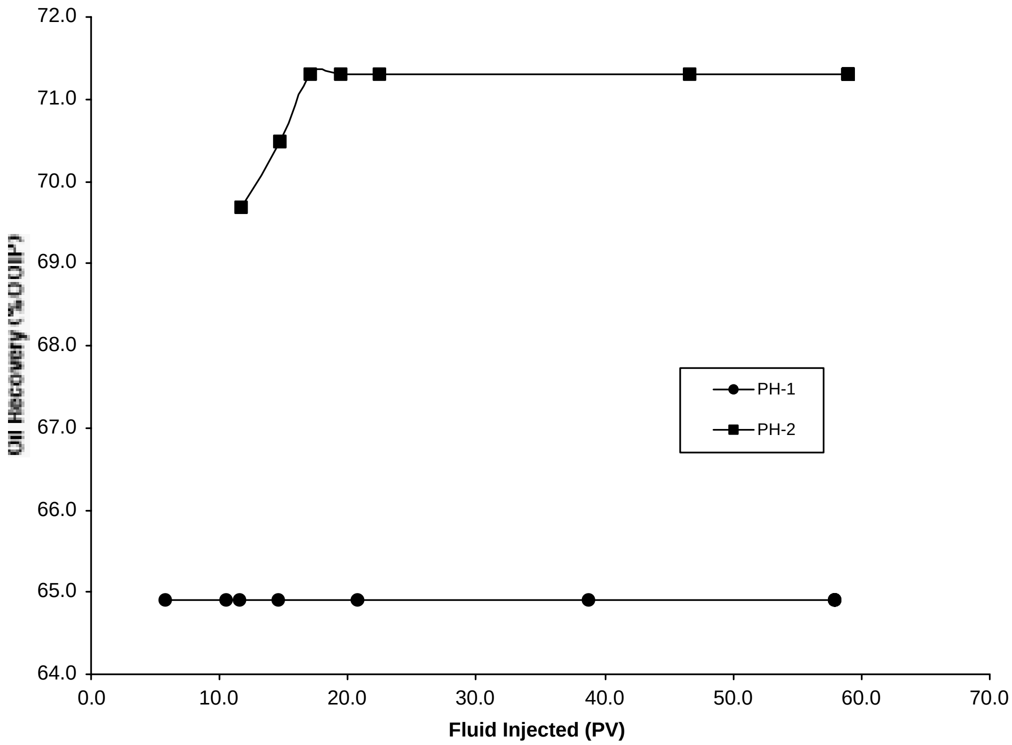

Figure 3. Sand packs PH-1 and 2 oil recovery results.

Results of the 10 foot sand pack flood are shown in Figure 4. Oil production was increased from 77.5% by waterflooding alone to 80.7% after nutrient treatment.

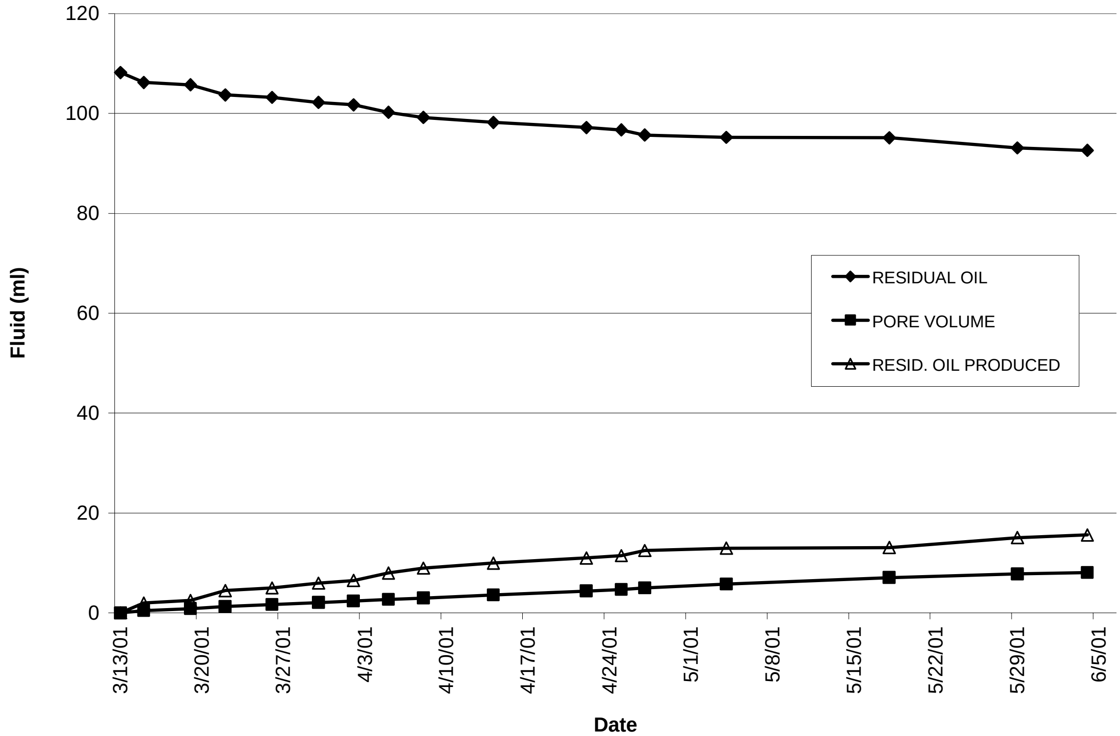

Figure 4. 10 ft. sand pack microbial flood.

Conclusions

- Low-cost inorganic nutrients can be used to stimulate growth of indigenous bacteria.
- Indigenous oilfield bacteria can be stimulated to produce biopolymer and cause a decrease in flow rate using a nitrate/acetate-based nutrient.
- In most cases, the addition of both nitrate and acetate was necessary for increased oil production.

CHAPTER 3
Field Evaluation of New Technology/Products

Introduction

As results have been obtained from the laboratory investigations and are made available to field operations through technology transfer, the findings have been offered and applied to field studies, situations, and operations. As the laboratory results are incorporated into pilot field projects, these field operations are being closely followed and monitored. The identifications of such fields and participation of the operators will provide additional feedback data from such projects. These pilot field evaluations are being 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. will be minimized. A pilot study has been implemented with operator assistance. This approach has allowed rapid introduction and evaluation of systems/products that have been developed by this program and provides directly comparable data. This method of field testing offers a low cost and easily approved and operated system to introduce the technology/products which have been developed in this research program.

Pilot Field Tests

Two field tests with Aera Energy are currently underway in California.

One field test was started in March 2001 in the Lost Hills field. The Lost Hills oil field was discovered in the early 1900's (1910 to 1915). Production has grown since that time. The zone associated with this microbial enhanced recovery is the deep marine diatomaceous shale. The very high porosity varies from 45 to 70% with a very low permeability of 0.1 to 3 millidarcies. Oil saturations vary from 30 to 60% with producing API gravities from 26 to 28 driven by a solution gas drive. The reservoir thickness varies from 700 to 1700 feet with the top of the formation varying from 1500 to 2300 feet.

The field has been waterflooded for several years. The test area includes a set of control wells (two injection wells and seven production wells) and a set of treatment wells (three injection wells and nine production wells). Treatment was started on March 20, 2001 using a proprietary blend of Max-Well 2000 product. The process relies on nutrient stimulation of the indigenous microbial population to produce oil-releasing byproducts such as nitrogen, carbon dioxide, methane, surfactants, solvents, alcohols, and biopolymers. The nutrient is being injected continuously with the waterflood, which has a temperature of 100° F. Results to date are shown in Figures 5-8.

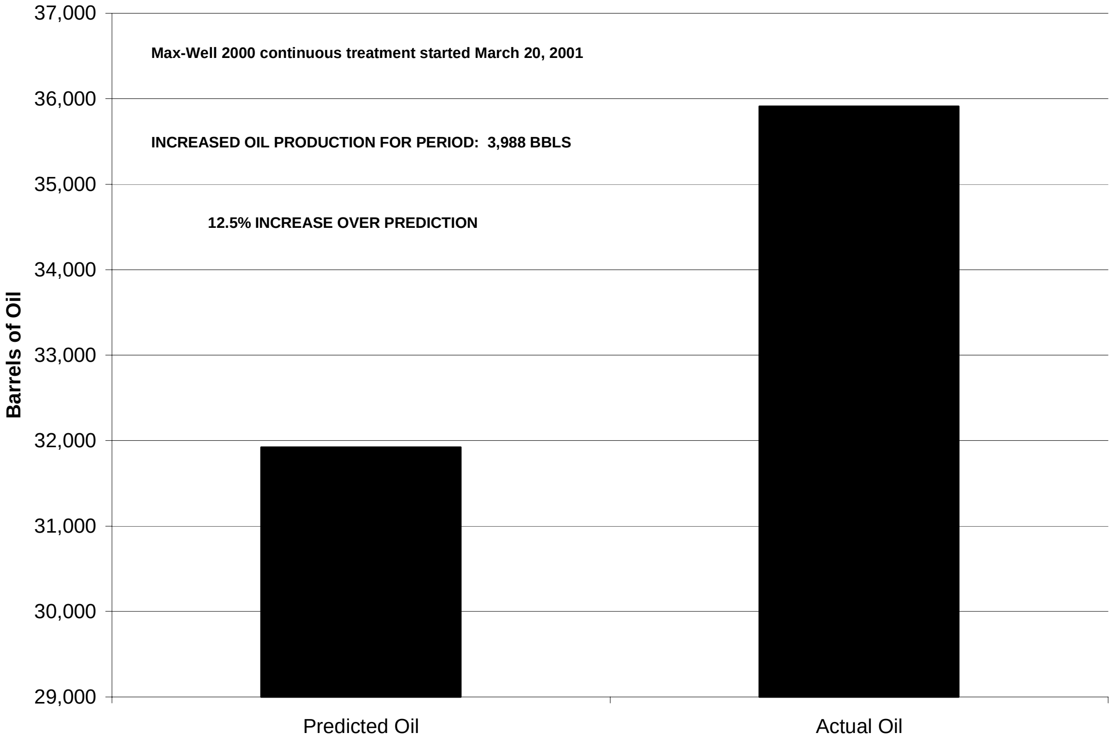

Figure 5. Combined production for nine test wells, Mar. 20 – Sept. 30, 2001.

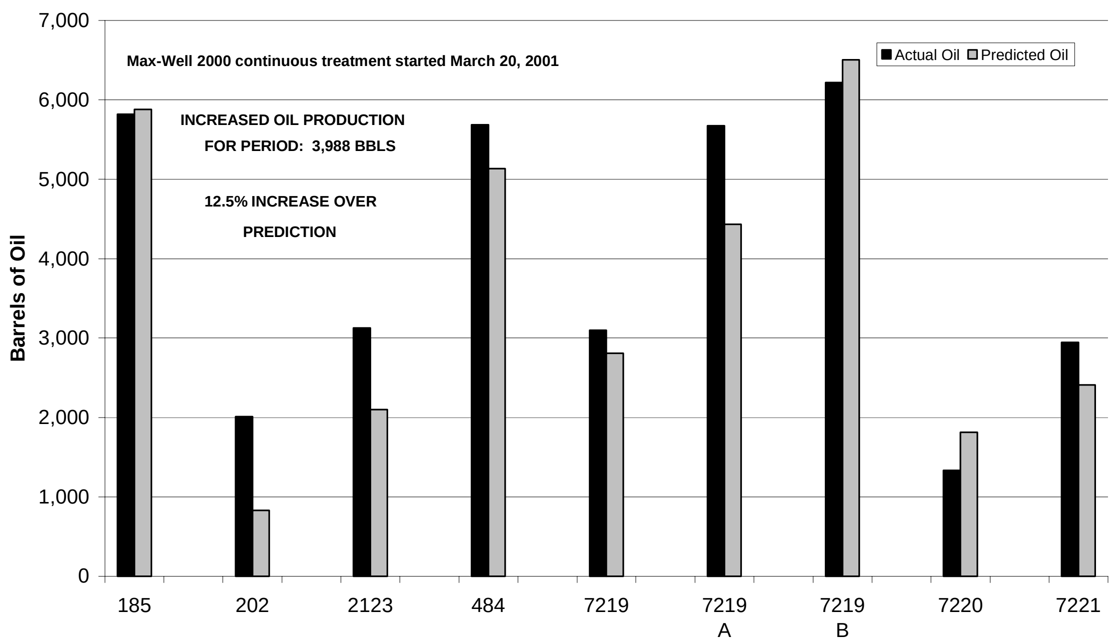

Figure 6. Test well production Mar. 20 – Sept. 30, 2001.

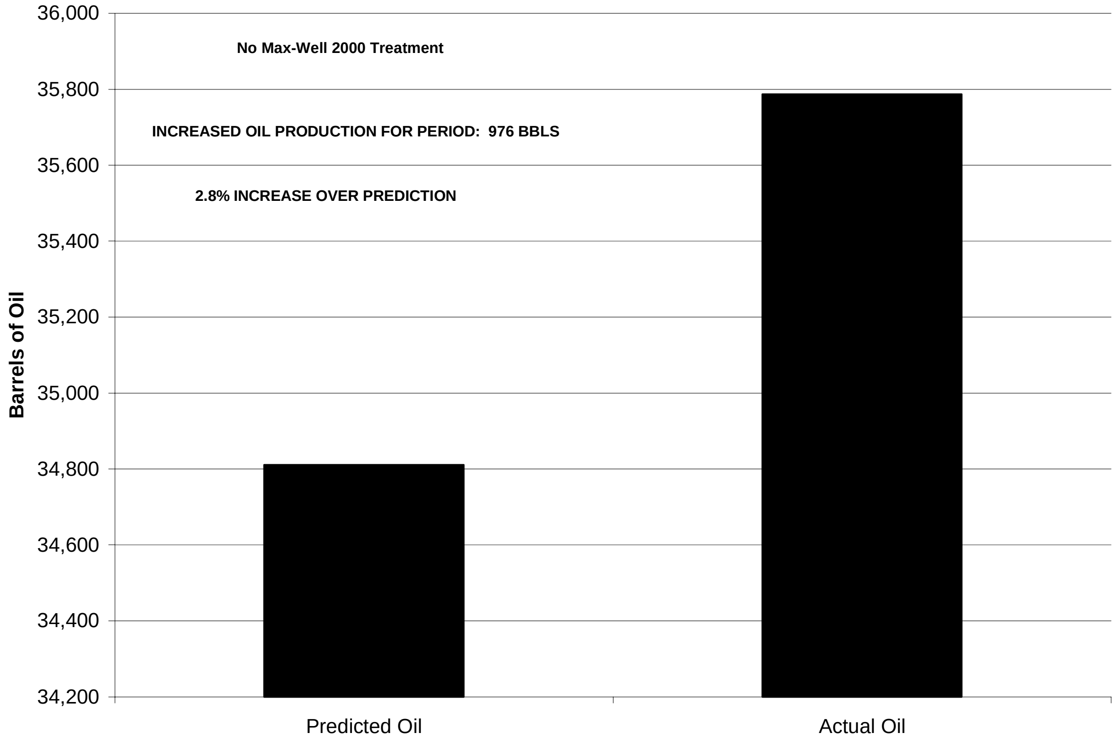

Figure 7. Combined production for seven control wells, Mar. 20 – Sept. 30, 2001.

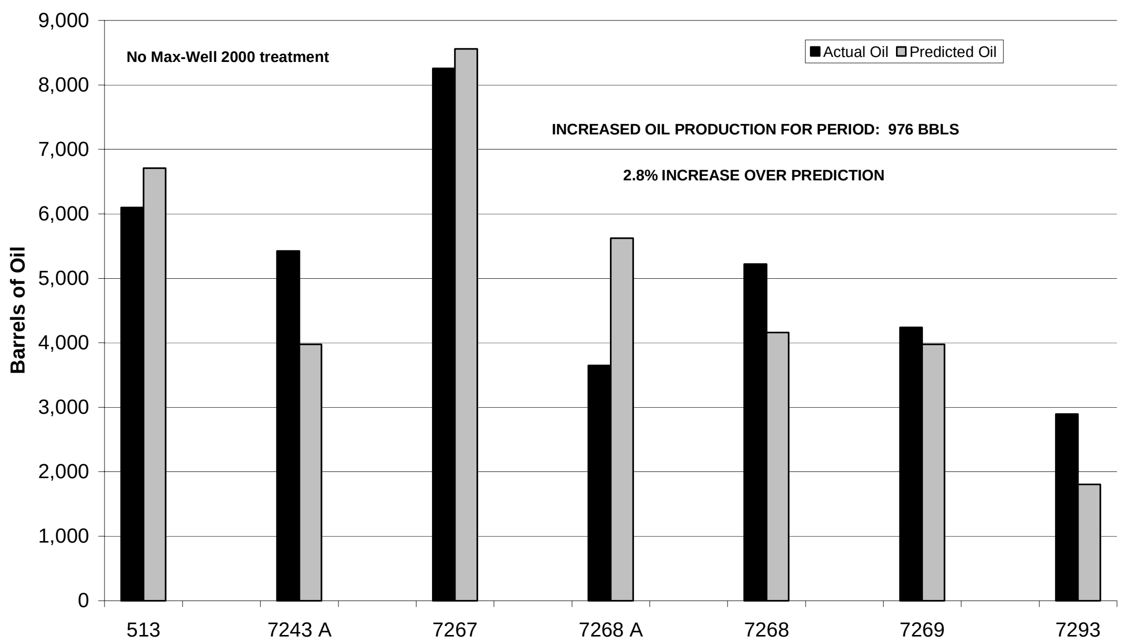

Figure 8. Control well production Mar. 20 – Sept. 30, 2001.

A second field test is being conducted with Aera Energy in the Belridge field. The objective is to use a different Max-Well nutrient product to reduce H_2S and improve the water/oil ratio (WOR) in three ways: suppress growth of sulfate reducing bacteria while increasing the population of denitrifying bacteria; reduce iron sulfide in the near-wellbore area to free up production pathways; and stimulate indigenous bacteria to produce oil-releasing byproducts. The treatments were started September 14, 2001. The field will be treated with monthly batch treatments, rather than on a continual basis. Results will be available in the next report.

CHAPTER 4
Reports and Technology Transfer

Introduction

Reports have been issued semiannually, and will also be published in a final comprehensive report. Reports will be issued and offered to industry.

The third Semi-Annual report was delivered on schedule.

Presentations and publications

Hitzman, D. O., and S. A. Bailey. 2000. Innovative MIOR Process Utilizing Indigenous Reservoir Constituents. DOE Semi-Annual Report, January 2000.

Hitzman, D. O., S. A. Bailey, and A. K. Stepp. 2000. Innovative MIOR Process Utilizing Indigenous Reservoir Constituents. DOE Semi-Annual Report, July 2000.

A presentation on the project was made at the Oil Technology Program Contractor Review Meeting in Denver in June 2000 by Scott Bailey.

Hitzman, D. O. and A. K. Stepp. 2001. Innovative MIOR Process Utilizing Indigenous Reservoir Constituents. DOE Semi-Annual Report, January 2001.

Presentations as part of GMT Exhibit Booth

Society of Geophysicists (SEG) Annual Convention, October 31-November 5, 1999, Houston.

GEO 2000, Middle East Oil and Gas Exposition, March 27-29, 2000, Bahrain.

Society of Petroleum Engineers (SPE) DOE Improved Oil Recovery Symposium, April 2-5, 2000, Tulsa.

American Association of Petroleum Geologists (AAPG) Annual Convention, April 16-19, 2000, New Orleans.

NAPE (North American Prospect Exposition), January 31-February 1, 2001, Houston.

AAPG, March 9-13, 2001, Dallas.

SPE, March 24-27, 2001, Oklahoma City.

Oklahoma Geological Survey, May 8-9, 2001, Oklahoma City.

AAPG Annual Convention, June 2-7, 2001, Denver.

CSPG (Canadian Society for Petroleum Geologists), Annual Convention, June 16-20, 2001, Calgary.

REFERENCES

1. ZoBell, C. E. 1946. Bacteriological Process for Treatment of Fluid-Bearing Earth Formations. U.S. Patent No. 2,413,278.

2. Hitzman, D. O. 1962. Microbiological secondary recovery of petroleum. U.S. Patent No. 3,032,472

3. Hitzman, D. O. 1983. Petroleum Microbiology and the History of Its Role in Enhanced Oil Recovery. Proc. of the 1982 International Conference on Microbial Enhancement of Oil Recovery, Afton, OK, May 16 – 21, 1982.

4. Sperl, G. T., P. L. Sperl, and D. O. Hitzman. 1993. Use of Natural Microflora, Electron Acceptors and Energy Sources for Enhanced Oil Recovery, In: E. T. Premuzic and A. Woodhead (ed.), Microbial Enhancement of Oil Recovery - Recent Advances, Elsevier Science Publishers, New York, NY.

5. Hitzman, D. O., and S. A. Bailey. 2000. Innovative MIOR Process Utilizing Indigenous Reservoir Constituents. DOE Semi-Annual Report, January 2000.