

Status Report

**DEVELOPMENT OF AN MEOR PROCESS SIMULATOR FOR
LABORATORY AND POROUS MEDIA STUDIES**

Project BE3, FY90 Annual Research Plan, Milestone 6

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ABSTRACT

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 purpose of this study is to investigate the efficiency of microbes to modify reservoir heterogeneity and improve oil recovery. The transport of microorganisms in the subsurface formation is governed by many complicated physical, chemical, and biological phenomena, such as adsorption, interaction between microorganisms and substrate, and the growth and decay of cells. Little information exists concerning the transport, growth and metabolism of viable cells in subsurface environments. Some of the phenomena are still not well understood. This report will present our progress on development of a three-dimensional, three-phase, multiple-component numerical model to describe microbial transport phenomena in porous media.

INTRODUCTION

Microbial methods for increasing oil recovery are potentially cost-effective even at relatively low crude oil prices. The technology is comparatively easy and inexpensive to implement so that it can be applied by independent petroleum producers once the optimal system has been designed. Microbial formulations can be applied in a variety of methods including well stimulation treatments, permeability modification treatments, and microbial-enhanced waterflooding. The flexibility and potential cost-effectiveness of the technology make it attractive, but further understanding of the mechanisms of oil mobilization by microorganisms and the development of a sound engineering methodology for optimizing microbial formulations are needed to realize its potential. Development of the methodology for applying microbial technology for improving oil recovery requires an integrated laboratory and field research effort to identify and understand the mechanisms of oil recovery, to determine the relative importance of these mechanisms in oil mobilization by laboratory experimentation, to develop mathematical correlations and models to describe the physical phenomena, and to develop and apply a mathematical computer reservoir simulator to match laboratory

coreflooding results and ultimately match and predict oil recovery performance in field applications. The goal of project BE3 is to develop methods that can be used reliably to design microbial formulations for cost-effective field applications. This status report describes the work conducted during FY90 in the initial development of an MEOR mathematical simulator to match laboratory coreflooding results.

BACKGROUND

Prior work at NIPER has identified the mechanisms of oil mobilization by certain microbial formulations. Mechanisms that have been shown to be important include wettability alteration, emulsification, solubilization, and alteration in interfacial forces. Recent experiments at NIPER have demonstrated that oil mobilization by microbial formulations is not merely the result of the effects of the metabolic products from the in situ fermentation of nutrient. The relationships between transport of microbes, nutrients, metabolic products, and mobilized crude oil need to be clarified and interpreted with mathematical models for fluid flow in porous media.

Physical phenomena that affect the microbial oil recovery process include: (1) dynamic growth of microorganisms; (2) mass transfer and transport of microorganisms, nutrients, metabolic chemical products, oil and brine; (3) changes in microscopic properties such as interfacial tension, wettability, and adsorption that govern oil mobilization and affect fractional flow and relative permeabilities; (4) changes in rheology of the flowing phases; and (5) certain other physical phenomena that are peculiar to microorganisms. The phenomena that affect oil mobilization by microorganisms must be understood, and mathematical models and correlations must be developed to relate the phenomena to oil recovery efficiency.

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 will obviously require close coordination between laboratory mechanistic studies and oil displacement experiments under carefully controlled conditions to develop and validate a computer model. The accuracy of a simulator that is designed for MEOR processes will be strongly dependent upon the accuracy of the equations that are used to describe the important phenomena. It is also important to recognize the unique constraints and variation in conditions that occur in actual field applications but are not always accounted for in controlled laboratory experiments.

Thus, an accurate reservoir simulator for MEOR methods can best be developed through an integrated program of acquisition of laboratory and field data with the feedback loop being the reservoir simulation model.

NIPER has amassed a wealth of laboratory and field data on the mechanisms of oil mobilization of microbial formulations and the effects of various design parameters on oil recovery efficiency. The research program for FY90 has focused on laboratory experiments to further define key mechanisms of oil mobilization, development of correlations and mathematical models to describe the physical phenomena that are important in MEOR methods, and development of a mathematical computer simulator to model and predict performance of microbial formulations in oil recovery applications.

All prior work, both from the laboratory and the field, has been reviewed to identify and rank the various phenomena that are believed to significantly affect oil mobilization by microbial formulations. Prior efforts to develop mathematical models and reservoir simulators for various EOR processes, including MEOR methods, have been considered, and a plan has been formulated to develop an improved and comprehensive reservoir simulator for microbial EOR applications. Laboratory data from NIPER have been used to develop correlations and mathematical models for specific phenomena, and linear coreflooding data will be used to test the simulator in an iterative process. The simulator development and laboratory testing aspects of this project have been carefully coordinated so that the results from testing the simulator with oil displacement experiments can be used to design laboratory experiments to clarify and quantify certain physical effects from which correlations will be refined and modified and incorporated into the simulator. The goal has been to develop a flexible and accurate reservoir simulator that can be extended to match and predict performance in actual field applications.

A reservoir model was selected as a starting point for development of an improved MEOR reservoir simulator to implement the initial steps in the development plan. Initial efforts have focused on incorporating the most important phenomena for which mathematical models or correlations are available or can be available in a reasonably brief period of time.

DESCRIPTION OF MODEL

Modeling Microbial Transport in Porous Media

Two methodologies for developing mathematical models for MEOR processes were formulated. The first approach was to develop a mathematical model to predict the propagation and distribution of microorganisms and nutrients in a one-dimensional core. The transport of microbes in porous media is governed by many complicated physical, chemical, and biological aspects such as adsorption, interaction between microbes and nutrients, and growth and decay of the cells. Based on available information, the decay of microbes is assumed to be a first-order reaction, and the growth of microbes is assumed to follow the Monod equation.¹ The governing equation for microbial transport was coupled with a transport equation for microbial nutrients. Porosity reduction due to cell clogging has been considered in this model. The nonlinear coupling equations are solved by the Crank-Nicolson² finite difference method. This model can be used to predict the concentration distributions for the injected nutrients and microorganisms with various injection modes.

The second approach used for microbial transport in porous media was to utilize NIPER's existing three-dimensional numerical simulator. This was accomplished by incorporating the transport equations for microorganisms and microbial nutrients into a three-dimensional, three-phase (oil, water, and gas) black oil simulator (BOAST). The distribution of pressure and oil/water/gas saturation in the reservoir was first calculated according to the injection/production strategy. The fluid flow due to the pressure gradient in the reservoir was then used in the transport calculation for microorganisms and microbial nutrients. Using this simulator, the transport of microorganisms can be investigated, and the effect of the microbial system on oil recovery can be studied.

Mathematical Formulation

Corapcioglu and Haridas³ have developed the governing equations for the transport and fate of microbial contaminants in the presence of a substrate. The starting point is the macroscopic mass balance equation for a species in a porous medium. Nomenclature is given on page 20.

$$\frac{\partial(\theta C)}{\partial t} + R_a = -\vec{\nabla} \cdot \vec{J} + R_{df} + R_{gf} \quad (1)$$

The left-hand side of the equation is the accumulation of microorganisms in the flowing phase and the rate of deposition of microbes on grain surfaces (R_a). The first term ($\nabla \cdot J$) of the right-hand side is the net flux of microbes by convection and dispersion. The last two terms are the decay rate (R_{df}) and the growth rate (R_{gf}) of microbes. A detailed discussion for each term is given below:

Diffusion by Brownian Motion

Like colloidal particles, microorganisms are subject to Brownian motion by which the path of the individual particle appears quite erratic. The mass transfer flux of microbes by Brownian motion is expressed by:

$$J_B = -D_B \theta \vec{\nabla} C \quad (2)$$

where D_B is the diffusion coefficient of the suspended particles (microbes).

Tumbling of Microbes

The chaotic, random movement of motile microbes is referred to as "tumbling". This random movement is assumed to be superimposed upon mechanical dispersion by introducing an effective diffusivity, D_T

$$J_T = -D_T \theta \vec{\nabla} C \quad (3)$$

Chemotaxis of Microbes

Microorganisms move systematically toward a richer food supply, and this motion, which is induced by the presence of nutrients, is termed chemotaxis. In chemotaxis the motion of a cell is influenced by the molecules of the nutrients through a chemical interaction rather than by the direct impact characteristic of Brownian motion. So far this biochemical interaction is not well known. We can assume that the chemotactic flow is superimposed upon the hydrodynamic flow and the total flow is expressed by:

$$J_f = (v_f + v_m + v_g) \theta C = u \theta C \quad (4)$$

where v_f is the water flow velocity; v_m is the chemotactic velocity; and v_g is the gravitational settling velocity.

Equations 2 through 4 relate to the total equation 5.

$$J = J_B + J_T + J_f \quad (5)$$

Decay of Microorganisms

The death of microorganisms is expressed as an irreversible first order reaction,

$$R_{df} = -k_d \theta C; \quad R_{ds} = -k_d \rho \sigma \quad (6)$$

where k_d is the specific decay rate, R_{df} is the decay term in free state in water, and R_{ds} is the decay rate in the adsorbed state. k_d is assumed to be the same in free and adsorbed states.

Growth of Microorganisms

Microbial growth occurs with the utilization of the substrate. The growth of microbes is assumed to follow the Monod equation.¹ This equation describes a relationship between the concentration of a limiting nutrient and the growth rate of microorganisms. Similar to the decay process, we assume that microbes can grow in the deposited state as well as in suspension at the same rate. Then, a generalized Monod equation can be written as:

$$R_{gf} = \mu \theta C; \quad R_{gs} = \mu \rho \sigma \quad (7)$$

where μ is the specific growth rate and R_{gf} and R_{gs} denote the growth terms in free and adsorbed states, respectively. The functional relationship between μ and an essential nutrient's concentration, C_f , was proposed by Monod:

$$\mu = \frac{\mu_m C_f}{K_s + C_f} \quad (8)$$

where μ_m is the maximum growth rate achievable. K_s is that value of the concentration of the substrate where the specific growth rate has half its maximum value. Values of μ_m and K_s can be obtained from experimental results.

Deposition of Microbes on Grain Surfaces

The accumulation of microbes on grain surfaces forms clusters called dendrites. The straining effects increase with dendritic growth, resulting in further growth, until the clusters become so large that they are unstable and break off. The process is repeated at sites downstream, resulting in the movement of a "saturated front" of clusters. The rate of removal depends on the flow rate and the size and density of the microbial clusters. The deposition (clogging) of the microbes occurs by various mechanisms: adsorption, straining, sedimentation. The rate of deposition, R_a , can be expressed by a kinetic equation:

$$R_a = k_c \theta C \cdot k_y \rho \sigma^h \quad (9)$$

where k_c and k_y are the clogging and declogging rate constants, respectively, and h is a constant. In this model, we assume $h=1$. The conservation equation for the deposited material may be written as:

$$\frac{\partial(\rho\sigma)}{\partial t} = R_a + R_{ds} + R_{gs} \quad (10)$$

where R_{gs} and R_{ds} are the growth and decay terms, respectively, in the deposited state, which are given in equations 6 and 7; ρ is the density of the microbes; and σ is the volume of deposited microbes per unit volume of bulk rock. The deposition (clogging) of microbes on grain surfaces will change the porosity of the medium,

$$\theta = \phi - \sigma \quad (11)$$

where ϕ is the original porosity of the medium.

Transport of Nutrients

The concentration of nutrient, C_f , which is consumed by the microbes at a rate R_f is assumed to be transported by convection and dispersion. Our experiments have

shown that adsorption of nutrients (sucrose, molasses) on Berea sandstone rock can be ignored. Thus the mass conservation equation for C_f can be written as:

$$\frac{\partial(\theta C_f)}{\partial t} = -\nabla \cdot (-D_f \nabla \theta C_f + v_f \theta C_f) + R_f \quad (12)$$

where C_f is defined as mass of nutrients per unit volume of water, and R_f is the rate of nutrient consumption. The rate of nutrient consumption is assumed to be proportional to the microbial growth rate,

$$R_f = -\frac{\mu}{Y} (\theta C + \rho \sigma) \quad (13)$$

where Y is called the yield coefficient, which is defined as the mass of cells produced per unit of substrate removed. Y values are given in table 1.

TABLE 1. Statistical summary of sludge yield values for heterogeneous populations of wastewater origin grown on various carbon sources (adapted from Gaudy and Gaudy¹)

Carbon source	Avg Cell yield, %	No. of determinations	95% Confidence limits
Fructose	53.0	8	44.4-61.6
Galactose	51.9	24	47.1-56.7
Glucose	61.9	118	59.6-64.2
Glycerol	46.5	31	43.1-49.9
Lactose	47.1	12	42.4-51.8
Mannose	52.2	8	41.1-63.3
Ribose	45.7	9	40.8-50.8
Sorbitol	50.6	39	48.7-58.5
Sorbose	52.0	12	41.4-62.6
Sucrose	53.1	12	44.2-62.0
Xylose	50.4	18	44.8-56.0

Cell yield is expressed as the percentage of the organic carbon source that is converted to cells, i.e., (dry weight of cells produced/weight of carbon source utilized) x 100.

Complete Set of Model Equations

For microbes:

$$R_a = k_c C^* - k_y \sigma D \frac{\partial^2 C^*}{\partial x^2} - u \frac{\partial C^*}{\partial x} + (\mu - k_d) C^* = \frac{\partial C^*}{\partial t} + R_a \quad (a)$$

$$R_a = k_c C^* - k_y \sigma^* \quad (b)$$

$$\frac{\partial \sigma^*}{\partial t} = (\mu - k_d) \sigma^* + R_a \quad (c)$$

For nutrients:

$$D_f \frac{\partial^2 C_f^*}{\partial x^2} - v_f \frac{\partial C_f^*}{\partial x} - \frac{\mu}{Y} (C^* - \sigma^*) = \frac{\partial C_f^*}{\partial t} \quad (d)$$

where

$$C^* = \theta C$$

$$\sigma^* = \rho \sigma$$

$$\mu = \frac{\mu_m C_f}{K_s + C_f}$$

Initial conditions:

$$C = C_f = \sigma = 0; \text{ at } t = 0$$

Boundary conditions:

$$u C_0 = u C - D \frac{\partial C}{\partial x}, \text{ at } x=0, t > 0$$

$$\frac{\partial C}{\partial x} = 0, \text{ at } x=L, t > 0$$

A similar set of equations can be written for nutrient concentration C_f .

Numerical Solution

The governing equations exhibit a high degree of complexity. With non-linearity and coupling, it is impossible to obtain analytical solutions for C , σ , and C_f even for a one-dimensional space. The Crank-Nicolson finite difference method was used in the numerical solution. The Crank-Nicolson finite difference method is more stable than other methods such as forward difference or backward difference methods. This numerical method has been tested with reported results for other models. Table 3 and figure 1 describe the injection modes used for these simulation studies. Several sample calculations for various injection modes with assumed values for the model parameters (given in table 2) are presented in figures 2-7.

TABLE 2. Model parameters

Parameter	Value
Model length (L)	122 cm (4 ft)
Porosity (ϕ)	0.20
Flow velocity (u)	1.27 cm/hr (1 ft/day)
Density of microorganisms (ρ)	1 mg/mL
Dispersion coefficients:	
microbes (D)	0.775 cm ² /hr
nutrients (D _f)	0.775 cm ² /hr
Injection microbe conc. (C ₀)	30 mg/mL
Injection nutrient conc. (C _{f0})	40 mg/mL
Cell yield coefficient (Y)	0.53
Monod half growth constant (K _S)	100 mg/mL
Maximum growth rate (μ_m)	0.38 1/hr
Clogging rate constant (k _c)	0.234 1/hr
Declogging rate constant (k _y)	1.566 1/hr
Specific decay constant (k _d)	0.0036 1/hr

TABLE 3. Injection protocols for figures 2 - 7

Injection model	Sequence of injectants (right to left)
(A)	WNNN
(B)	WMM
(C)	WNMNM
(D)	WMMNNN
(E)	WNWNWN
(F)	WNMNMN

W = Waterflood.
N = Nutrient (molasses).
M = Microbes.

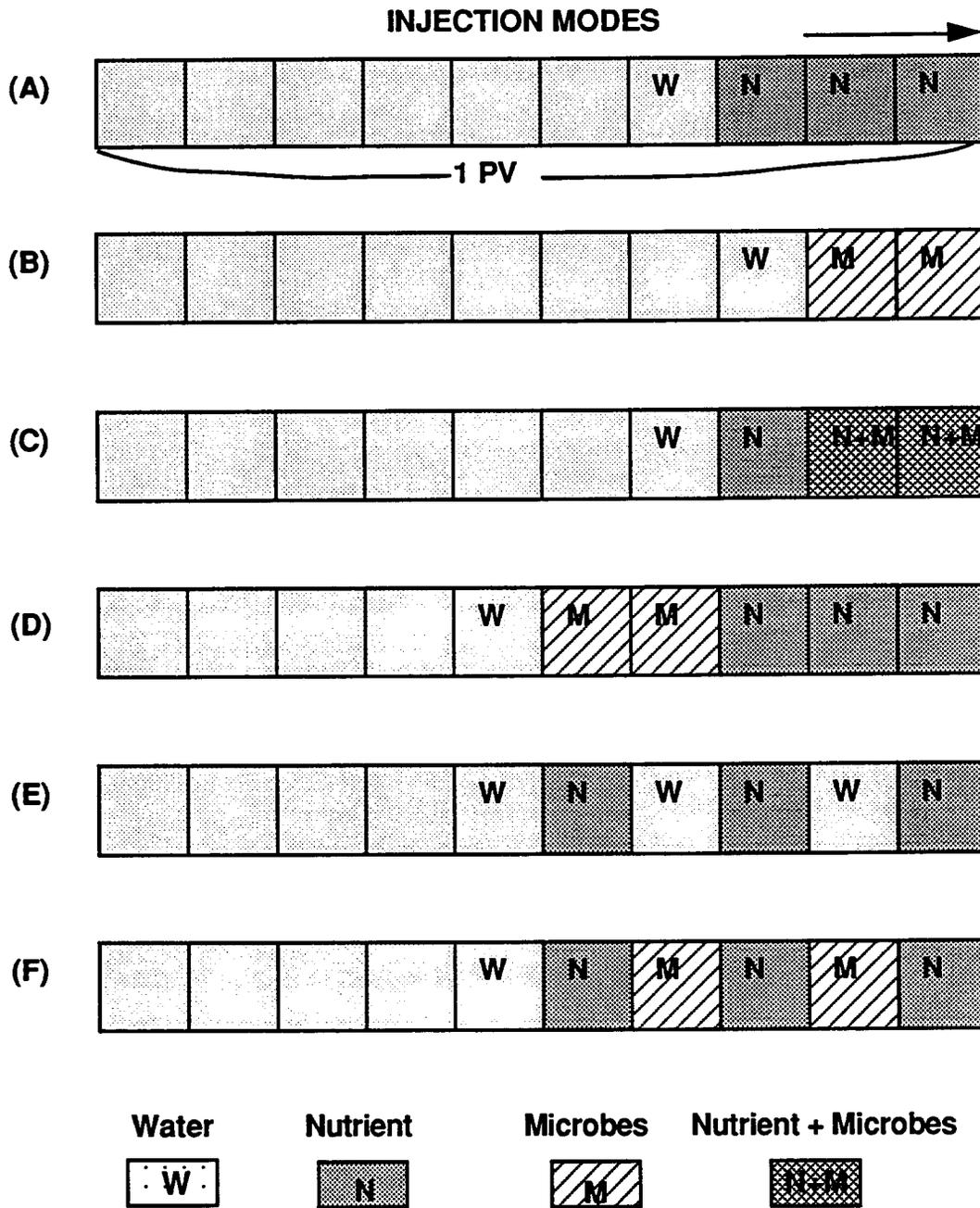


FIGURE 1.— Schematic of injection strategies (A) through (F). Each square represents 0.1 pore volume (PV).

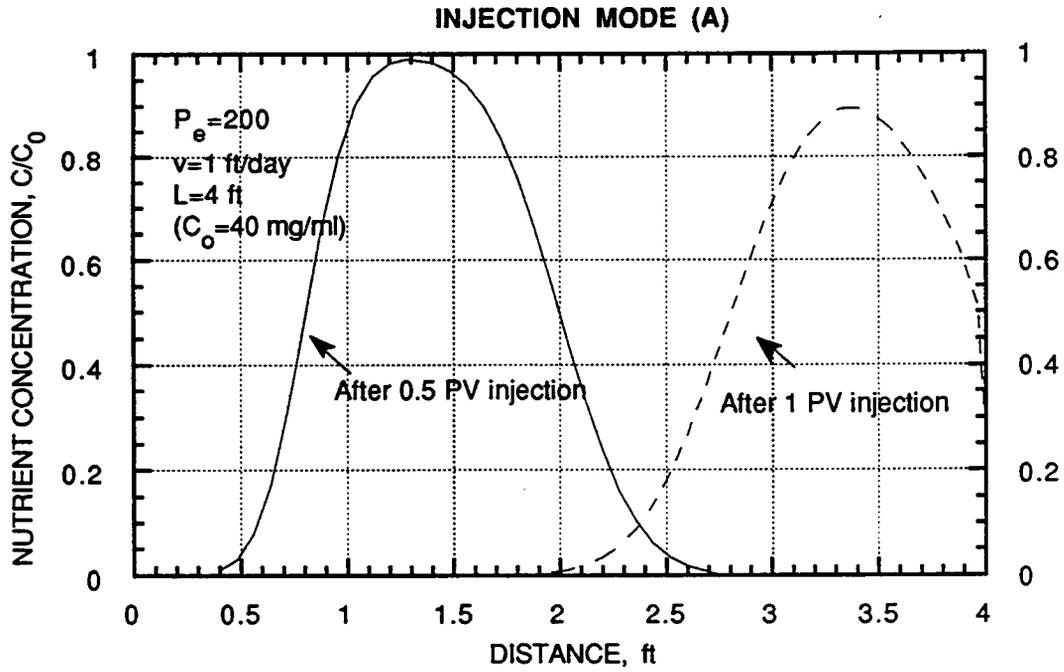


FIGURE 2.—Distribution of concentrations using injection protocol (A).

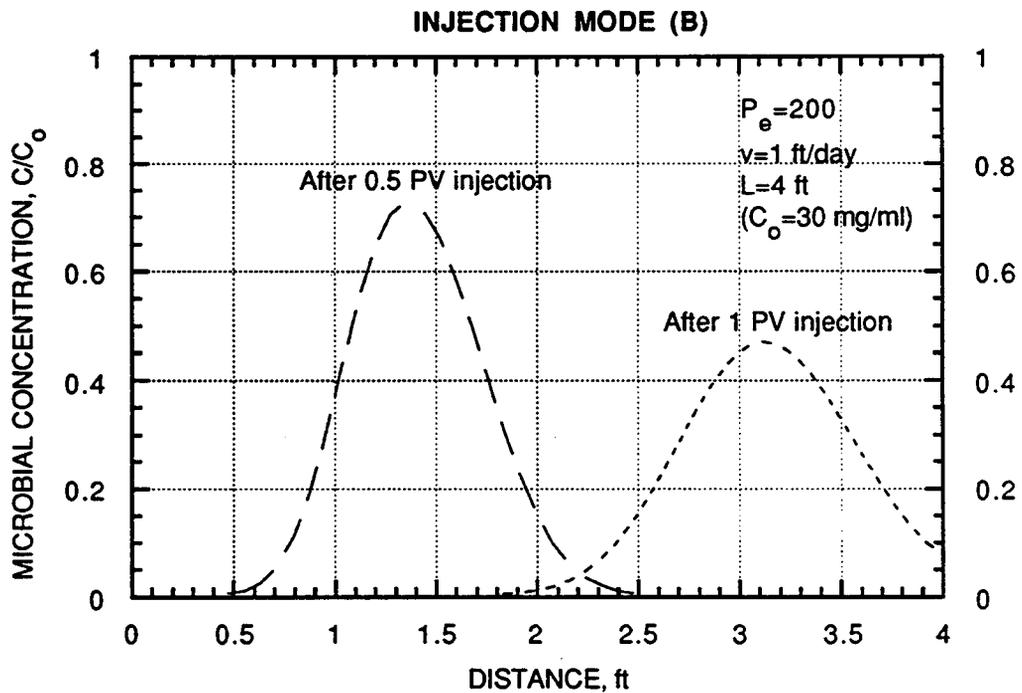


FIGURE 3.—Distribution of concentrations using injection protocol (B).

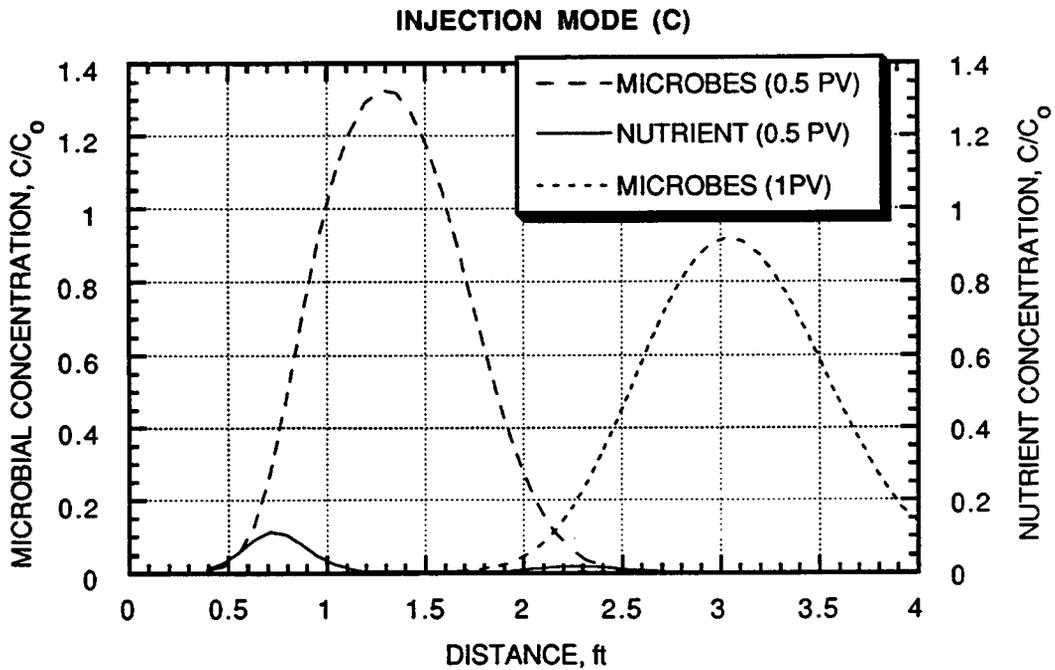


FIGURE 4.—Distribution of concentrations using injection protocol (C).

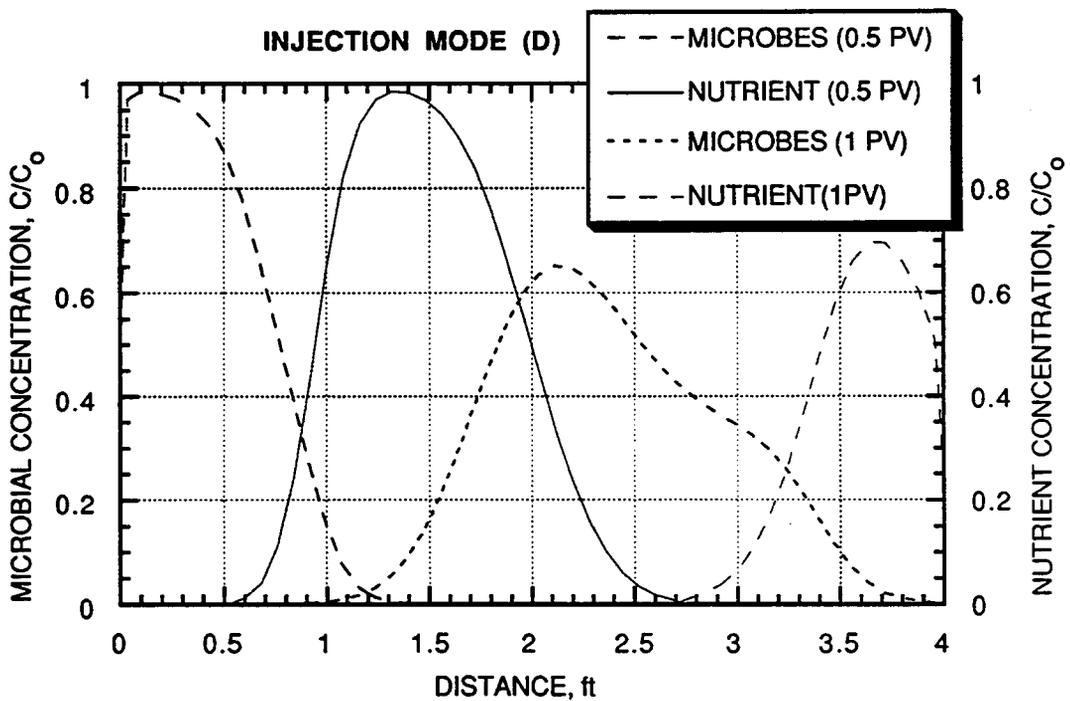


FIGURE 5.—Distribution of concentrations using injection protocol (D).

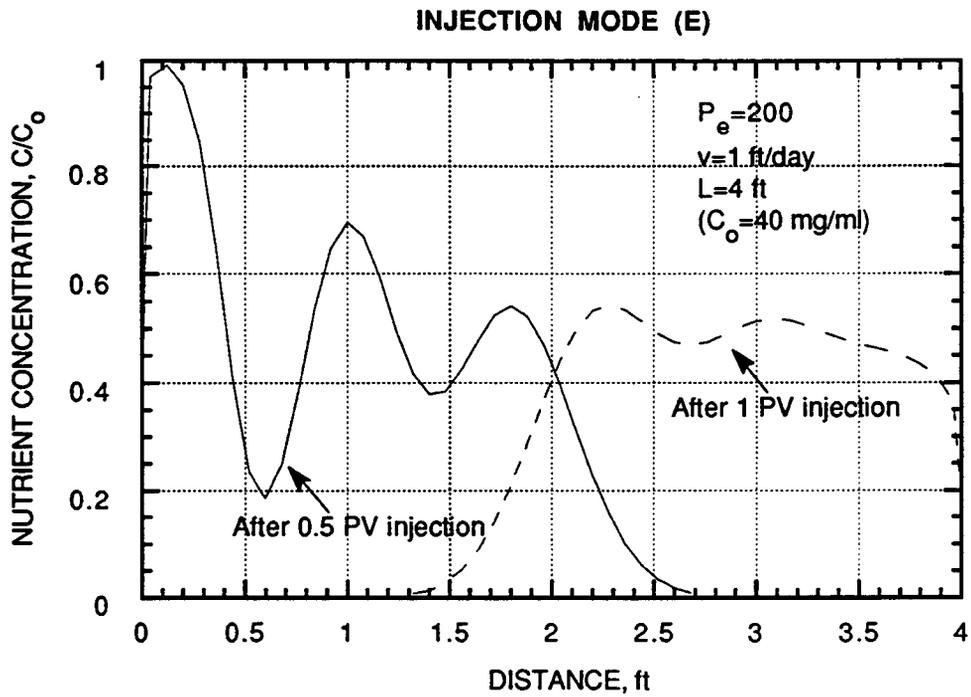


FIGURE 6.—Distribution of concentrations using injection protocol (E).

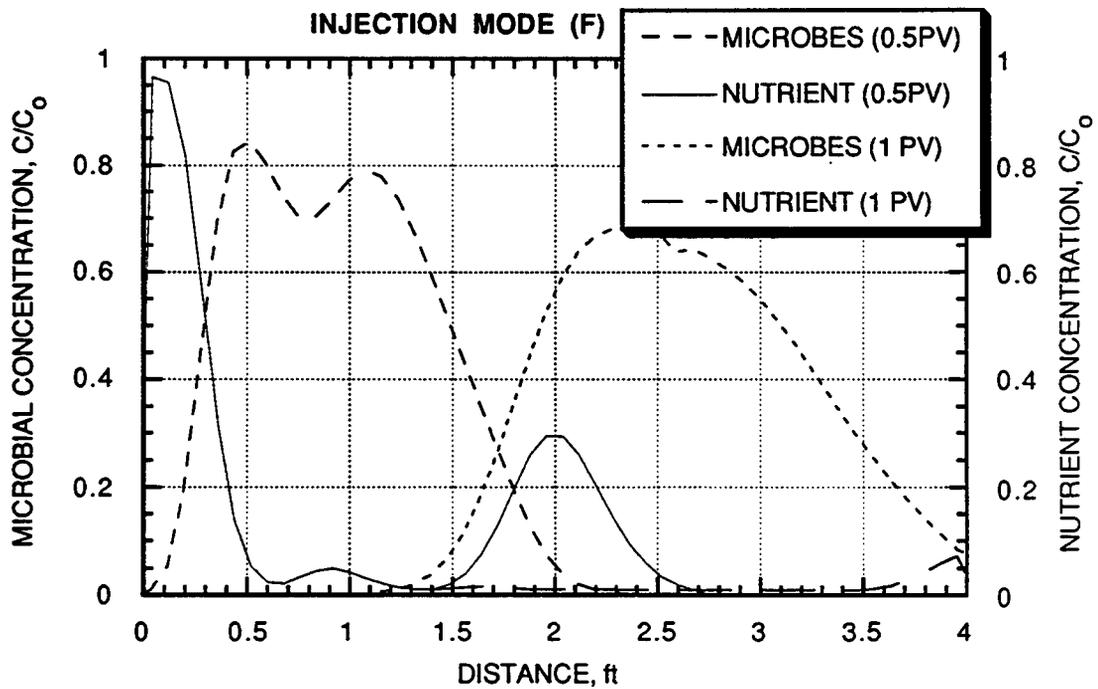


FIGURE 7.—Distribution of concentrations using injection protocol (F).

The preliminary results from these simulation runs indicate that the microbial population behaves as a slug, and that this model, after additional fine-tuning, may be used to predict effects of various injection strategies on microbial and nutrient transport in porous media. The simulator development and laboratory testing aspects of this project will be continued in FY91 and coordinated, so that the results from testing the simulator with oil displacement experiments will be used to design laboratory experiments to clarify and quantify certain physical effects from which correlations will be refined and modified and incorporated into the simulator. The simulator will be the primary deliverable from this research. The overall goal of the project is to develop a method for predicting and evaluating microbial EOR processes in porous media.

Simulation of MEOR Processes Using a Three-Dimensional, Three-Phase Simulator

Simulator Description

Model Equations and Numerical Solution Methods

Transport equations solved in this two-component (microorganism and nutrient), three-dimensional reservoir MEOR simulator are similar to those in the previous one-dimensional laboratory model, except the boundary conditions used. In contrast of the fixed concentration imposed at the end of the core in the laboratory model, sources (injectors) and sinks (producers) at various strengths are assigned in the three-dimensional reservoir model. Note the well rate term (Q) in the following transport equations:

For microbes:

$$D \frac{\partial^2 C^*}{\partial x^2} - u \frac{\partial C^*}{\partial x} + (\mu - k_d) C^* + Q C^* = \frac{\partial C^*}{\partial t} + R_a \quad (14)$$

For nutrients:

$$D_f \frac{\partial^2 C_f^*}{\partial x^2} - V_f \frac{\partial C_f^*}{\partial x} - \frac{\mu}{Y} (C^* + \sigma^*) + Q C_f = \frac{\partial C_f^*}{\partial t} \quad (15)$$

Only one nutrient component is considered in the current model; however, multiple nutrient components can be incorporated into the model with limited effort.

Based on the Hagen-Poiseuille and Darcy equations, the permeability reduction due to deposition of microorganisms to the rock pore space can be predicted by:

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3 \quad (16)$$

Instead of constant values entered by users in one-dimensional laboratory models, values of flow velocity (u , v_f) in the three-dimensional reservoir simulator are obtained by solving the pressure distribution from the continuity equation in the black oil simulator. Therefore, the flow velocity which varies from grid by grid and time step by time step in reservoir simulations offers more flexibility in studying the MEOR processes.

The Crank-Nicolson method was used in setting up the finite difference formulation of transport equations. For simplicity, the numerical solution transport equations of the microorganisms and the nutrient are decoupled and solved separately. Component concentrations are solved implicitly in space using a direct solution method. The amount of deposition of microorganism is then calculated, and the permeability value is adjusted for pressure calculations for the next time step.

Capability and Limitations

The newly developed MEOR reservoir simulator which was developed from BOAST, is able to model oil, water, and gas flow in a three-dimensional reservoir with heterogeneous distributions of permeability, porosity, and saturation. It allows a flexible assignment of well locations in the model and a study of different injection and production strategies in the microbial system. This MEOR reservoir simulator models the transport process and the permeability reduction resulting from the microbial system. However, effects of gas, surfactant, and other products released by the microorganisms on oil recovery are not included in this first phase of development. Effects of increasing gas saturation on relative permeability will be incorporated into this model in the coming fiscal year (FY 91).

Because of decoupling of transport equations of microorganisms and nutrients in solving the concentration distribution, the numerical solution might become unstable when values of certain interaction parameters between microorganisms and nutrients are large.

Simulation Results

Test runs were conducted with this three-dimensional microbial simulator. Table 4 shows the reservoir model and the microbial system parameters used in the test run. The two-layer reservoir was first waterflooded for 200 days (0.187 pore volumes) before injection of microorganisms and nutrient for 15 days. This microbial system was followed by a continuous waterflood. Calculated from a two-dimensional cross-section simulation, figures 7 and 8 present distributions of microorganisms and nutrient concentration, respectively. Depending on the values of clogging and declogging rate constants, the calculated porosity reduction varies from less than 0.1 to 10%.

TABLE 4. Reservoir model and microbial system parameters in a two-dimensional cross-section run

Parameter	Value
Reservoir length	500 ft
width	100 ft
thickness (top/bottom layers)	15 ft and 15 ft
Porosity, ϕ	0.2
Permeability	
kx, ky, kz (top layer)	100, 100, 10 md
kx, ky, kz (bottom layer)	1,000, 1,000, 100 md
Injection rate	50 bbl/day
Production rate	50 bbl/day
Initial oil saturation	75 %
Initial water saturation	25 %
Injected microbial conc.	30 mg/mL
Injected nutrient concentration	40 mg/mL
Diffusion coefficient	
microbes	0.775 ft * ft/day
nutrient	0.775 ft * ft/day
Clogging rate constant	0.00234 1/day
Declogging rate constant	0.01 1/day
Cell yield coefficient (Y)	0.53
Monod half growth constant	100 lb/cu ft
Maximum growth rate	0.38 1/day
Specific decay constant	0.0036 1/day

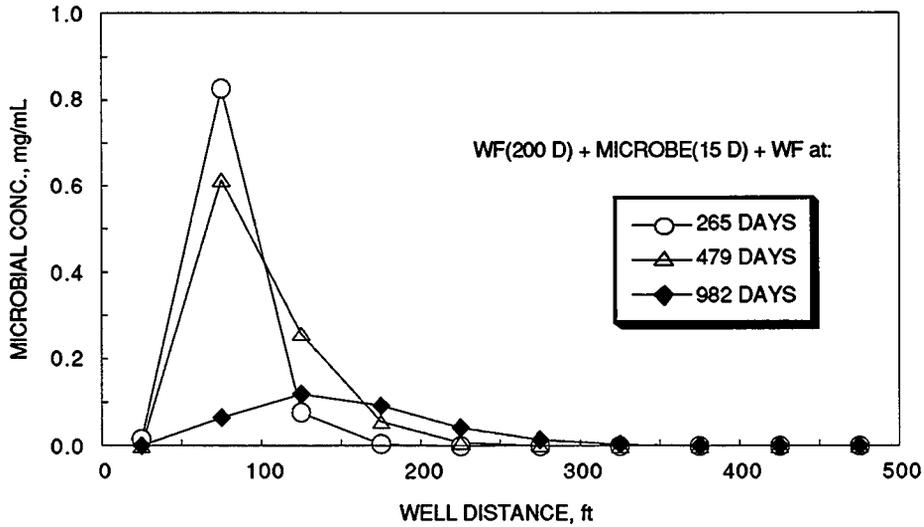


FIGURE 8.—Distribution of microorganisms from simulation studies during a two-dimensional cross section run.

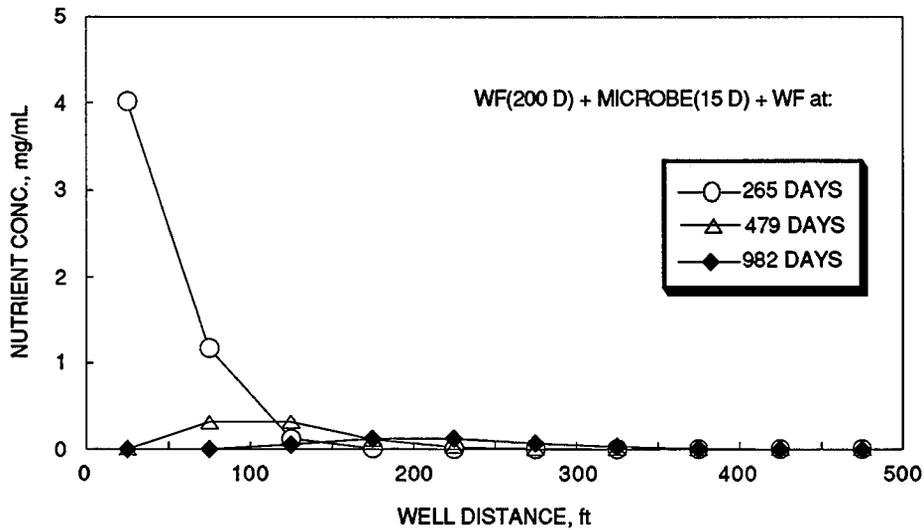


FIGURE 9.—Distribution of nutrient from simulation studies during a two-dimensional cross section run.

The model equations 14 and 15 that describe the transport of microbes and nutrients in porous media together with the relationship between the porosity and permeability (eq. 16) have also been incorporated into NIPER's permeability

modification simulator,⁴⁻⁵ which used an extended method of lines⁶⁻⁷ to solve the coupled nonlinear model equations. The modified simulator is being tested. Results will be compared with those from the above Crank-Nicolson method.

The preliminary runs with this simulator have demonstrated the feasibility of using this simulator for microbial oil recovery processes. There are many other variables which must be considered, including the metabolites produced by microorganisms. Work for FY91 will continue to develop the critical parameters, correlations, and mathematical models to describe the physical phenomena that are important in MEOR methods, and a mathematical computer simulator will be developed to model and predict performance of microbial formulations in oil recovery applications.

NOMENCLATURE

- C – concentration of microorganisms (mg/mL)
- C_f – substrate (nutrient) concentration (mg/mL)
- D – effective dispersion coefficient (cm²/hr)
- D_f – hydrodynamic dispersion coefficient for nutrient (cm²/hr)
- K_s – Monod half constant (mg/mL)
- k_c – clogging rate constant (hr⁻¹)
- k_d – specific decay rate (hr⁻¹)
- k_y – declogging rate constant (hr⁻¹)
- L – total length of the model (cm)
- t – time (hr)
- u – flow velocity (cm/hr)
- v_f – velocity of water flow (nutrient) (cm/hr)
- x – distance (cm)
- Y – growth yield coefficient (mg of microorganisms/mg of substrate utilized)
- ρ – density of microorganisms (mg/mL)
- θ – actual porosity
- σ – volume of deposited microorganisms per unit volume of total porous medium (mL/mL)
- ϕ – original porosity of the porous medium

REFERENCES

1. Gaudy, A.F. Jr. and E.T. Gaudy, *Microbiology for Environmental Scientists and Engineers*, McGraw-Hill Book Co., 1980.
2. Von Rosenberg, D.U. *Methods for Numerical Solution of Partial Differential Equations*. Elsevier, New York, N.Y., 1977. p. 56.
3. Corapcioglu, M.Y. and A. Haridas. Transport and Fate of Microorganisms in Porous Media: A Theoretical Investigation. *J. of Hydrology*, v. 72, 1984, pp 149-169.
4. Gao, H.W. and M.M. Chang. A Three-Dimensional, Three-Phase Simulator for Permeability Modification Treatments Using Gelled Polymers. U.S. Dept. of Energy Report No. NIPER-388, March, 1990. NTIS Order No. DE90000227.
5. Gao, H.W., M.M. Chang, T.E. Burchfield, and M.K. Tham. Studies of the Effects of Crossflow and Initiation Time of a Polymer Gel Treatment on Oil Recovery in a Waterflood Using a Permeability Modification Simulator. Pres. at the SPE/DOE 7th Symp. on Enhanced Oil Recovery, Tulsa, April 22-25, 1990. SPE/DOE paper 20216.
6. Sorbie, K.S., L.J. Roberts, and P.J. Clifford. Calculation on the Behavior of Time-Setting Polymer Gels in Porous Media. Pres. at the AIChE Meeting, Houston, March, 1985.
7. Ames, W.F. *Numerical Methods for Partial Differential Equations*. 2nd Edition. Academic Press, Inc., New York, 1977.