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SCREENING CRITERIA FOR MICROBIAL EOR PROCESSES

Topical Report

By
Rebecca Smith Bryant

December 1990

Performed Under Cooperative Agreement No. FC22-83FE60149

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Bartlesville, Oklahoma

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U. S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

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TABLE OF CONTENTS

TABLES

FIGURE

SCREENING CRITERIA FOR MICROBIAL EOR PROCESSES

Rebecca S. Bryant

ABSTRACT

The National Institute for Petroleum and Energy Research (NIPER) has maintained a microbial enhanced oil recovery (MEOR) field project data base since 1985. One of the major goals of this data base is to continue to document characteristics of reservoirs used for MEOR field projects and to assist the U. S. Department of Energy by revising published screening criteria for MEOR processes. Since the last update of this data base in 1987, the number of MEOR field projects entered has increased from 39 to 65. Microbial EOR has been recognized as a potentially cost-effective method, particularly for stripper well production. Stripper wells are particularly in need of cost-effective EOR because independent operators produce about 40% of the total oil recovered, but cannot conduct needed EOR research. Microbial methods for improving oil recovery are potentially cost-effective and particularly well suited to be applied in today's economic climate. The lower price of crude oil as well as a more general acceptance of use of biotechnological processes has probably contributed to this increase. Although in some instances information was unavailable or not reported for each element of the data base, there exists adequate data to demonstrate both the viability and variety of options for using microbial technology for improved oil production.

This report updates the data base and provides a summary of several of the more important MEOR field experiments conducted during the 1970s and 1980s.

INTRODUCTION

NIPER has maintained a microbial enhanced oil recovery (MEOR) field project data base since 1985. One of the major goals of this data base is to continue to document characteristics of reservoirs used for MEOR field projects and to assist the U. S. Department of Energy by revising published screening criteria for MEOR processes.

Several laboratories have published reservoir screening criteria, including the University of Oklahoma,[1] the Baas Becking Geomicrobiological Laboratory in Australia,[2] and NIPER.[3] These publications were reviewed to determine which reservoir parameters are the most important for successful microbial EOR field tests. The U.S. DOE Reservoir Data Base (public copy) was used to screen several oil-producing states for the number of reservoirs that satisfied the following criteria: injected and connate water salinities less than 100,000 ppm, rock permeability greater than 75 millidarcies, and a depth less than 6,800 feet, which corresponds to a temperature limitation of about 75° C. Table 1 shows the number of reservoirs that satisfied these parameters and a graph of the percent of reservoirs in each state that satisfied these limiting criteria, and the total is shown in figure 1.

TABLE 1. Number of reservoirs by state with potential for MEOR technology

State	Total no. of reservoirs	No. of reservoirs that fit the criteria	%
OK	97	14	14
TX	461	115	25
LA	190	25	13
KS	39	17	44
CA	179	85	47
CO	40	27	68
MS	44	4	9
NM	65	3	5
WY	67	23	34
IL	46	14	30
TOTAL	1228	327	27

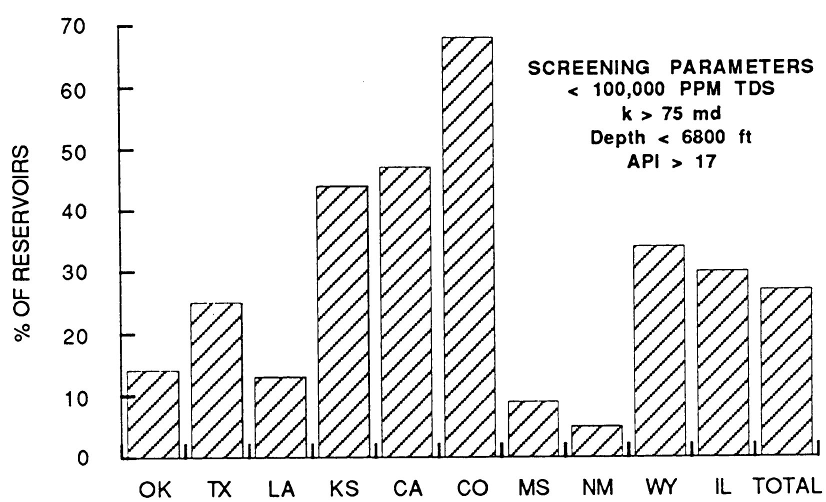

FIGURE 1 –Graph showing percent of reservoirs in major oil-producing states that have potential for MEOR processes.

Since the most recent publication[3] of NIPER's MEOR Field Project Data Base, interest and application in MEOR field technology have increased. Bryant and Burchfield have recently published an overview of MEOR technology.[4] Because of political changes in Eastern Europe and other countries, some MEOR field trials have now been made public by researchers from countries such as the USSR, Germany, Romania, and China. This report updates the data base and provides a summary of several of the more important MEOR field experiments conducted during the 1970s and 1980s.

MEOR FIELD PROJECT DATA BASE

NIPER has continued to maintain a data base on all available information regarding MEOR field tests in the United States and in other countries. The data base was designed to be incorporated into the U. S. Department of Energy's EOR Project Data Base that is part of the Tertiary Oil Recovery Information System (TORIS). The DOE Project Data Base incorporated two new records for MEOR field projects: MEOR Project Info and MEOR Bacteria Info. These two records describe information pertaining to any field project using microorganisms and details the available information regarding the microbial process used. All other data from NIPER's MEOR Field Project Data Base can be incorporated into existing records. A sample data entry sheet is presented in table 2. The MEOR Field Project Data Base was created using Microsoft ™ Excel software for the Macintosh SE personal computer.

TABLE 2. Data elements from NIPER's MEOR Field Project Data Base

Data element	Definition
Reference Number	Number to designate project
Organization	Organization conducting project
Year of Test	Year project was initiated
Oilfield Name	Ex., Delaware-Childers
Formation	Ex., Bartlesville Sandstone
Permeability, md	Brine permeability of rock, usually an average
Porosity, %	Rock porosity, usually an average
Salinity, %	Usually total dissolved solids value
pH	Usually an average
Temperature, ° F	Usually an average
Depth, ft	Bottom of the net pay
Pressure, psi	Bottomhole pressure
Production Mode	Single pumping wells, or waterflooded

TABLE 2. Data elements from NIPER's MEOR Field Project Data Base (continued)

Data element	Definition
Res. Oil Sat., %	Oil saturation, usually an average
Well spacing, acres	Ex., 5-acre spacing
Net Pay, ft	Thickness of pay zone
No. of Inj. Wells	Number of injection wells
No. of Prod. Wells	Number of production wells
Rock Comp.	Type of rock, ex., sandstone
Oil Visc., cP	Viscosity of the crude oil
Oil Gravity, ° API	API gravity of the crude oil
Oil Density, gm/cc	Density of the crude oil
WOR	Water-oil ratio
Oil Prod., bbl/d	Oil production
Water Prod., bbl/d	Water production
INJECTION INFO	
Preflush	Was a preflush used?
Inj. Fluid Comp.	Composition of injection fluid, ex. microbial
Microbial Type	Name of microorganisms used, ex. *Bacillus*
Inj. Fluid Visc.	Viscosity of microbial fluid
Spores	Does the microbe form spores? Y-N
Anaerobic	Can the microbe grow without oxygen? Y-N
Pathogen	Is the microbe pathogenic? Y-N
H_2S Producer	Does microbe produce hydrogen sulfide?Y-N
Gases	Does the microbe produce gas?
Acids	Does the microbe produce acids?
Solvents	Does the microbe produce solvents?
Surfactants	Does the microbe produce surfactants?
Polymer	Does the microbe produce polymer?
Nutrient Comp.	What is the nutrient used, ex. molasses?
Inj. Fluid Vol., bbl/d	Volume of the injected fluid
Inj. Fluid Conc.	Concentration of microbes in the injection fluid, ex. 1 x 10^7 cells/mL
Inj. Nut. Vol., bbl/d	Volume of the injected nutrient

TABLE 2. Data elements from NIPER's MEOR Field Project Data Base (continued)

Data element	Definition
Inj. Nutrient Conc.	Concentration of nutrient, ex. 4% by wt.
PILOT INFO	
Test Length, months	How long was the project monitored?
Shut-in Period, days	Days that the well(s) was shut-in, if any
Shut-in Pressure	Pressure that occurred during shut-in
Oil Prod., bbl/d	Oil production (after treatment)
Water Prod., bbl/d	Water production (after treatment)
WOR	Water-oil ratio (after treatment)
Oil Viscosity, cP	'iscosity of crude oil after treatment
pH	pH of fluids after treatment
Comments, % Inc.	% Incremental recovery
Comments	

Several of the parameters listed in table 2 were added specifically because of the nature of microbial enhanced oil recovery processes. These parameters include: injected microorganisms, type of microorganism used; whether they produce spores; their metabolic products, including gases, acids, polymers, solvents, surfactants and hydrogen sulfide; nutrient information; and presence of indigenous microorganisms in the reservoir, flood waters, or nutrients.

Because of the diverse nature of MEOR technology, several different oil production problems have been addressed by microbial and/or nutrient injection. Some classification scheme is required to separate these different processes. To differentiate among field projects using microorganisms, they are separated according to the following classification (table 3)

TABLE 3 - A classification of different microbial reservoir treatments

MEOR process	Production problem	Type of microorganism used
Microbial well stimulation	Lack of reservoir pressure Injectivity problems Trapped oil due to capillary forces	Generally surfactant, gas, acid, and alcohol producers
Microbial-enhanced waterflooding	Trapped oil due to capillary forces	Generally surfactant, gas, acid, and alcohol producers
Microbial permeability modification	Water bypassing oil	Microorganisms that produce polymer and/or copious amounts of biomass
Microbial wellbore cleanup	Paraffin problems Scaling	Microorganisms that produce emulsifiers, surfactants, and acids Microorganisms that degrade hydrocarbons
Microbial polymerflooding	Water bypassing oil Unfavorable mobility ratio	Microorganisms that produce polymer
Mitigation of coning	Water bypassing oil	Microorganisms that produce polymer and/or copious amounts of biomass

The processes listed in table 3 will be used for classification only; in some instances, no field projects using the process are being conducted, but field work has been planned based upon laboratory results.

MICROBIAL WELL STIMULATION

The most practiced MEOR technique involves cyclic treatments of producing wells. These types of treatments have been conducted since 1953; however, those conducted most recently have involved some improved nutrient and microbial processes. These tests are addressed in this report.

In well stimulation treatments, improvements in oil production can result from removal of paraffinic or asphaltic deposits from the near-wellbore region or from mobilization of residual oil in the limited volume of the reservoir that is treated. Because there is a potential for improved residual oil mobilization, these treatments are distinguished from those that use microorganisms specifically for wellbore cleanup. Well stimulation treatments generally use microorganisms that require the addition of nutrient to survive and thrive for periods of several months in the well, whereas microorganisms used for wellbore cleanup are those that generally do not survive for extended periods of time and are injected on a regular basis, somewhat similar to regular injection of hot oil. They generally do not survive outside the wellbore region without nutrient injection because they are oxygen-requiring microbes. Typically well stimulation treatments can be implemented with only a few minor modifications to existing surface facilities, and they are relatively inexpensive.

Well stimulation treatments can be considered successful not only by improving oil production rate but also by decreasing the cost of maintenance and operation of a well. As an example, a microbial formulation that reduces BS&W (bottom sediments and water) can improve injectivity of a well and decrease the life of the well. By improving injectivity, maintenance treatments of a well, such as hot oil or solvent treatments, may not have to be implemented as often.

During the 1950s and 1960s, countries such as Czechoslovakia, Poland, Hungary, and the USSR conducted numerous well stimulation treatments with a wide variety of microorganisms and injection protocols. Underlying trends in all of these early single-well injections are that they used inexpensive sources of nutrients (usually molasses), and that they were generally successful, i.e., had increases in oil production rate ranging from 50 to 300%.

In the 1970s and 1980s, researchers at some universities and small companies in the United States conducted probably as many as 300 well stimulation treatments. Unfortunately, the information resulting from all but a few of these is unavailable to the public. Those for which information is available are presented in table 4.

TABLE 4 - Well stimulation tests in the United States and other countries from 1980 to 1990

Project conducted by	Year of test	Field/State	Reported results[1]
Oklahoma State University	1983	Oklahoma	Oil production increased
Oklahoma State University	1985	Texas	Slight increase in oil production
Microbial Systems Corp.	1984	Oklahoma	230% increase in oil production rate for 7 months (0.5 to 2 bbl/day)
Fairleigh Dickinson Lab.	1986	Gailjo field Texas	Operator left
Fairleigh Dickinson Lab.	1987	Wildcat field Texas	Slight increase in oil production
Petroleum Bioresources, Inc.	1983-84	Westfork field Colorado	Rapid increase in oil production rate with rapid decline after 5 months
Alpha Environmental, Inc.	1986	Lavernia field Texas	Slight increase in oil production rate in off-pattern leases

TABLE 4 - Well stimulation tests in the United States and other countries from 1980 to 1990 (continued)

Project conducted by	Year of test	Field/State	Reported results[1]
Alpha Environmental, Inc.	1986-87	Longwood field Texas	BS&W[2] decreased
BWN Oil (Australia)	1988-89	Alton field, Australia	Oil production increased and BS&W[2] decreased

[1]See references 5 and 6.
[2]Bottom sediments and water.

MICROBIAL-ENHANCED WATERFLOODING

For a microbial-enhanced waterflood, it is important that the microorganisms be capable of moving through the reservoir and producing chemical products to mobilize crude oil. Microorganisms can produce surfactants that can reduce oil/water interfacial tension (IFT) and cause emulsification. In addition, surfactants can alter the relative permeability of rock to oil by changing the wettability of the reservoir rock and thereby increasing oil recovery. Microbes also produce gases such as CO_2, N_2, H_2, and CH_4 that could improve oil recovery by increasing reservoir pressure and by reducing the viscosity and swelling of individually trapped droplets of crude oil. Sometimes, particularly with heavy crude oils, production of CO_2 may decrease the viscosity of the oil enough to lead to some improvement in oil production. In carbonate formations or sandstone rocks with carbonaceous cementation, acid-producing microorganisms can increase permeability and thereby improve oil recovery.

Microorganisms that are most commonly used for MEOR field processes are species of *Bacillus* and *Clostridium*. These species have a greater potential for survival in petroleum reservoirs because they produce spores. Spores are dormant, resistant forms of the cells that can survive more stressful environmental conditions. *Clostridium* species produce surfactants, gases, alcohols and solvents, while *Bacillus* species produce surfactants, acids, and some gases. There are also *Bacillus* species that produce polymers.

More care must be taken to ensure that the microorganisms can transport in a waterflood rather than in single-well stimulation treatments. However, the potential for a much greater increase in oil production is high because of the larger amount of reservoir contacted or treated. One of the first successful MEOR field pilots occurred in 1954, and consisted of an injection well and a production well.[7] More recent microbial-enhanced waterflood projects have been conducted by the National Institute for Petroleum and Energy Research (NIPER),[8-9] Imperial Energy Corporation, Alpha Environmental, as well as by countries such as Romania, East Germany, and the USSR (table 5).

Many of these microbial waterfloods showed increases in oil production rate. The MEOR process responsible for the improved production is generally attributed to gas and surfactant production by the microorganisms.

TABLE 5 - Recent microbial-enhanced waterflood field projects

Project conducted by:	Year of test	Field/State	Reported results[1]
NIPER/Microbial Systems Corp. and INJECTECH, Inc.	1986	Delaware/Childers field Oklahoma	Oil production increased and water/oil ratio decreased
NIPER/Microbial Systems Corp. and INJECTECH, Inc.	1990	Chelsea-Alluwe field Oklahoma	Injected in June, 1990
Imperial Energy Corp.	1988	Loco field, Oklahoma	Oil viscosity decreased
Alpha Environmental, Inc.	1988	Longwood field Illinois	Oil production increased
Romania Test 1	1987	Romania	Oil production increased
Romania Test 2	1987	Romania	Oil production increased
Romania Test 3	1987	Romania	Oil viscosity decreased
Romania Test 4	1987	Romania	Oil viscosity decreased
East Germany	1987	East Germany	Oil production increased and water/oil ratio decreased
USSR	1987	Bondyuzhskoe USSR	Significant oil production increase

[1] See references 5 - 10.

MICROBIAL PERMEABILITY MODIFICATION

Another application for microorganisms in a waterflood is fluid diversion. Since many types of microorganisms produce polymers, it has been suggested that some microorganisms could be used in situ to plug high-permeability zones in reservoirs preferentially and thus improve sweep efficiency.[11] In 1958, researchers in The Netherlands conducted a selective plugging experiment using *Betacoccus dextranicus* and reported significant increases in oil production as well as an improved water/oil ratio. Microorganisms that produce polymers, biomass, and slimes have been shown to reduce core permeability under reservoir conditions in the laboratory. More recent field tests are reported in table 6. The University of Oklahoma is currently planning a field test for its fluid diversion MEOR process.[12]

TABLE 6 - Microbial permeability modification field tests

Project conducted by	Year of test	Field/State	Reported results[1]
University of Oklahoma	1990	SE Vasser Vertz Sand Oklahoma	Planned
Nova Husky Research Corp.	1988	Lloydminister Canada	Results appeared promising although permeability channels not obstructed
USSR	1989	Romashkinskoye USSR	Additional oil recovered

[1]See references 5, 11-13.

MICROBIAL WELLBORE CLEANUP

Use of microorganisms in the near-wellbore region can greatly improve injectivity and mitigate certain production problems. Several different companies promote microbial wellbore cleanup technology; however, information from most of these production operations is usually proprietary. One microbial treatment company, Micro-Bac International, provided a listing of petroleum regions where its microbial products are in use and several case histories of microbial wellbore cleanup.[14] That company has estimated that 2,500 to 3,000 wells have been treated using its microbial products, and this number does not include production tank or barge treatments for bottom sediments and water (BS&W) or paraffin. Oil production increases have occurred in about 50% of all wells treated, with increases in total fluid produced ranging from 100 to 10%. Table 7 lists petroleum-producing regions treated with the product from Micro-Bac International, Para-Bac®. From the available information, it is clear that in certain instances, microbial injection in the near-wellbore region can rival certain existing chemical treatments, both in efficiency and cost.[15]

TABLE 7.– Petroleum regions under treatment with Para-Bac® products

Region	State
Anadarko Basin	OK
Appalachian Basin	PA,KY
Arkoma Basin	AR
Austin Chalk	TX
Dalhart Basin	TX
Gulf Coast Salt Dome Basin	LA
Hugoton Embayment	KS,OK
Illinois Basin	IL
LaSalle Uplift	IL
Michigan Basin	MI
Midland Basin	TX
Palo Duro Basin	TX
Powder River Basin	WY
Sabine Uplift	LA
San Luis Basin	CO
Sweetgrass Arch	MT
Tyler Basin	TX
Tucumcari Basin	NM
Unita Basin/Uplift	UT
Williston Basin	MT

All regions are in the United States; data current as of August, 1990.

MICROBIAL POLYMERFLOODING

Few data have been published regarding MEOR processes where the amount of injected microorganisms that produce polymer is actually equivalent to that of a conventional polymerflood. Moses[16] has conducted laboratory research in this area, but no field test results have been published. Researchers in China recently reported on laboratory tests involving novel microorganisms that produce polymer which they intend to field test sometime later in 1990.[17]

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No MEOR field projects have been reported where the pressures and temperatures were too high for microbial growth. The usual biological limitation for temperature is about 158° F (70° C), and the pressure limitation is about 20,000 psi. The testing of microbial compatibility with reservoir fluids under reservoir conditions is recommended prior to any microbial field test, even well stimulation treatments. The temperature constraints for microbial growth occur with individual microbial species and therefore will not be considered under revised screening criteria. The presence of indigenous microorganisms, as cited in previous screening criteria, is still a major concern. The microorganisms used for crude oil mobilization must survive and thrive in the reservoir. Compatibility testing using the indigenous microorganisms of that particular reservoir is also highly recommended. In those reservoirs with more harsh environmental characteristics for microbial survival, the possibility of stimulating indigenous microorganisms is feasible.

Although most MEOR field projects have been conducted with light crude oils having API gravities around 30° to 40°, successes have been reported with heavy crudes having gravities around 20° API. Obviously the higher the viscosity of a crude oil, the more difficult it will be to mobilize; yet, the principal mechanisms of microorganisms for improved displacement efficiency, gas, surfactant and solvent production, and wettability alteration should still apply.

TABLE 8 - Reservoir characteristics for single-well stimulation field projects

Project conducted by	TDS, %	Permeability, md	Depth, ft	Oil gravity, °API
Oklahoma State University	3.0	([1])	1,750	([1])
Oklahoma State University	4.6	([1])	450	36
Microbial Systems Corp.	11.0	26	700	34
Fairleigh Dickinson Lab.	([1])	([1])	2,550	40
Fairleigh Dickinson Lab.	0.8	([1])	350	20
Petroleum Bioresources, Inc.	([1])	([1])	5,200	([1])
Alpha Environmental, Inc.	1.0	43	1,500	32
Alpha Environmental, Inc.	4.0	25	2,120	39
BWN Oil Co. (Australia)	([1])	260	([1])	Medium-light

[1] Denotes value unavailable or not reported.

TABLE 9 - Reservoir characteristics for microbial-enhanced waterflood field projects

Project conducted by	TDS, %[1]	Perm, md	Depth, ft	Oil Gravity, °API	Visc.[2], cP	Temp., °F	Rock type
NIPER/Microbial Systems and INJECTECH, Inc.	0.02	92	650	34	7.0	77	SS
NIPER/Microbial Systems and INJECTECH, Inc.	2.6	31	450	31	8.2	75	SS
Imperial Energy Corp.	3.8	([3])	([3])	21	([3])	([3])	SS
Alpha Environmental, Inc.	([3])	5-165	2,620	37	([3])	80	SS
Romania - Test 1	0.5	245	2,461	([3])	16	117	SS
Romania - Test 2	0.45	100-1,000	2,560	([3])	26	97	SS
Romania - Test 3	0.5	100-500	2,297	([3])	46	113	LS
Romania - Test 4	0.9	400-1,300	3,937	([3])	33	124	SS
East Germany	32.0	10-50	4,068	30.6	([3])	150	LS
USSR	0.02	500	5,577	([3])	([3])	90	SS

[1]Produced water.
[2]Viscosity at reservoir temperature.
[3]Denotes value unavailable or not reported.
SS = Sandstone
LS = Limestone

CONCLUSIONS

The increasing number of microbial enhanced oil recovery field projects and the variety of different microbial processes that are applicable demonstrates the difficulty and complexity of placing reservoir limitations on the technology. Rather, it is recommended to the national laboratories, universities, small companies, and foreign governments conducting these projects that emphasis should be placed upon the adequate design of a particular field project prior to its implementation. Some thought must be given to what type of microbial process is desired, which means that first some knowledge of the reservoir problem must be obtained. Knowledge of the reservoir problem must be determined before a microbial solution to that problem can be designed. Simple compatibility studies between reservoir fluids and microorganisms can be adequate in many cases to predict whether microorganisms can be applied successfully. Compatibility tests are usually test tube experiments in which several microbial formulations are grown in the presence of reservoir fluids and sometimes reservoir rock. Measurements of the growth and metabolite production of the microorganisms and comparisons are made. Essentially, a revision of screening criteria for MEOR processes in the oilfield becomes a matter of selection of particular microbial formulations for specific reservoir conditions after the problem is defined. The most important reservoir criteria to be considered are listed in table 10.

TABLE 10 - Recommendations for screening procedures for application of MEOR processes in the oilfield

Parameter	Screening procedure
Microorganism used	Determine potential mechanisms for increasing oil production
Salinity	Use compatibility testing to assay for microbial growth and metabolism
Temperature/depth	Use compatibility testing to assay for microbial growth and metabolism under reservoir conditions
Trace minerals	Use compatibility testing to determine deleterious effects on microbial growth and metabolism
Reservoir rock permeability	If multiwell process, conduct a single-well injectivity test and coreflooding studies
Indigenous microorganisms	Use compatibility testing to assay for microbial growth and metabolism under reservoir conditions

The nature of the reservoir to be used for MEOR technology will severely affect the success of the process. If the reservoir is highly channeled, injecting a microorganism that produces only a surfactant may not recover a significant amount of oil since the microorganisms will continue to remain in the water phase and thus bypass much of the trapped crude. By contrast, if there is no channeling and the reservoir permeability is low, injecting a microorganism that produces only a polymer and biomass may decrease injectivity and cause undesirable plugging. Sometimes the mineral content of the connate water may inhibit the growth of the selected microorganisms. If that happens, it may be possible to stimulate microorganisms that are indigenous to the water so that they can act to mobilize crude oil. Researchers at the University of Oklahoma found that they were required to try this approach when the salinity of the brine was much higher than their microorganisms could tolerate.[9] In the USSR, scientists are conducting microbial EOR field trials by stimulating indigenous microorganisms with injection of aerated and carbonated water.[19] A revised list of screening criteria is presented in table 11.

TABLE 11 - Revised screening criteria for application of MEOR processes in the oilfield

Parameter	Recommended range
Salinity	< 10% sodium chloride; total TDS may be higher
Temperature/depth	< 170° F; < 8,000 ft
Trace minerals	< 10-15 ppm of arsenic, mercury, nickel, selenium
Reservoir rock permeability	> 50 millidarcies, unless highly fractured
Indigenous microorganisms	Compatible with injected microorganisms in selected MEOR process
Crude oil type	> 15 °API; not enough information available yet for heavier crude oils
Residual oil saturation	> 25% ; may be some exceptions
Well spacing	< 40 acres; a response can generally be seen sooner on closer well spacing

Clearly, there are many options available to oil producers interested in microbial enhanced oil recovery. Because of the nature of microbial growth and the ability of microorganisms to utilize relatively inexpensive chemicals as nutrients, the economics should be attractive under almost any circumstance. No one microbial process will be a panacea, nor be successful in every reservoir; yet, the fact that there are so many options remains the exciting and challenging facet of MEOR technology.

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