NIPER/BDM-0072

DRAFT

Status Report

LABORATORY EXPERIMENTS FOR DEVELOPMENT OF MICROBIAL EOR PROCESS SIMULATOR

by
Anita Stepp and Rebecca S. Bryant, Ph.D.

September 1994

Work Performed Under Contract No.
DE-AC22-94PC91008

Prepared for
U.S. Department of Energy
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Distribution Category UC-122

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ABSTRACT

Application of microbial enhanced oil recovery (MEOR) technology to increase oil production requires careful laboratory design of the microbial formulation to optimize its performance for the particular application, reservoir characterization to define the important geological parameters, and reservoir engineering design to ensure the method is applied in an efficient, environmentally acceptable, and cost-effective manner. Microbial methods for improving oil recovery are particularly well suited to be applied in today's economic climate. The lower price of crude oil and a more general acceptance of use of biotechnological processes have contributed to increased interest in MEOR.

The goal of BDM-Oklahoma MEOR research is to develop an engineering methodology for designing and applying MEOR to improve oil recovery. Different types of microorganisms can improve oil recovery in various ways. NIPER's research has focused primarily on surfactant and gas-producing microbes that are capable of improving microscopic oil displacement efficiency. Microorganisms can also be used to plug high-permeability channels to divert injected fluid. Work this year concentrated on developing a biopolymer-based method of imparting sweep improvement.

Work on identifying an alternative biochemical system is promising. Conditions where this system can be applied have been mapped. An upper limit for salinity tolerance and applicable pH range has been determined and an upper temperature limit for polymer production has been established. Optimum sucrose concentration to maximize growth of the cells was determined. Initial coreflooding tests with this system indicated positive performance in reducing the effective permeability of a consolidated core.

Further studies need to be conducted to evaluate the potential of this system to impart fluid diversion. These studies would include additional corefloods to determine the effect of gas production without polymer production on permeability reduction. Additional insight into controlling in-depth placement of this type of treatment will be needed.

ACKNOWLEDGMENTS

This work was sponsored by the U.S. Department of Energy under M&O contract agreement DE-AC22-94PC91008. The authors wish to thank Drs. Arfon H. Jones and Feliciano M. Llave of BDM-Oklahoma for their guidance and advice in conducting the study, Kathleen M. Bertus, Idell A. Cook, Deanna B. Evans, also of BDM-Oklahoma, and Renee Horning and Scott Bailey, DOE/AWU Summer Internees, for their assistance in all phases of the experimental work performed for this project.

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1.0 INTRODUCTION

NIPER's microbial research has achieved both long-term and near-term goals, including the improved understanding of the mechanisms of oil mobilization by microbial formulations and transport of microbes and their metabolites in porous media. Results have shown that a key component in the oil mobilization mechanism is the capability of microorganisms to produce localized high concentrations of products at an oil-water interface. The concepts and data from this basic research project have formed the basis of applied research needed to develop an engineering methodology for designing and optimizing microbial formulations for specific field applications.

The available information developed at NIPER for specific microbial formulations is now being expanded to design and develop a simulator for MEOR processes. One of the major constraints to MEOR technology has been the lack of simulation data to adequately describe and predict the MEOR processes both in the laboratory and in the field. While several attempts have been made to modify existing reservoir simulators to describe microbial processes, no model has yet fully incorporated all of the complex phenomena that are believed to be important. The unusual complexity of oil recovery by microbial formulations requires close coordination between laboratory mechanistic studies and oil displacement experiments under carefully controlled conditions to develop and validate a computer model. Mechanisms considered to be important for oil recovery include changes in microscopic properties such as interfacial tension, wettability, and adsorption that govern oil mobilization and affect fractional flow and relative permeabilities. Other oil recovery mechanisms traditionally associated with fluid flow changes include polymer and biomass production by microorganisms.

2.0 MICROBIAL EOR PROCESS SIMULATOR

Microbial methods for increasing oil recovery are potentially cost-effective, even at relatively low crude oil prices. Microbial formulations can be applied in a variety of methods, including permeability modification treatments, single-well stimulation, and microbial-enhanced waterflooding. The flexibility and potential cost-effectiveness of the technology make it attractive, but further understanding of the transport mechanisms of microorganisms and development of a sound engineering methodology for optimizing microbial formulations and injection strategies through modeling studies are needed to realize its potential.

The transport of microorganisms (bacteria, fungi, and viruses) in porous media governs many phenomena in bioremediation of environmental pollution problems and microbial enhanced oil recovery. The transport of microorganisms in subsurface formations is associated with complicated physical, chemical, and biological phenomena such as adsorption, interaction between microorganisms and substrate, and growth and decay of cells. However, limited information exists concerning the transport, growth, and metabolism of viable cells in subsurface environments. Some of the phenomena are still not well understood.

Although several attempts have been made to describe microbial processes, no model has yet fully incorporated all of the complex phenomena believed to be important. The complexity of oil recovery by microbial formulations requires close coordination between laboratory mechanistic studies and oil displacement experiments under carefully controlled conditions to develop and validate a computer model.

The microbial transport simulator (MTS) is a three-dimensional, three-phase, multiple-component numerical model that permits the study of the transport of microorganisms and nutrients in porous media. Microbial parameters incorporated into MTS include: microbial growth and decay, microbial deposition, chemotaxis, diffusion, convective dispersion, tumbling, and nutrient consumption. Governing equations for microbial and nutrient transport are coupled with continuity and flow equations under conditions appropriate for a black oil reservoir.

Incorporation of MTS into a Microbial EOR Process Simulator will be a key factor to establishing a capability to engineer a microbial enhanced recovery project. Comparisons of the Microbial EOR Process Simulator predictions will be made with results of critically designed laboratory experiments.

2.1 Recommendations

Results from experiments conducted this year will be incorporated into the Microbial EOR Process Simulator. Further experiments are needed to provide more data for the simulator. Relative permeability and pressure drop experiments would provide useful data for the simulator.

3.0 MICROBIAL PERMEABILITY MODIFICATION

A polymer-producing microorganisms designated as NIPER 11 was isolated from frozen peas. This microorganism was tested with various nutrients to find the best polymer-producing system. Many experiments were conducted to define conditions in which this system would be effective for permeability modification. This strain of microbe ferments sucrose and produces lactic acid, acetic acid, ethanol, and a polymer, dextran. This polymer can be used to plug high-permeability zones in petroleum reservoirs, diverting fluids to oil-bearing low-permeability zones.

Experiments were conducted to evaluate the effects of salinity, pH, temperature, and nutrient concentration on growth of microorganisms and polymer production. Coreflooding experiments were conducted to determine the feasibility of the application of this system for pore plugging.

3.1 Materials

Solutions were prepared on a weight/volume basis. Microbial counts were determined using the Standard Plate Count Method. An Orion model 301 pH meter was used for all pH measurements. Berea sandstone core was used for all corefloods.

3.2 Salinity Tolerance

An experiment was conducted with NIPER 11 in standard nutrient (10% sucrose and 1% peptone in deionized water) using salinity concentrations ranging from 0% NaCl–5% NaCl. The test tubes were incubated aerobically at 28°C. In the range from 0%–4%, good growth was achieved, although it took longer to reach maximum growth at the higher salt concentrations (Figure 3–1). In the range of 4.5 to 5%, growth remained level throughout the length of the experiment (103 hours). Polymer production was good at 0% and 0.5% NaCl, but no polymer was visible in the tubes with higher salt concentrations up to the end of the experiment. The tubes were checked again at 552 hours, and polymer was observed in the salinity range up to 2% NaCl.

A second salinity gradient experiment was conducted over a longer time period to determine if growth would eventually increase at the higher salinity levels. NaCl concentrations ranged from 4% to 6% (Fig. 3–2). Microbial counts decreased in all concentrations of NaCl, but increased after 100 hours for the 4% NaCl. Growth could be delayed by the NaCl. Small amounts of polymer were produced in 4% NaCl after 300 hours incubation at room temperature (approximately 25°C, which is optimum for polymer production according to the literature). The upper limit for microbial growth appears to be 4% NaCl. Sample size seems to affect polymer production and/or consistency of the gel. When 10-mL test tubes are used, polymer is easily visible as a solid mass. When larger flasks are used, polymer is not visible as a solid mass, but is observed as more particulate. This may be due to adhesion of cells to surfaces, which would occur more readily in smaller volumes such as test tubes.

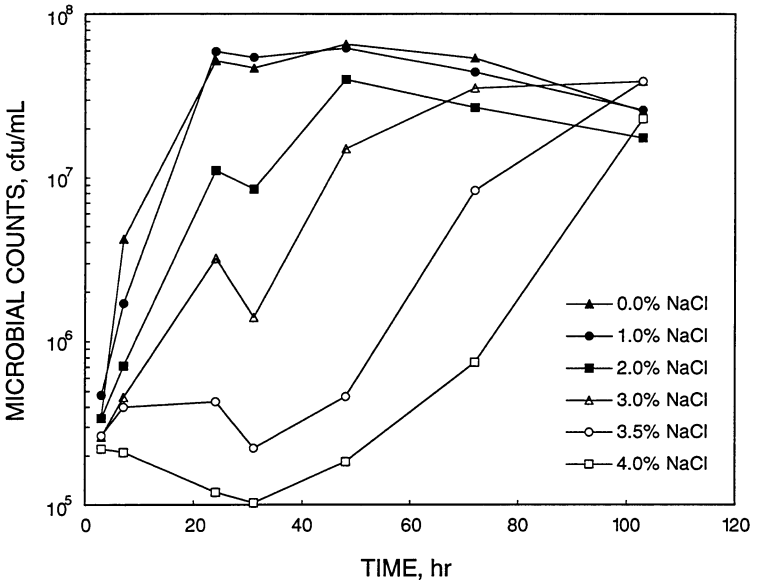

Figure 3–1 Effect of salinity on growth of NIPER 11 (0%–4%NaCl)

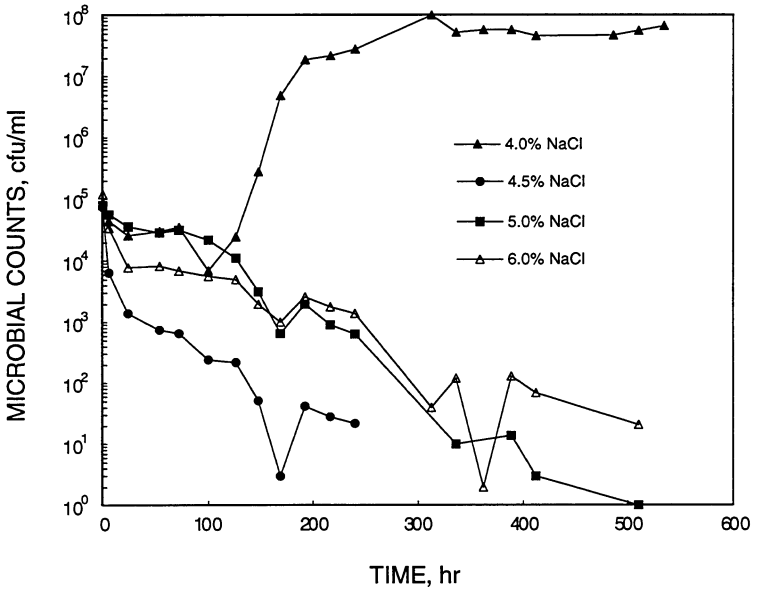

Figure 3–2 Effect of salinity on growth of NIPER 11 (4%–6% NaCl)

3.3 pH Experiments

An experiment to evaluate growth and polymer production in standard nutrient with a pH range of 3–6.45 was conducted. The flasks were incubated aerobically at 28°C. Acid production by NIPER 11 reduced the pH to around 4 (Fig. 3–3). Growth was very good in the pH range of 4.5–6.45. Polymer was produced only in the pH range of 5.5–6.45. An experiment was conducted using buffered solutions to keep the pH constant. The standard nutrient solution was buffered with soluble buffers ranging from pH 3 to pH 6.45 (Fig. 3–4). The flasks were incubated aerobically at 28°C. Small amounts of polymer were produced in nutrient with pH 5, 6, and 6.45. No polymer was produced at pH 3 and 4. The pH had to be adjusted daily in the pH 6 and 6.45 flasks. Further experiments studied the effect of using insoluble buffers in the nutrient solutions on overall solution properties. According to the literature, the pH of media used for growing bacteria that produce large amounts of acid cannot be controlled by soluble buffers. Experiments were conducted to test growth and polymer production of NIPER 11 in nutrient with a high pH since the coreflood effluent had a pH between 8 and 8.4. An experiment to evaluate growth and polymer production of NIPER 11 in standard nutrient (10% sucrose, 1% peptone, and 0.5% NaCl in deionized water) buffered with 0.3% calcium carbonate was conducted. Each of the nutrients were adjusted to pH 5, 6, 7, 8, and 9. Flasks were incubated aerobically at 30°C. Polymer production was apparent in the pH 5 nutrient only. Growth was considerably less in the higher pH range (Fig. 3–5).

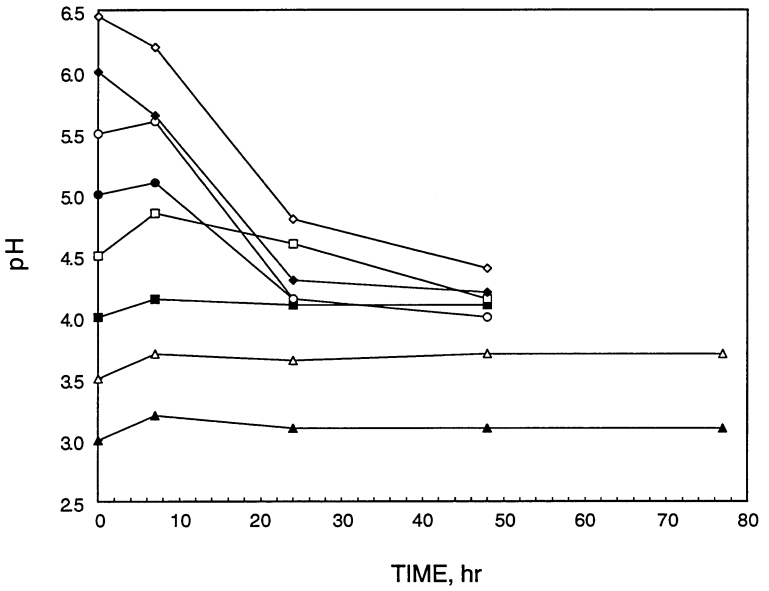

Figure 3–3 Microbial alteration of pH.

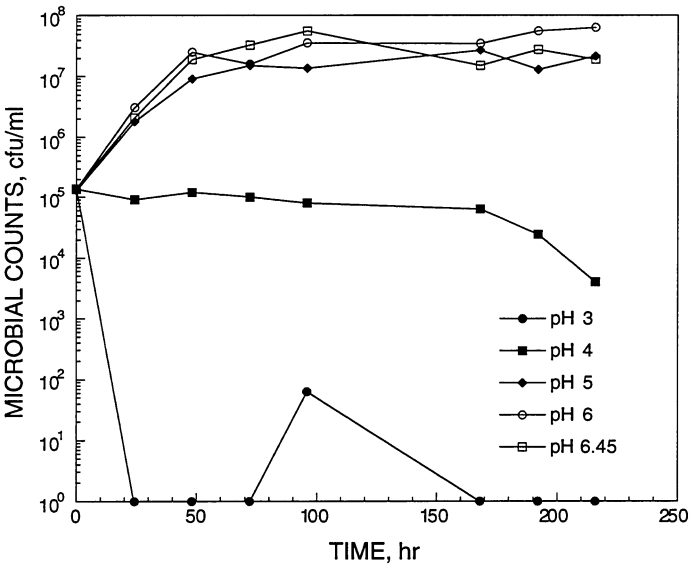

Figure 3–4 Effect of pH on growth of NIPER 11 (pH 3 –6.45).

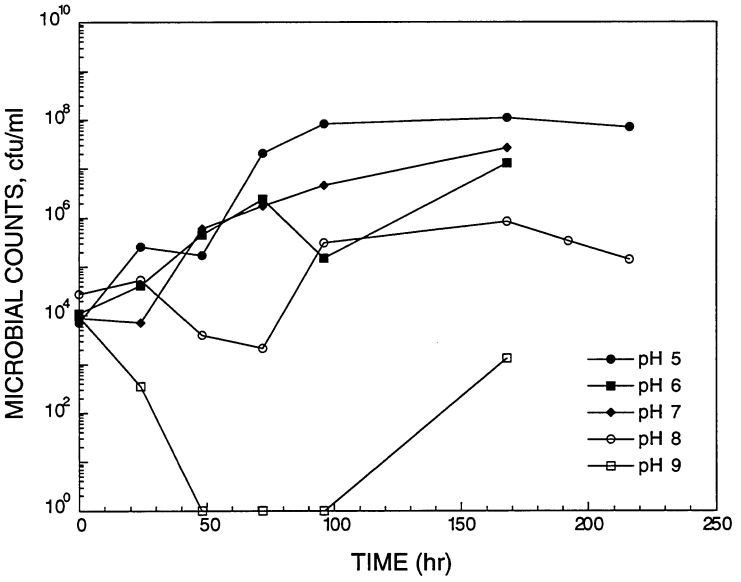

Figure 3–5–Effect of pH on growth of NIPER 11 (pH 5–9).

3.4 Temperature Effects

NIPER 11 was incubated at 35°C to test the effects of this temperature on bacterial growth and polymer production. Standard nutrient was used, and the bacteria were incubated aerobically. (Fig. 3–6). A small amount of polymer was produced.

3.5 Nutrient Concentration Experiments

A nutrient concentration experiment was conducted (Fig. 3–7). The media contained 1% peptone, 0.5% NaCl, and sucrose ranging from 2.5%–30%. The flasks were incubated aerobically at 28°C. A small amount of polymer was produced in all concentrations of sucrose. The pH was reduced from around 6.4 to 4.2 in all concentrations. A sucrose concentration of 10% is enough to give good growth and polymer production, so higher concentrations are not necessary.

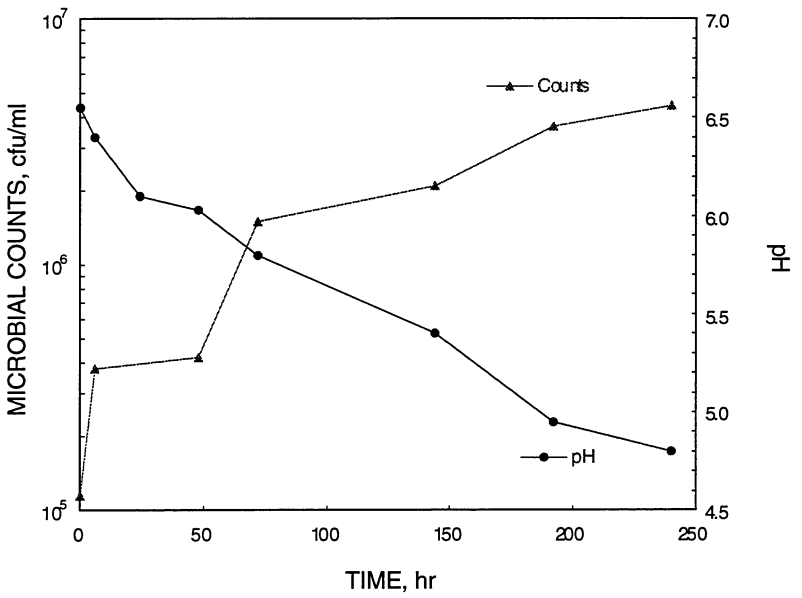

Figure 3–6 Effect of temperature on growth and acid production of NIPER 11 (0–250 hrs).

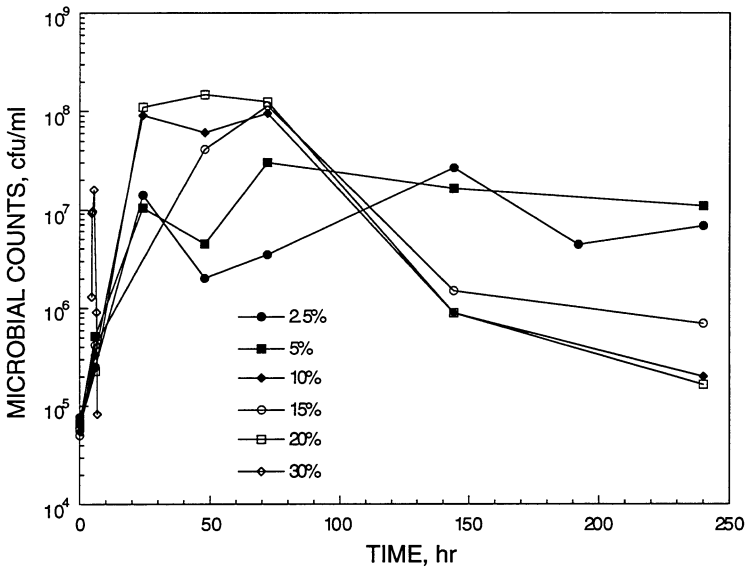

Figure 3–7 Effect of sucrose concentration (wt%) on growth of NIPER 11.

Attempts were made to measure the viscosity of NIPER 11 polymer with the Brookfield viscometer. The polymer was too thick to be measured by this instrument. Other methods will have to be used to evaluate polymer viscosity.

An experiment was conducted to determine whether polymer production would be increased by the presence of glass beads in a test tube. This would provide more surface area for cell adhesion. Ten-mL test tubes were packed with 5-mm-diameter glass beads. The test tubes were then filled with standard sucrose-peptone nutrient and inoculated with NIPER 11. A control tube was also used, which did not contain glass beads. The tubes were incubated aerobically at 30°C for five days. The polymer was thicker in the control tube than in the glass bead tubes. Other methods for enhancing polymer production will be investigated.

3.6 Coreflooding Experiments

A brine-saturated high permeability brown Berea core was injected with NIPER 11 microbes grown in standard nutrient to determine if microbial polymer production would cause plugging. The microbes were injected at 0.22 mL/min. The pressure drop increased from 0.25 psi to 39.5 psi after injecting 6 PV of microbes. The permeability was reduced from 3 darcies to 19 mD (Table 3–1).

A 467-mD Berea core was saturated with brine, followed by oil, then waterflooded to residual oil saturation. The permeability after waterflooding was 54 mD. The core was then injected with 0.5 PV NIPER 11 in nutrient broth, followed by 0.5 PV nutrient broth. The core was shut in for five days, then waterflooded at 1 ft/D. The additional oil recovery was low, 4.9% recovery efficiency, but the permeability was reduced to 3 mD. The pressure drop during waterflooding rose to 35 psi.

A 483-mD Berea core was saturated with brine, followed by oil, then waterflooded to residual oil saturation. The permeability after waterflooding was 26 mD. The core was then injected with 0.2 PV NIPER 11 in nutrient broth, followed by 0.3 PV nutrient broth. The core was shut in for five days, then waterflooded at 1 ft/D. Recovery efficiency was 10.8%. Permeability was reduced to 5 mD. Pressure drop during waterflooding rose to 33.5 psi.

Another coreflood was completed using NIPER 11. A Berea core was saturated with 0.5% NaCl brine, then injected with 1 PV of standard nutrient that had just been inoculated with NIPER 11 microorganisms. The injection was done at 1 ft/D; then the core was shut in and incubated for six days at room temperature. The permeability of the core was reduced from 500 mD to 30 mD. NIPER 11 also produces gas, so the reduction in permeability may be due to both gas and polymer production.

An experiment to evaluate gas production by NIPER 11 in various nutrients was conducted. NIPER 11 was incubated aerobically at 30°C in 10 mL of each nutrient solution. Each solution consisted of 10% sugar, either 1% peptone or 2% yeast extract, and either 0% NaCl or 2% NaCl. Gas production and growth were evaluated after 48 hours incubation. NIPER 11 grew well in all the nutrients. Good gas production was observed in most of the nutrient solutions (Table 3–2).

Table 1 Biopolymer Corefloods

Initial Permeability (mD)	Permeability After Treatment(mD)	Maximum Pressure Drop (psi)
3,000	19	39.5
467	54	35.0
483	26	33.5
500	30	N/A

Table 2 NIPER 11 Gas Production With Various Nuitrients

Nutrient	Gas Production (cc)
Fructose, yeast extract	1.4
Fructose, yeast extract, NaCl	1.3
Glucose, yeast extract	1.5
Glucose, yeast extract, NaCl	1.5
Fructose, peptone	1.4
Fructose, peptone, NaCl	0.1
Glucose, peptone	0.0
Glucose, peptone, NaCl	0.0
Fructose, TSB (tryptic soy broth)	1.6
Fructose, TSB, NaCl	1.4
Glucose, TSB	1.4
Glucose, TSB, NaCl	1.0

3.7 Summary and Recommendations

Work on identifying an alternative biochemical system for permeability modification is promising. Conditions where this type of system can be applied have been mapped. An upper limit for salinity tolerance for NIPER 11 has been determined to be 4% NaCl. A salinity gradient approach has been speculated as a means of providing in-depth permeability modification for this system. The applicable pH range for this system has been established at 4.5–8. The maximum temperature limit for polymer production appears to be between 30° and 35°C. A minimum sucrose concentration for polymer production was determined to be 10%. Coreflooding experiments with NIPER 11 effectively reduced permeability.

Further studies need to be conducted to evaluate the potential of this system to impart fluid diversion. These studies would include corefloods to determine the effect of gas production without polymer production on permeability reduction. Other factors to be investigated are the effect of container or sample size on the amount of polymer production. A method to evaluate polymer amount and consistency or viscosity should be developed. Additional insight into controlling in-depth placement of this type of treatment will be needed.

4.0 MICROBIAL THREE-PHASE RELATIVE PERMEABILITY

An investigation was conducted to determine if treating a brine and oil saturated Berea core sample at residual oil saturation conditions with a microbial solution would cause a change in the shape of the sample's oil relative permeability curve. Imbibition cycle oil/brine steady-state relative permeability measurements were recorded first. Next, three pore volumes of a broth containing NIPER 1A and NIPER 6 microbes were injected through the core. The broth pumped into the core was turbid. The produced fluid was clear. The pressure drop across the core increased as the broth was injected, indicating material filtered from the broth reduced the permeability of the core. During the following eight-day shut-in period, no gas was produced, suggesting the microbes were not active. No additional oil was produced. Several additional oil/brine steady-state measurements were recorded during a final drainage cycle. Post-microbial injection relative permeabilities were fairly similar to the pre-injection values. Differences were probably the result of plugging from biomass filtered from the broth by the core.

After this experiment, the three-phase relative permeability apparatus was modified and now requires that the oil and brine both be tagged. Tests were conducted to determine whether the microorganisms would be compatible with chemicals used for tags. The minimum recommended concentration of these chemicals is seven percent sodium iodide and seven percent bromodecane. Another possible inhibitory effect is the metal cylinder used to inject microbes into the coreholder, so this was also tested by placing a piece of stainless steel tubing into test tubes. Microorganisms NIPER 1A and NIPER 7A were grown in ten milliliters TSB with and without metal tubing, and with and without sodium iodide and bromodecane (seven percent sodium iodide in TSB, with one milliliter Soltrol 100 oil containing seven percent bromodecane added). Growth and gas production were very good in tubes with TSB and TSB with metal tubing. Growth and gas production were very poor in tubes containing sodium iodide and bromodecane.

4.1 Materials

Nutrient solutions were prepared on a weight/volume basis. Brine and oil solutions were prepared on a weight/weight basis. Berea sandstone core was used for the coreflood. The oil used, Soltrol 100, is an isoparaffinic product of Phillips Petroleum Company.

4.2 Recommendations

Use of the three-phase relative permeability apparatus for microbial coreflooding experiments is not feasible unless a lower concentration of these chemicals can be used. Other methods of conducting the experiments should be investigated.