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Microbial Enhanced Oil Recovery (MEOR) with Special Emphasis to the "Uneconomical Reserves"

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Abstract

While demand for petroleum products continuous to rise, petroleum production worldwide is in a steady decline. However, new developments in technology and the rise in world oil prices give promise that substantial portions of otherwise neglected oil can be recovered. So in the continues race of exploring petroleum, recovery of known reserves must be improved if the goal of avoiding shortages is to be met.

One of the promising recovery methods is the microbiological enhanced oil recovery (MEOR). MEOR technology has the potential to be one of the reliable technologies that suits best the economic constraints of the current oil markets. The technology is a potential alternative to other EOR/ IOR methods, as it is being implementing in most parts of the world with satisfactory results not only from economics point of view but also from having lesser environmental impact.

The paper provides a review on MEOR technology and discusses it with special emphasis to marginal and/or uneconomical reserves. The goal of cost reduction, which is a major objective in any recovery methods, can be met by using MEOR technology which involves injecting a small amount of a solution containing microorganisms to spread through the reservoir and consequently produce desirable chemicals and gases that will enhance oil recovery and therefore profit. The paper also outlines the strategies to identify and meet the challenge of recovering large proportions of oil using MEOR techniques which could be very helpful in closing the energy gap by draining large proportions of oil which is left behind and minimizing the supply and demand difference in today's "energy hungry world".

Introduction

One of the major concerns facing the oil industry today is the recovery of large percentage of oil remaining unrecovered in the mature and near depleted producing oil fields. New technology or advancements in technology are necessary to extend producing life and increase reservoir recovery. The prime reasons for the advancements in the technology are the ever increasing demand for energy i.e. Oil and Gas, and the increase in 'energy price'. These reasons are actually driving the oil industry to produce the zones which were considered a 'No No' in the past due to the economic and technological constraints.

Microbial enhanced oil recovery (MEOR) is the new technology that can enhance oil production and recoveries by treatment programs of existing producing wells. The use of microorganisms and their metabolic products to stimulate oil production is currently receiving renewed interest worldwide. This technique involves the injection of selected microorganisms into the reservoir and the subsequent stimulation and transportation of their in situ growth products, in order that their presence will aid in further reduction of residual oil left in the reservoir after secondary recovery is exhausted. Although unlikely to replace conventional microbial enhanced oil recovery, this unique process seems superior in many respects. Self-duplicating units, namely the bacteria cells are injected into the reservoir and by their in situ multiplication they magnify beneficial effects. This method of EOR reduces or eliminates the need to use harsh chemicals during oil drilling. it is an environmentally compatible method of carrying out tertiary oil recovery. MEOR will become increasingly economically feasible particularly for marginal or uneconomical reserves as genetic engineering develops more effective microbial bacteria that may subsist on inexpensive and abundant nutrients.

The concept of using microorganisms to enhance oil recovery, MEOR, was first proposed in 1926 by Beckman; but, it was not until the 1950's that the concept was actively researched by ZoBell and his colleagues. Since that time, a multiplicity of microbiological technologies has been developed to enhance oil recovery. From those tests ZoBell found that

the mechanism by which bacterial oil release could occur are

1. *In situ* generation of CO_2 for pressure and solubilization
2. microbial production of organic acids
3. conversion of hydrocarbons to lower molecular weight
4. production of surface active agents
5. encouragement of consolidation of oil to droplets
6. enzymatic modification of hydrocarbons
7. viscosity improvement

Microorganisms produce different chemicals such as surfactants, polymers, or solvents that are useful in oil recovery processes.

Microbial Enhanced Oil Recovery (MEOR) relies on microbes to ferment hydrocarbons and produce a by–product that is useful in the recovery of oil. MEOR functions by channeling oil through preferred pathways in the reservoir rock by closing/ plugging off small channels and forcing the oil to migrate through the larger pore spaces. Nutrients such as sugars, phosphates, or nitrates frequently must be injected to stimulate the growth of the microbes and aid their performance. The microbes generate surfactants and carbon dioxide that help to displace the oil.

The paper provides a review on MEOR technology and discusses it with special emphasis to marginal and/or uneconomical reserves, also discusses the MEOR field application strategies as well. In the end some real results are presented to support the theoretical discussion.

Microbial growth can be either within the oil reservoir (in situ) or on the surface where the byproducts from microbes grown in vats are selectively removed from the nutrient media and then injected into the reservoir. For in situ MEOR processes, the microorganisms must not only survive in the reservoir environment, but must also produce the chemicals necessary for oil mobilization. The following Figure (1) illustrates microbes inside an oil drop. To get microbes to grow and multiply fast enough, scientists are testing ways to inject food into a reservoir for the microbes to eat. Some microbes feed on nutrients in a reservoir and release gas as part of their digestive process, creating a gas reservoir or gas cap over oil.

Why need for EOR Methods?

Recovering oil usually requires three stages. Primary recovery typically recovers 10 to 35% of a reservoir's oil-in-place. Secondary recovery, which most often involves waterflooding, can increase recovery by 20% or more. Enhanced oil recovery (EOR), also called tertiary oil recovery, enables oil producers to extract as much as 30 to 60% of a reservoir's original oil content. So, much of the oil is left behind in the reservoir after convention recovery methods.

To produce the remaining oil different improved and enhanced oil recovery methods are used i.e. thermal recovery, chemical flooding, miscible displacement (gas injection) and MEOR all have been explored as tertiary techniques. One of the major factors in the selection of any recovery method is the economic potential of the remaining reserves. MEOR is a potentially effective technology to drain this by-passed oil, increasing oil recovery. MEOR is a chemical enhanced oil recovery but with chemicals generated in situ i.e. it differs from chemical EOR in the manner in which the chemicals are introduced into the reservoir. Figure (2) illustrates the positions of injection and production wells for the recovery of oil, left behind after conventional recovery methods.

MEOR Implementation

Implementation of MEOR will entail inoculation of injection wells with microbes, shut-in for a suitable incubation period and resumption of waterflooding with water containing appropriate nutrients. This process is illustrated in Figure (3).

The incubation period establishes bioreactors extending a radial distance r_m from each injector. Microbes are assumed to remain stationary once established. This assumption is convenient but not crucial to the constraints to be derived. When waterflooding resumes, the microbes within each bioreactor convert the injected nutrients and the carbon source into chemicals that move with the aqueous phase into the reservoir and displace the target oil.

MEOR Design Options

Microbial growth can be either within the oil reservoir (in situ) or on the surface where the byproducts from microbes grown in vats are selectively removed from the nutrient media and then injected into the reservoir. Table (1) summarizes the design options for the base case implementation of MEOR. The carbon source may be Ex-situ (included in the injected stream) or In-situ (residual oil within the bioreactor). The economic and logistic advantages are greatest for an in situ carbon source. The possibility of using indigenous microbes (bacteria native and hence specific to individual reservoir) and exogenous (bacteria cultivated for utility in MEOR), also present some constraints in certain circumstances.

Basic Processes Involved in MEOR

The following are the basic processes responsible for oil recovery in MEOR:

1) Well bore clean up
2) Well stimulation
3) Enhanced water floods

Wellbore Clean up

In this process microbes improve the oil drainage to the well bore by romoving paraffinic and scale deposits. The following products perform this job:

Acids: The acids react with various minerals, especially carbonates, and loosen clay particles and other inorganic deposits.
Solvents: Solvents dissolve or swell the precipitated organic deposits, improving the mobility of the oil phase.

Biogas: After a shut-in period of about 1 to 4 weeks for anaerobic growth, the pressure around the well bore was raised to 200-300 psi. When the well was opened and allowed to blow out, a considerable amount of sludge and drilling mud were removed. The well was then placed back in production.

A wide range of microbial reaction products is commonly cited as being relevant to enhanced oil recovery, discussed in Table (2). The effects of the chemicals correspond exactly to those cited in the literature of those processes.

Well Stimulation

The stimulation of oil production by in situ bacterial fermentation is thought to proceed by one or a combination of the following mechanisms:

1) Improvement of the relative mobility of oil to water by biosurfactants and biopolymers

2) Partial repressurization of the reservoir by methane and CO_2 gases

3) Reduction of oil viscosity through the dissolution of organic solvents in the oil phase

4) Increase of reservoir permeability and widening of the fissures and channels through the etching of carbonaceous rocks in limestone reservoirs by organic acids produced by anaerobic bacteria

5) Cleaning of the wellbore region through the acids and gas from in situ fermentation. The gas serves to push oil from dead space and dislodge debris that plugs the pores. The average pore size is increased and, as a result, the capillary pressure near the wellbore is made more favorable for the flow of oil

6) Selective plugging of highly permeable zones by injecting slime-forming bacteria followed by sucrose solution which "turns on" the production of extra cellular slimes. Aerial sweep efficiency is improved

Microbial permeability profile modification (MPPM)

Microbial permeability modification is another advantage of MEOR technology wherein the addition of nutrients to the reservoir enables the microflora present to grow, thereby altering the sweep pattern of the injection water in a conventional waterflood operation. Thus, injection water is diverted from the larger channels to previously unswept areas of the reservoir resulting in an increased efficiency of the waterflood operation. It is important to note that employing this technology does not interfere with the normal waterflood operation. Also, it should be emphasized that the technology is environmentally friendly in that neither microorganisms nor hazardous chemicals are introduced into the environment. The microorganisms upon which the technology depends are already present in the reservoir and the microbial nutrients are commonly used plant fertilizers. This process is the cheapest of all EOR processes and can be applied to mature fields which were once considered uneconomical due to the absence of a cost effective method. This phenomenon of permeability midification is illustrated in Figure (4).

Enhanced Water Floods

Enhanced waterfloods in which they reduce permeability variations and block water channels. This is specifically true for injection well modification where microorganisms reduce high water production from permeability variations. However conventional water flooding involves injecting microbes in the reservoir, then stimulating their growth by injection of nutrients.

Table (3) summarizes the basic MEOR processes and their claimed effects.

The Science of MEOR

The microorganisms used in MEOR can be applied to a single oil well or to an entire oil reservoir. They need certain conditions to survive, so nutrients and oxygen are often introduced into the well at the same time. MEOR also requires that water be present. Microorganisms grow between the oil and the well's rock surface to enhance oil recovery by the following methods:

Reduction of oil viscosity

Oil is a thick fluid that is quite viscous, meaning that it does not flow easily. Microorganisms help break down the molecular structure of crude oil, making it more fluid and easier to recover from the well.

Production of carbon dioxide gas

As a by-product of metabolism, microorganisms produce carbon dioxide gas. Over time, this gas accumulates and displaces the oil in the well, driving it up and out of the ground.

Production of biomass

When microorganisms metabolize the nutrients they need for survival, they produce organic biomass as a by-product. This biomass accumulates between the oil and the rock surface of the well, physically displacing the oil and making it easier to recover from the well.

Selective plugging

Some microorganisms secrete slimy substances called exopolysaccharides to protect themselves from drying out or falling prey to other organisms. This substance helps bacteria plug the pores found in the rocks of the well so that oil may move past rock surfaces more easily. Blocking rock pores to facilitate the movement of oil is

known as selective plugging.

Production of biosurfactants

Microorganisms produce slippery substances called surfactants as they breakdown oil. Because they are naturally produced by biological microorganisms, they are referred to as biosurfactants. Biosurfactants act like slippery detergents, helping the oil move more freely away from rocks and crevices so that it may travel more easily out of the well.

Factors to be Considered Before Applying MEOR

Candidate selection for MEOR processes require consideration of number of parameters before MEOR can be successfully implemented. The application of improved oil recovery (IOR) technology is being applied worldwide, and can only be expected to increase, due to diminishing development of new fields and the decline of more mature ones. MEOR processes address the same physical parameters as chemical enhanced oil recovery processes; hence they are subject to the same technical difficulties.

Reservoir Characteristics

Selecting the reservoir for MEOR processes, especially in case of marginal assests can prove to be a challenging task. In case of mature assets in-situ MEOR is mainly targeted towards the residual oil left after the primary and secondary recovery techniques. Marginal assets after going through various production cycles and techniques and require in depth study of various parameters which may have been altered over the course of time.

Around the world where existing producing fields have shown signs of maturity stage, increasing water and gas production, this scenario ncecessitates the operators to find ways of extending field life beyond the primary and secondary recovery techniques. MEOR, if properly designed and implemented can also maintain reservoir pressure by selective microbial degradation processes in mature assets. In short, MEOR has the potential to sustain reservoir pressures and maintain a steady production.

Many reservoir characteristics must be determined before applying MEOR. This technology requires consideration of the physicochemical properties of the reservoir in terms of salinity, pH, temperature, pressure and nutrient availability. Rock factors are also important. Natural fractures may alter how microbes can effectively be introduced to the reservoir. The presence of clays may preferentially adsorb biopolymers and biosurfactants, rendering them useless. Carbonates may quickly utilize acids and produce larger quantities of beneficial gasses, such as carbon dioxide. Many petroleum reservoirs have high NaCI concentrations and require the use of bacteria that can tolerate these conditions. Bacteria-producing biosurfactants and polymers can grow at NaC1 concentrations of up to 8% and selectively plug sandstone to create a biowall to recover additional oil.

The following are the common factors that need to be considered before we apply MEOR to a certain reservoir. These parameters can vary widely from reservoir to reservoir and in some cases novel parameters may also be considered before MEOR is implemented.

1) Structural Analysis
2) Permeability Analysis
3) Petrophysical Analysis
4) Geological Comlexity
5) Pattern of the wells to be drilled in the reservoir
6) Temperature
7) Depth of reservoir
8) Remaining oil saturation
9) Fluid evaluation: Hydrocarbon composition analysis

Only bacteria are considered promising candidates for MEOR. Molds, yeasts, algae and protozoa are not suitable due to their size or inability to grow under the conditions present in reservoirs as discussed above. Table (4) represents the growth requirements for the mirobes in the reservoir.
The other factors include:

- The identification of chemicals that need to be produced and the job they need to perform
- Selecting the right bacteria
- Selecting the right nutrients for bacteria
- Fluids chemistry and composition
- Net oil increment
- Economic aspects
- Pilot testing: A deciding factor in successful application of MEOR
- Bio-Filter Process

Pilot Testing

Pilot testing is a deciding factor in the successful application of MEOR. The methodology of designing and optimizing MEOR field tests has yet to be estableished, however, different results have indicated that there are some necessary procedures that need to be followed for a successful pilot testing of a project. Following parameters require strict analysis in pilot testing

- Well Selection
- Oil Production

- Standard Core Test Analysis
- Huff-n-Puff Tests
- Incremental reserves
- Evidence of New Oil in Produced Fluids
- Distribution of Nutrients throughout the reservoir
- Maintenance and Growth Media
- Modeling of Microbial Enhanced Oil Recovery
- Performance of Nutrient-Injectro Wells
- Evidence of Microbial Proliferation in reservoir
- Incremental Production Cost Per Barrel

Bio-Filter™ Process

The BioFILTER™ Process is an innovative, environmentally safe Microbial Enhanced Oil Recovery (MEOR) that enhances oil production while also decreasing water cut, thereby giving operators the dual benefits of increased revenue and reducing expenses associated with working in mature fields.

BioFILTER™ is our patented process for increased recovery using the "Huff and Puff" technique. Well-specific volumes of a customized microbe consortia & nutrient pairing are injected under carefully controlled conditions. The well is shut-in to develop a down-hole bioreactor, which stimulates the in-situ growth of the active agents. The shut-in period may last up to three weeks after which the well is returned to production. There will be an initial unloading period followed by increased oil production and decreased water cut which can be expected to last for 6 to 8 months, after which the wells can be re-treated. Figure (5) shows the fluid distribution in the reservoir with and without Bio-Filter.

International field applications of the technology have yielded (to date) an aggregate:

- 200% increase in oil production
- 30% aggregate decrease in water cut
- Improvement in viscosity of 28%
- Improvement in API gravity of 8-10%

The interaction of the customized microbe and nutrients down-hole generate metabolites that include CO2, Acid, Solvents, Surfactants and polymers that improve mobility of oil and increase permeability of the reservoir within a 32 feet radius of the wellbore.

Potential of MEOR Process

The production of oil in the world is entering a tertiary phase because the discovery of new oil fields has decreased with time. Whereas, the waterflooding of the existing fields is steadily becoming less productive as the water-to-oil production ratio approaches the economic limit of operation. The oil left in place is trapped by capillary forces and chemical adhesion to the reservoir rock minerals. Thus, efforts to displace this residual oil require addition of considerable energy to the petroleum reservoir in the form of chemical reactants, heat, or solvents. A potential source of supplemental energy for petroleum reservoirs and other petroleum operations is from microorganisms (Donaldson, 1982).

So, the use of biotechnology in the petroleum industry is thought of as a fully understood and integrated process that has produced tangible benefits improving production from depleted and marginal reservoirs. MEOR is promising technique but in order to keep this technology rosy there is a need of special contribution from microbiologist, geologists and petroleum engineers. Further more it requires research on interaction of microbes with reservoir, and laboratory work to optimize the oil production with fewer losses.

Field Apllications of MEOR & Strategies

Field application of MEOR projects, especially to marginal reserves require sound knowledge of reservoir engineering with and added knowledge of microbiology. A complete set of methodologies and best practice for MEOR projects is yet to be defined. However increasing application of MEOR to maturing and marginal assets can formulate reliable literature and results upon which best practices for an MEOR project can be defined.

As the main objective of application of Microbial Enhanced Oil Recovery to un-economical reserves is increasing the ultimate recovery factor. So, characterization of target reservoirs is important in defining a MEOR project. It means a careful analysis of reservoir properties is required i.g. in a certain case some high permeability streaks is the reservoir needs to be plugged while in other parts permeability needs to be enhanced. However, the reservoir lithology also plays a vital part in the successful application of MEOR to uneconomical reserves.

Microbes growth requiremnt is the other factor to be considered in the successful application of MEOR. To obtain the required results and targets the proper quality nutrients should be injected to the reservoir. Moreover care should be taken that the injection of nutrients with various minerals dissolved may stimulate the growth of inactive bacteria already present in the reservoir such as sulfate reducing bacteria.

Thus, microbial treatment for enhanced oil recovery is a favourable option in the highly volatile oil market and difficult financial times. The application of MEOR to marginal or uneconomical reserves may produce a fractional increase in production from a certain resevoir. However, increased production from a large number of

marginal reserves can significantly increase the commulative oil recovered.

Steps involved in successful application of MEOR projects and strategies are as under:

1) Feasibility Study

2) Experimental Study and Pilot Testing

Feasibility Study

Defining your objective: Benefits from the application of MEOR can be obtained in different ways i.e. you might want to reduce the oil viscosity, plug pores for greater sweep efficiency in water case of water flooding. Since in uneconomical reserves there is no chance for error so a through study must be performed before adopting any recovery method.

Simulation Study: Simulation studies can provide one of the most useful and economical solution to MEOR feasibility studies. Stimulation studies can effectively determine

- Whether the prevailing conditions are beneficial for MEOR process or not. Is it possible to change prevailing conditions in case of marginal reserves to enhance recovery?
- What kind of nutrients will be beneficial
- Whether continuous or intermittent injection will be beneficial
- Where the injection will maximize recovery etc.

Screening criteria: In screening criteria different approaches are used like one should consider specific reservoir properties and should look for in a reservoir before it is declared a favourable candidate for MEOR.

Economics: Economic factors are the basic factor in a strategy that decides whether this project should be implemented or abandoned. Economics in an EOR project can prove to be a great challenge especially in case of marginal or mature assets. Therefore a stringent economic analysis should be made before a project is given a go ahead.

Experimental Study and Pilot Testing

Materials: Materials, nutrients and supplements, used in the microbial profile modification are an important part of evaluation. There are many sources of nutrients susch as sucrose, molasses, corn steep liquor, black liquor, soybean whey, tapioca whey, etc. the combination of nutrient with nitrogen, phosphorous, minerals, and proteins is called here "the media".

Microbes: Microbe selection is crucial for a successful MEOR project result. For this purpose the best strategy would be to gather a multidisciplinary team consisting of microbiologists, geologists and petroleum engineer. And chalk out a strategy of core testing and other tests using different strains of bacteria and then selecting the best strain on the basis of results comparison.

Nutrient: Microbes require for growth sources of the major elements which make up cell material carbon, nitrogen, phosphorous, oxygen, sulphur, minor components such as iron, zinc, manganese, and a source of energy for the synthesis process involved in growth. In the laboratory, bacteria can be feed with different nutrients and the resultant by products are analyzed. The nutrients giving the best by products and acting in the desired way on oil should be chosen. Water is usually the preferred medium of choice. However, medium properties and its interaction with oil and formation should also be studied.

Water: Testing formation water for salinity, trace minerals and all other minerals dissolved in it, is incorporated as a part of the experimentation. Formation water testing reveals a great deal on the ability of the microorganisms to survive in the formation and reproduce at the required rate.

Testing: Testing of MEOR projects to give a formal go ahead for MEOR application in various fields include the following steps:

a) **Site Selection**: By site selection means the selection of suitable area of the reservoir, which will allow spreading and distribution of microbes in a uniform manner. The targeted areas, which are to be treated using the microbe injection or stimulation of microbes that, are already present in the reservoir. Thus the injection well should be able to flood the required reservoir region and microbes' injection should be done at such a place where where they will produce the required outcome. Geochemical analysis and interpretations, when integrated with pressure trends and a geologic and geophysical framework provide important input to development and production planning. Exploitaion geochemical

approaches are especially pertinent to help determine continuity or segmentation of reservoir compartments when pressure or geologic data are ambiguous. Understanding reservoir continuity is critical to optimizing field-development planning. Identification of reservoir segmentation is also important to the efficient placement of injector/ producer pairs when pressure maintenance by water injection is planned. Differences in biodegradation level can sometimes indicate segmented compartments. Geochemical analyses can also detect gradients in hydrocarbon properties within continuous reservoirs (caused by gravity segregation). Recognition of such gradients is important for reservoir models and field planning. In heavy-oil fields, geochemical analyses of sidewall cores can help to identify oil quality variations and sweet spots for targeted production.

b) **Sampling and Analysis of Well Fluids:** Compatibility tests are usually run to evaluate survival of microbes in the presence of reservoir brine, rock and nutrients. Laboratory tests under controlled conditions such as flask tests, test tube tests and other PVT tests in the core lab can help accurately determine the reservoir fluid properties. Some of the parameters which should be considered in the fluid analysis are:

- PH
- Eh
- Temperature
- Pressure
- Dissolved gases
- Inert particulate matter
- Multiphase systems (oil, gas, water)
- Geometry and physical size of pores
- Ions, minerals and salts
- Microbial flora

c) **Selection of microbial formulation and compatibility tests:** These tests are one of the important factors of testing. From these tests information regarding the "Residence time vs Reaction time" and their compatibility with a certain reservoir under different conditions can be studied. After the injection of microbes a waiting time is required so that the microbes can act on various areas of the reservoir and produce the required results. Thus shut-in time should also be formulated using predetermined laboratory tests.

d) **Base line determination of producing wells:** In the base line determination of the producing wells frequent production measurements are made of the producing wells for a specific period, prior to injection.

e) **Growth of microbial formulation and injection of microbes and nutrients:** In this method microbial formulation according certain standards is done and then final inoculation is done at site.

f) **Shut-in period**: After the injection of bacteria and required nutrients, the well is shut in for specific period to allow for the growth of bacteria in the oil-producing formation.

g) **Productions Follow Up:** After completing the shut-in period the well is put back in operation and the increase in production is recorded or the production follow up period is the period in which testing is conducted again after a certain specific period of time. With this the pilot testing is completed. The tests help to determine:

- Changes in physical properties of oil such as viscosity
- Microbial count in the reservoir and are they acting in the right manner
- Changes in the oil composition
- Are the nutrients nourishing bacteria and are causing them to produce the right bacteria
- Changes in the reservoir and study of harmful effects such as stimulation of sulfur reducing bacteria
- Are the microbes corroding or promoting corrosion in the tubulars
- Should we continue with the microbial injection and MEOR process?

- What would be the frequency of microbial batch injection?
- Study of residence time vs injection time
- Expansion of injection program if required
- Microbial analysis
- Are the wells being injected transport them to the required places or should we change the site of injection
- Study of huff-n-puff tests
- Is there stimulation of any in-situe flora due to nutrients injection and what is the effect of stimulation of these in-situ microbes?

Some Real Results of MEOR Field Applications Around the World

MEOR has been successfully applied to various fields around the world. A few of these are presented here to support the whole disscussion.

1) Dostalek and Spurney (1957), in Czechoslovakia, conducted field tests by injecting a mixed culture of sulfate-reducing (Desulfovibrio) bacteria and paraffin-exidizing bacteria (Pseudomonas) with a molasses base nutrient solution. They stated that the daily average oil production increased by approximately 7% during the 6-month period.
2) Jaranyi et al. (1963), working in Hungary, used a mixture of anaerobic, thermophilic bacteria that fermented molasses in a field containing naphthenic-type crude oil. In later field triels, they used raw sewage as the inoculum (1 litre of sewage mixed in 300 litres of 2-3% molasses). The deepest reservoir treated was 2500m (8200 ft). They reported beneficial results to oil production in 7 out of 10 reservoirs that were treated, but the specific increases of production were not given.
3) In Northwest Peru20, in the Talara basin the Providencia and Lobitos fields of Block Z-2 in 2003, produced 95,000 BOPD while consuming 163,000 B/D. seven producing wells were selected to evaluate MEOR for enhanced oil recovery. The MEOR resulted in average 13,907 to 19,410 bbl of incremental oil. After this test it was concluded that, MEOR is equally feasible for single or commingled production.
4) Karaskiewicz (1962) conducted 18 field trials in Poland between 1961 and 1969 with microbial cultures obtained from soil and water samples taken in the vicinity of the oil fields and from sugar factory waste-waters. The cultures were grown in 10-litre bottles containing formation water plus 4% molasses at 32C. The wells that were treated ranged in depth from 500 to 1525m (1650 to 5000 ft). According to Hitzman (1983), Karaskiewicz reported increases of oil production rates that ranged from 20 to 200% over the original rate of production.
5) During the period 1977-1981, Johnson (1979) inoculated approximately 150 stripper wells in the United States with a mixed culture of Bacillus-clostridium. The carbonate reservoir depths ranged from 60 to 300 m and porosity from 10 to 30%. Johnson injected the inoculum into the production wells, shut the wells in for 10-14 days, and then opened them once more for production. Production increases of 20-30% were obtained when the API gravity of ranged from 15 to 30 and the formation water contained less than 100,000 ppm salt.
6) Hitzman (1983) reported that Petrogen, Inc., tested the Johnson method in 24 wells ranging in depth from 90 to 1400m (300 to 4600 ft). the production rates of four of the wells doubled for a period of 6 months, and 12 of the wells showed a 3-month production increase of 50%.

During the last 10 years of research studies in the Arabic area it was found that some of the Saudi, Iraqi and Egyptian oil fields can be very good candidates for MEOR processes. Also, depleted or marginal oil fields in Egypt and Syria can be activated by injection of microorganisms, which can be beneficial in producing more oil. Recently a state of the art of the MEOR process was presented at the 6th international conference of MPM held in Cairo University. It was concluded that more extensive laboratory and field research should be carried out in order to develop a technology in the area of MEOR under reservoir conditions of temperature, pressure, permeability and formation water salinity.

Current Research Areas

The processes that facilitate oil production are complex and usually involve multiple biochemical processes. MEOR systems represent high-risk processes to oil producers looking for efficient and predictable oil recovery. Microbial biomass or biopolymers might: plug high-permeability zones and lead to a redirection of the waterflood; produce surfactants, leading to increased mobilization of residual oil; increase gas pressure by producing CO_2 or methane; or reduce oil viscosity due to digestion of large molecules.

While methanogenic bacteria have been shown to be active in oil and coal-bed methane reservoirs, they must function as part of a reaction chain to effectively produce methane. This includes breaking down the large chain hydrocarbon, converting the molecules to simple acids and alcohols, and then finally converting the simple molecules to methane. Each part of the chain is processed by different microbial consortia. All of these consortia are sensitive to environmental changes, such as the introduction of oxygen, which could sterilize the population, break the chain, and shut down the entire process.

Biogenesis is being looked at for converting coal, shale and residual oil to methane in commercial quantities. This in-situ microbial conversion to methane has the potential to create significant amounts of natural gas in days rather than millions of years. In experiments administered on Dietz coals of the Powder River basin, tested samples of coal and unamended formation water resulted in a steady increase in methane in the headspace, slightly exceeding 3% by 135 days. However, when a nutritional enhancer was added, methane levels reached nearly 9% in a comparable time-frame, with methane representing nearly 100% of the newly generated gas.

Researchers are working to create strains of bacteria that are better able to survive harsh environmental conditions in oil wells but still retain the ability to carry out the chemistry needed for MEOR. Genetic engineering is being used to develop microorganisms that not only live in high temperatures, but can also subsist on inexpensive nutrients, remain chemically active and produce substantial amounts of biosurfactants. Some researchers are developing bacteria that can be grown on inexpensive agricultural waste material, which is abundant in supply and is environmentally friendly.

Conclusions

Almost a decade ago MEOR might have been considered as a technology in its fantacy but the current oil crisis has established this cost-effective technology as a viable candidate for further research and application. At the moment emphasis has been shifted towards producing marginal and by passed oil by the application of new effective and economic techniques. MEOR is one such effective solution that has seen increasing applications in the oil industry. The successful application of this technology as an oil recovery process is evolving and being readily accepted. Marginal, by-passed and mature assets have taken the centre stage, shrinking oil reserves and limited new discoveries have now prompted the global oil industry to improve recovery factors from the existing oil fields. Since conventional EOR methods are cost intensive and not suitable for marginal and mature assets, so MEOR has stepped in as a suitable alternative.

Microbial enhanced oil recovery (MEOR) projects are being applied worldwide and it is predicted that this technology would save the industry's millions of dollars by increasing the amount of recoverable oil within a shorter time frame. But in order to keep this technology rosy there is a constant need to innovate and develop the existing technology.

Nomenclature

API = American Petroleum Institute
bbl = barrels
B/D = Barrels per day
BOPD = Barrels of oil per day
EOR = Enhanced Oil Recovery
IOR = Improved Oil Recovery
MEOR = Microbial Enhanced Oil Recovery
MPPM = Microbial Permeability Profile Modification
Rm = Radial extent of bioreactor

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Table 1: MEOR Design Options

Design Feature	Design Options
Reactor Type	Fixed Growing Mobile
Carbon Source	In-situ Ex-situ
Microbe Provenance	Indigenous Exogenous

Table 2: Microbial Products and Their Contribution to Enhanced Oil Recovery

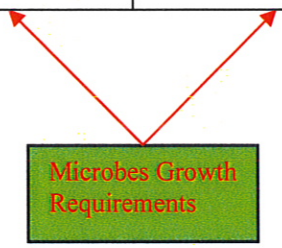
Microbial	Effect
Acids	Modification of reservoir rock Improvement of porosity and permeability Reaction with calcareous CO2 production
Biomass	Selective or nonselective plugging Emulsification through adherence to hydrocarbons Modification of solid surfaces, e.g., wetting Degradation and alteration of oil Reduction of oil viscosity and oil pour point Desulfurization of oil
Gases (CO_2, CH_4, H_2)	Reservoir repressurization Oil swelling Viscosity reduction Increase of permeability due to solubilization of carbonate rocks by CO2
Solvents	Dissolving of oil
Surface active agents	Lowering of interfacial tension Emulsification
Plymers	Mobility control Selective or nonselective plugging

Table 3: Types of Microbial Processes for Oil Recovery

Process	Production problem	Types of activity or product needed
Well bore cleanup (improve oil drainage into well bore)	Paraffin and scale deposits	Emulsifiers, Biosurfactants, solvents, acids, hydrocarbon degradation
Well stimulation (stimulate release of oil entrapped by capillaries and brine)	Formation damage, pore damage High water production	Gas, acids, solvents, Biosurfactants, Biomass and polymer production
Enhanced waterfloods (reduce permeability variation and block water channels)	Poor displacement efficiency Poor sweep efficiency Scouring	Biosurfactants, solvents, polymers, Biomass and polymer production, Nitrate reduction

Table 4: Reservoir properties necessary for microbes growth

Friendly Reservoir	Suitable Temperature for Microbes Survival
Porosity, Permeability	Oxiants Availibility



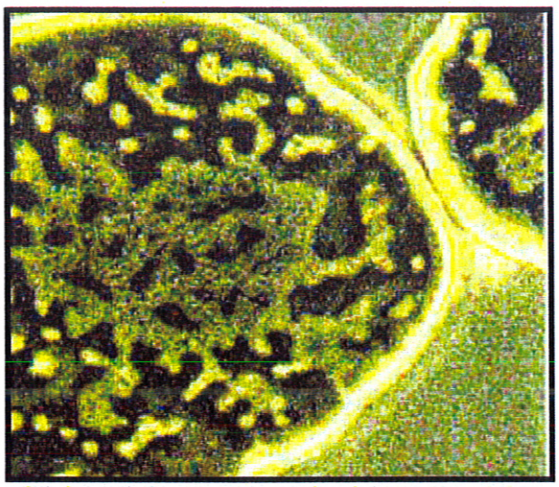


Figure 1: Microbes within an oil droplet (Sources: U.S Department of Energy)

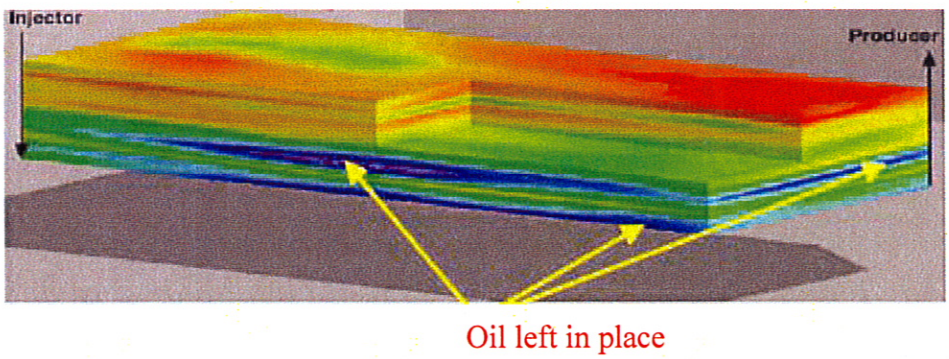


Figure 2: Illustration of bypassed oil and position of injection and production wells

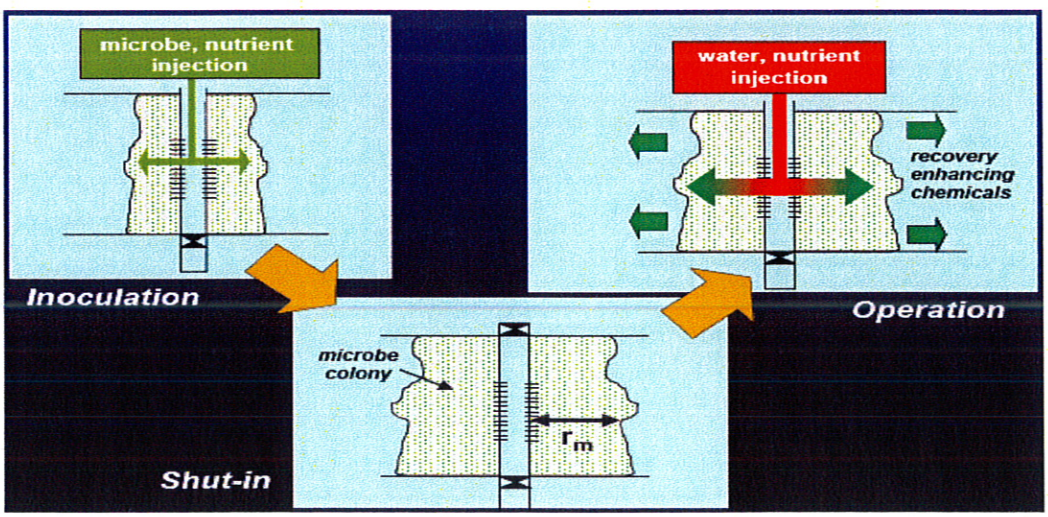


Figure 3: Base case implementaion of MEOR

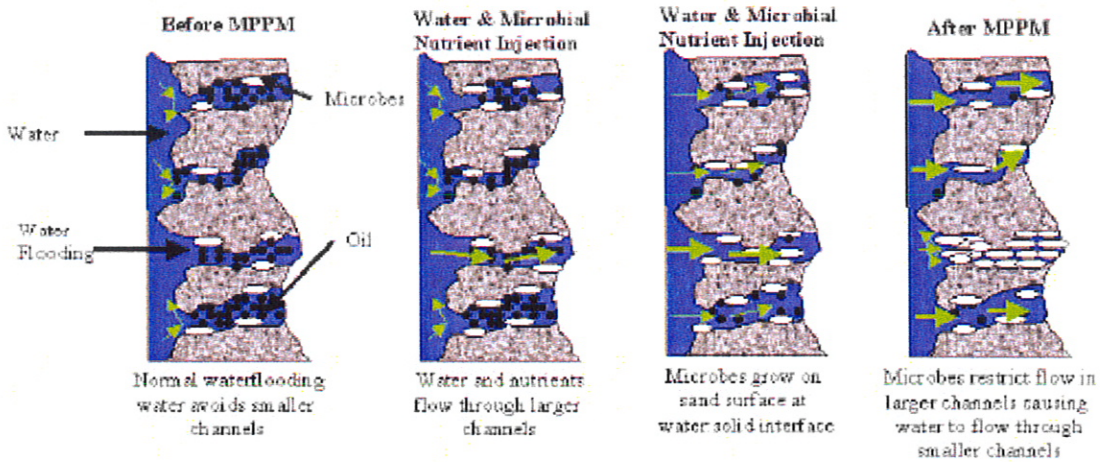


Figure 4: Mechanism of microbial enhanced oil recovery (MEOR) using in situ microbial permeability profile modification (MPPM) to enhance oil recovery

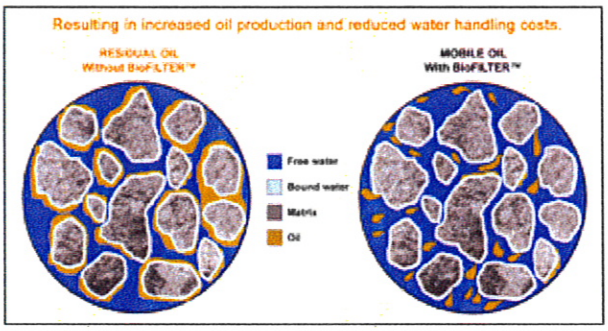


Figure 5: Fluid distribution in the reservoir with and without BioFILTER™

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Microbial Enhanced Oil Recovery (MEOR) with Special Emphasis to the "Uneconomical Reserves"

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Abstract

While demand for petroleum products continuous to rise, petroleum production worldwide is in a steady decline. However, new developments in technology and the rise in world oil prices give promise that substantial portions of otherwise neglected oil can be recovered. So in the continues race of exploring petroleum, recovery of known reserves must be improved if the goal of avoiding shortages is to be met.

One of the promising recovery methods is the microbiological enhanced oil recovery (MEOR). MEOR technology has the potential to be one of the reliable technologies that suits best the economic constraints of the current oil markets. The technology is a potential alternative to other EOR/ IOR methods, as it is being implementing in most parts of the world with satisfactory results not only from economics point of view but also from having lesser environmental impact.

The paper provides a review on MEOR technology and discusses it with special emphasis to marginal and/or uneconomical reserves. The goal of cost reduction, which is a major objective in any recovery methods, can be met by using MEOR technology which involves injecting a small amount of a solution containing microorganisms to spread through the reservoir and consequently produce desirable chemicals and gases that will enhance oil recovery and therefore profit. The paper also outlines the strategies to identify and meet the challenge of recovering large proportions of oil using MEOR techniques which could be very helpful in closing the energy gap by draining large proportions of oil which is left behind and minimizing the supply and demand difference in today's "energy hungry world".

Introduction

One of the major concerns facing the oil industry today is the recovery of large percentage of oil remaining unrecovered in the mature and near depleted producing oil fields. New technology or advancements in technology are necessary to extend producing life and increase reservoir recovery. The prime reasons for the advancements in the technology are the ever increasing demand for energy i.e. Oil and Gas, and the increase in 'energy price'. These reasons are actually driving the oil industry to produce the zones which were considered a 'No No' in the past due to the economic and technological constraints.

Microbial enhanced oil recovery (MEOR) is the new technology that can enhance oil production and recoveries by treatment programs of existing producing wells. The use of microorganisms and their metabolic products to stimulate oil production is currently receiving renewed interest worldwide. This technique involves the injection of selected microorganisms into the reservoir and the subsequent stimulation and transportation of their in situ growth products, in order that their presence will aid in further reduction of residual oil left in the reservoir after secondary recovery is exhausted. Although unlikely to replace conventional microbial enhanced oil recovery, this unique process seems superior in many respects. Self-duplicating units, namely the bacteria cells are injected into the reservoir and by their in situ multiplication they magnify beneficial effects. This method of EOR reduces or eliminates the need to use harsh chemicals during oil drilling. it is an environmentally compatible method of carrying out tertiary oil recovery. MEOR will become increasingly economically feasible particularly for marginal or uneconomical reserves as genetic engineering develops more effective microbial bacteria that may subsist on inexpensive and abundant nutrients.

The concept of using microorganisms to enhance oil recovery, MEOR, was first proposed in 1926 by Beckman; but, it was not until the 1950's that the concept was actively researched by ZoBell and his colleagues. Since that time, a multiplicity of microbiological technologies has been developed to enhance oil recovery. From those tests ZoBell found that

the mechanism by which bacterial oil release could occur are

1. *In situ* generation of CO_2 for pressure and solubilization
2. microbial production of organic acids
3. conversion of hydrocarbons to lower molecular weight
4. production of surface active agents
5. encouragement of consolidation of oil to droplets
6. enzymatic modification of hydrocarbons
7. viscosity improvement

Microorganisms produce different chemicals such as surfactants, polymers, or solvents that are useful in oil recovery processes.

Microbial Enhanced Oil Recovery (MEOR) relies on microbes to ferment hydrocarbons and produce a by–product that is useful in the recovery of oil. MEOR functions by channeling oil through preferred pathways in the reservoir rock by closing/ plugging off small channels and forcing the oil to migrate through the larger pore spaces. Nutrients such as sugars, phosphates, or nitrates frequently must be injected to stimulate the growth of the microbes and aid their performance. The microbes generate surfactants and carbon dioxide that help to displace the oil.

The paper provides a review on MEOR technology and discusses it with special emphasis to marginal and/or uneconomical reserves, also discusses the MEOR field application strategies as well. In the end some real results are presented to support the theoretical discussion.

Microbial growth can be either within the oil reservoir (in situ) or on the surface where the byproducts from microbes grown in vats are selectively removed from the nutrient media and then injected into the reservoir. For in situ MEOR processes, the microorganisms must not only survive in the reservoir environment, but must also produce the chemicals necessary for oil mobilization. The following Figure (1) illustrates microbes inside an oil drop. To get microbes to grow and multiply fast enough, scientists are testing ways to inject food into a reservoir for the microbes to eat. Some microbes feed on nutrients in a reservoir and release gas as part of their digestive process, creating a gas reservoir or gas cap over oil.

Why need for EOR Methods?

Recovering oil usually requires three stages. Primary recovery typically recovers 10 to 35% of a reservoir's oil-in-place. Secondary recovery, which most often involves waterflooding, can increase recovery by 20% or more. Enhanced oil recovery (EOR), also called tertiary oil recovery, enables oil producers to extract as much as 30 to 60% of a reservoir's original oil content. So, much of the oil is left behind in the reservoir after convention recovery methods.

To produce the remaining oil different improved and enhanced oil recovery methods are used i.e. thermal recovery, chemical flooding, miscible displacement (gas injection) and MEOR all have been explored as tertiary techniques. One of the major factors in the selection of any recovery method is the economic potential of the remaining reserves. MEOR is a potentially effective technology to drain this by-passed oil, increasing oil recovery. MEOR is a chemical enhanced oil recovery but with chemicals generated in situ i.e. it differs from chemical EOR in the manner in which the chemicals are introduced into the reservoir. Figure (2) illustrates the positions of injection and production wells for the recovery of oil, left behind after conventional recovery methods.

MEOR Implementation

Implementation of MEOR will entail inoculation of injection wells with microbes, shut-in for a suitable incubation period and resumption of waterflooding with water containing appropriate nutrients. This process is illustrated in Figure (3).

The incubation period establishes bioreactors extending a radial distance rm from each injector. Microbes are assumed to remain stationary once established. This assumption is convenient but not crucial to the constraints to be derived. When waterflooding resumes, the microbes within each bioreactor convert the injected nutrients and the carbon source into chemicals that move with the aqueous phase into the reservoir and displace the target oil.

MEOR Design Options

Microbial growth can be either within the oil reservoir (in situ) or on the surface where the byproducts from microbes grown in vats are selectively removed from the nutrient media and then injected into the reservoir. Table (1) summarizes the design options for the base case implementation of MEOR. The carbon source may be Ex-situ (included in the injected stream) or In-situ (residual oil within the bioreactor). The economic and logistic advantages are greatest for an in situ carbon source. The possibility of using indigenous microbes (bacteria native and hence specific to individual reservoir) and exogenous (bacteria cultivated for utility in MEOR), also present some constraints in certain circumstances.

Basic Processes Involved in MEOR

The following are the basic processes responsible for oil recovery in MEOR:

1) Well bore clean up
2) Well stimulation
3) Enhanced water floods

Wellbore Clean up

In this process microbes improve the oil drainage to the well bore by romoving paraffinic and scale deposits. The following products perform this job:

Acids: The acids react with various minerals, especially carbonates, and loosen clay particles and other inorganic deposits.
Solvents: Solvents dissolve or swell the precipitated organic deposits, improving the mobility of the oil phase.

Biogas: After a shut-in period of about 1 to 4 weeks for anaerobic growth, the pressure around the well bore was raised to 200-300 psi. When the well was opened and allowed to blow out, a considerable amount of sludge and drilling mud were removed. The well was then placed back in production.

A wide range of microbial reaction products is commonly cited as being relevant to enhanced oil recovery, discussed in Table (2). The effects of the chemicals correspond exactly to those cited in the literature of those processes.

Well Stimulation

The stimulation of oil production by in situ bacterial fermentation is thought to proceed by one or a combination of the following mechanisms:

1) Improvement of the relative mobility of oil to water by biosurfactants and biopolymers

2) Partial repressurization of the reservoir by methane and CO_2 gases

3) Reduction of oil viscosity through the dissolution of organic solvents in the oil phase

4) Increase of reservoir permeability and widening of the fissures and channels through the etching of carbonaceous rocks in limestone reservoirs by organic acids produced by anaerobic bacteria

5) Cleaning of the wellbore region through the acids and gas from in situ fermentation. The gas serves to push oil from dead space and dislodge debris that plugs the pores. The average pore size is increased and, as a result, the capillary pressure near the wellbore is made more favorable for the flow of oil

6) Selective plugging of highly permeable zones by injecting slime-forming bacteria followed by sucrose solution which "turns on" the production of extra cellular slimes. Aerial sweep efficiency is improved

Microbial permeability profile modification (MPPM)

Microbial permeability modification is another advantage of MEOR technology wherein the addition of nutrients to the reservoir enables the microflora present to grow, thereby altering the sweep pattern of the injection water in a conventional waterflood operation. Thus, injection water is diverted from the larger channels to previously unswept areas of the reservoir resulting in an increased efficiency of the waterflood operation. It is important to note that employing this technology does not interfere with the normal waterflood operation. Also, it should be emphasized that the technology is environmentally friendly in that neither microorganisms nor hazardous chemicals are introduced into the environment. The microorganisms upon which the technology depends are already present in the reservoir and the microbial nutrients are commonly used plant fertilizers. This process is the cheapest of all EOR processes and can be applied to mature fields which were once considered uneconomical due to the absence of a cost effective method. This phenomenon of permeability midification is illustrated in Figure (4).

Enhanced Water Floods

Enhanced waterfloods in which they reduce permeability variations and block water channels. This is specifically true for injection well modification where microorganisms reduce high water production from permeability variations. However conventional water flooding involves injecting microbes in the reservoir, then stimulating their growth by injection of nutrients.

Table (3) summarizes the basic MEOR processes and their claimed effects.

The Science of MEOR

The microorganisms used in MEOR can be applied to a single oil well or to an entire oil reservoir. They need certain conditions to survive, so nutrients and oxygen are often introduced into the well at the same time. MEOR also requires that water be present. Microorganisms grow between the oil and the well's rock surface to enhance oil recovery by the following methods:

Reduction of oil viscosity

Oil is a thick fluid that is quite viscous, meaning that it does not flow easily. Microorganisms help break down the molecular structure of crude oil, making it more fluid and easier to recover from the well.

Production of carbon dioxide gas

As a by-product of metabolism, microorganisms produce carbon dioxide gas. Over time, this gas accumulates and displaces the oil in the well, driving it up and out of the ground.

Production of biomass

When microorganisms metabolize the nutrients they need for survival, they produce organic biomass as a by-product. This biomass accumulates between the oil and the rock surface of the well, physically displacing the oil and making it easier to recover from the well.

Selective plugging

Some microorganisms secrete slimy substances called exopolysaccharides to protect themselves from drying out or falling prey to other organisms. This substance helps bacteria plug the pores found in the rocks of the well so that oil may move past rock surfaces more easily. Blocking rock pores to facilitate the movement of oil is

known as selective plugging.

Production of biosurfactants

Microorganisms produce slippery substances called surfactants as they breakdown oil. Because they are naturally produced by biological microorganisms, they are referred to as biosurfactants. Biosurfactants act like slippery detergents, helping the oil move more freely away from rocks and crevices so that it may travel more easily out of the well.

Factors to be Considered Before Applying MEOR

Candidate selection for MEOR processes require consideration of number of parameters before MEOR can be successfully implemented. The application of improved oil recovery (IOR) technology is being applied worldwide, and can only be expected to increase, due to diminishing development of new fields and the decline of more mature ones. MEOR processes address the same physical parameters as chemical enhanced oil recovery processes; hence they are subject to the same technical difficulties.

Reservoir Characteristics

Selecting the reservoir for MEOR processes, especially in case of marginal assests can prove to be a challenging task. In case of mature assets in-situ MEOR is mainly targeted towards the residual oil left after the primary and secondary recovery techniques. Marginal assets after going through various production cycles and techniques and require in depth study of various parameters which may have been altered over the course of time.

Around the world where existing producing fields have shown signs of maturity stage, increasing water and gas production, this scenario ncecessitates the operators to find ways of extending field life beyond the primary and secondary recovery techniques. MEOR, if properly designed and implemented can also maintain reservoir pressure by selective microbial degradation processes in mature assets. In short, MEOR has the potential to sustain reservoir pressures and maintain a steady production.

Many reservoir characteristics must be determined before applying MEOR. This technology requires consideration of the physicochemical properties of the reservoir in terms of salinity, pH, temperature, pressure and nutrient availability. Rock factors are also important. Natural fractures may alter how microbes can effectively be introduced to the reservoir. The presence of clays may preferentially adsorb biopolymers and biosurfactants, rendering them useless. Carbonates may quickly utilize acids and produce larger quantities of beneficial gasses, such as carbon dioxide. Many petroleum reservoirs have high NaCI concentrations and require the use of bacteria that can tolerate these conditions. Bacteria-producing biosurfactants and polymers can grow at NaC1 concentrations of up to 8% and selectively plug sandstone to create a biowall to recover additional oil.

The following are the common factors that need to be considered before we apply MEOR to a certain reservoir. These parameters can vary widely from reservoir to reservoir and in some cases novel parameters may also be considered before MEOR is implemented.

1) Structural Analysis
2) Permeability Analysis
3) Petrophysical Analysis
4) Geological Comlexity
5) Pattern of the wells to be drilled in the reservoir
6) Temperature
7) Depth of reservoir
8) Remaining oil saturation
9) Fluid evaluation: Hydrocarbon composition analysis

Only bacteria are considered promising candidates for MEOR. Molds, yeasts, algae and protozoa are not suitable due to their size or inability to grow under the conditions present in reservoirs as discussed above. Table (4) represents the growth requirements for the mirobes in the reservoir.
The other factors include:

- The identification of chemicals that need to be produced and the job they need to perform
- Selecting the right bacteria
- Selecting the right nutrients for bacteria
- Fluids chemistry and composition
- Net oil increment
- Economic aspects
- Pilot testing: A deciding factor in successful application of MEOR
- Bio-Filter Process

Pilot Testing

Pilot testing is a deciding factor in the successful application of MEOR. The methodology of designing and optimizing MEOR field tests has yet to be estableished, however, different results have indicated that there are some necessary procedures that need to be followed for a successful pilot testing of a project. Following parameters require strict analysis in pilot testing

- Well Selection
- Oil Production

- Standard Core Test Analysis
- Huff-n-Puff Tests
- Incremental reserves
- Evidence of New Oil in Produced Fluids
- Distribution of Nutrients throughout the reservoir
- Maintenance and Growth Media
- Modeling of Microbial Enhanced Oil Recovery
- Performance of Nutrient-Injectro Wells
- Evidence of Microbial Proliferation in reservoir
- Incremental Production Cost Per Barrel

Bio-Filter™ Process

The BioFILTER™ Process is an innovative, environmentally safe Microbial Enhanced Oil Recovery (MEOR) that enhances oil production while also decreasing water cut, thereby giving operators the dual benefits of increased revenue and reducing expenses associated with working in mature fields.

BioFILTER™ is our patented process for increased recovery using the "Huff and Puff" technique. Well-specific volumes of a customized microbe consortia & nutrient pairing are injected under carefully controlled conditions. The well is shut-in to develop a down-hole bioreactor, which stimulates the in-situ growth of the active agents. The shut-in period may last up to three weeks after which the well is returned to production. There will be an initial unloading period followed by increased oil production and decreased water cut which can be expected to last for 6 to 8 months, after which the wells can be re-treated. Figure (5) shows the fluid distribution in the reservoir with and without Bio-Filter.

International field applications of the technology have yielded (to date) an aggregate:

- 200% increase in oil production
- 30% aggregate decrease in water cut
- Improvement in viscosity of 28%
- Improvement in API gravity of 8-10%

The interaction of the customized microbe and nutrients down-hole generate metabolites that include CO2, Acid, Solvents, Surfactants and polymers that improve mobility of oil and increase permeability of the reservoir within a 32 feet radius of the wellbore.

Potential of MEOR Process

The production of oil in the world is entering a tertiary phase because the discovery of new oil fields has decreased with time. Whereas, the waterflooding of the existing fields is steadily becoming less productive as the water-to-oil production ratio approaches the economic limit of operation. The oil left in place is trapped by capillary forces and chemical adhesion to the reservoir rock minerals. Thus, efforts to displace this residual oil require addition of considerable energy to the petroleum reservoir in the form of chemical reactants, heat, or solvents. A potential source of supplemental energy for petroleum reservoirs and other petroleum operations is from microorganisms (Donaldson, 1982).

So, the use of biotechnology in the petroleum industry is thought of as a fully understood and integrated process that has produced tangible benefits improving production from depleted and marginal reservoirs. MEOR is promising technique but in order to keep this technology rosy there is a need of special contribution from microbiologist, geologists and petroleum engineers. Further more it requires research on interaction of microbes with reservoir, and laboratory work to optimize the oil production with fewer losses.

Field Apllications of MEOR & Strategies

Field application of MEOR projects, especially to marginal reserves require sound knowledge of reservoir engineering with and added knowledge of microbiology. A complete set of methodologies and best practice for MEOR projects is yet to be defined. However increasing application of MEOR to maturing and marginal assets can formulate reliable literature and results upon which best practices for an MEOR project can be defined.

As the main objective of application of Microbial Enhanced Oil Recovery to un-economical reserves is increasing the ultimate recovery factor. So, characterization of target reservoirs is important in defining a MEOR project. It means a careful analysis of reservoir properties is required i.g. in a certain case some high permeability streaks is the reservoir needs to be plugged while in other parts permeability needs to be enhanced. However, the reservoir lithology also plays a vital part in the successful application of MEOR to uneconomical reserves.

Microbes growth requiremnt is the other factor to be considered in the successful application of MEOR. To obtain the required results and targets the proper quality nutrients should be injected to the reservoir. Moreover care should be taken that the injection of nutrients with various minerals dissolved may stimulate the growth of inactive bacteria already present in the reservoir such as sulfate reducing bacteria.

Thus, microbial treatment for enhanced oil recovery is a favourable option in the highly volatile oil market and difficult financial times. The application of MEOR to marginal or uneconomical reserves may produce a fractional increase in production from a certain resevoir. However, increased production from a large number of

marginal reserves can significantly increase the commulative oil recovered.

Steps involved in successful application of MEOR projects and strategies are as under:

1) Feasibility Study

2) Experimental Study and Pilot Testing

Feasibility Study

Defining your objective: Benefits from the application of MEOR can be obtained in different ways i.e. you might want to reduce the oil viscosity, plug pores for greater sweep efficiency in water case of water flooding. Since in uneconomical reserves there is no chance for error so a through study must be performed before adopting any recovery method.

Simulation Study: Simulation studies can provide one of the most useful and economical solution to MEOR feasibility studies. Stimulation studies can effectively determine

- Whether the prevailing conditions are beneficial for MEOR process or not. Is it possible to change prevailing conditions in case of marginal reserves to enhance recovery?
- What kind of nutrients will be beneficial
- Whether continuous or intermittent injection will be beneficial
- Where the injection will maximize recovery etc.

Screening criteria: In screening criteria different approaches are used like one should consider specific reservoir properties and should look for in a reservoir before it is declared a favourable candidate for MEOR.

Economics: Economic factors are the basic factor in a strategy that decides whether this project should be implemented or abandoned. Economics in an EOR project can prove to be a great challenge especially in case of marginal or mature assets. Therefore a stringent economic analysis should be made before a project is given a go ahead.

Experimental Study and Pilot Testing

Materials: Materials, nutrients and supplements, used in the microbial profile modification are an important part of evaluation. There are many sources of nutrients susch as sucrose, molasses, corn steep liquor, black liquor, soybean whey, tapioca whey, etc. the combination of nutrient with nitrogen, phosphorous, minerals, and proteins is called here "the media".

Microbes: Microbe selection is crucial for a successful MEOR project result. For this purpose the best strategy would be to gather a multidisciplinary team consisting of microbiologists, geologists and petroleum engineer. And chalk out a strategy of core testing and other tests using different strains of bacteria and then selecting the best strain on the basis of results comparison.

Nutrient: Microbes require for growth sources of the major elements which make up cell material carbon, nitrogen, phosphorous, oxygen, sulphur, minor components such as iron, zinc, manganese, and a source of energy for the synthesis process involved in growth. In the laboratory, bacteria can be feed with different nutrients and the resultant by products are analyzed. The nutrients giving the best by products and acting in the desired way on oil should be chosen. Water is usually the preferred medium of choice. However, medium properties and its interaction with oil and formation should also be studied.

Water: Testing formation water for salinity, trace minerals and all other minerals dissolved in it, is incorporated as a part of the experimentation. Formation water testing reveals a great deal on the ability of the microorganisms to survive in the formation and reproduce at the required rate.

Testing: Testing of MEOR projects to give a formal go ahead for MEOR application in various fields include the following steps:

a) **Site Selection**: By site selection means the selection of suitable area of the reservoir, which will allow spreading and distribution of microbes in a uniform manner. The targeted areas, which are to be treated using the microbe injection or stimulation of microbes that, are already present in the reservoir. Thus the injection well should be able to flood the required reservoir region and microbes' injection should be done at such a place where where they will produce the required outcome. Geochemical analysis and interpretations, when integrated with pressure trends and a geologic and geophysical framework provide important input to development and production planning. Exploitaion geochemical

approaches are especially pertinent to help determine continuity or segmentation of reservoir compartments when pressure or geologic data are ambiguous. Understanding reservoir continuity is critical to optimizing field-development planning. Identification of reservoir segmentation is also important to the efficient placement of injector/ producer pairs when pressure maintenance by water injection is planned. Differences in biodegradation level can sometimes indicate segmented compartments. Geochemical analyses can also detect gradients in hydrocarbon properties within continuous reservoirs (caused by gravity segregation). Recognition of such gradients is important for reservoir models and field planning. In heavy-oil fields, geochemical analyses of sidewall cores can help to identify oil quality variations and sweet spots for targeted production.

b) **Sampling and Analysis of Well Fluids:** Compatibility tests are usually run to evaluate survival of microbes in the presence of reservoir brine, rock and nutrients. Laboratory tests under controlled conditions such as flask tests, test tube tests and other PVT tests in the core lab can help accurately determine the reservoir fluid properties. Some of the parameters which should be considered in the fluid analysis are:

- PH
- Eh
- Temperature
- Pressure
- Dissolved gases
- Inert particulate matter
- Multiphase systems (oil, gas, water)
- Geometry and physical size of pores
- Ions, minerals and salts
- Microbial flora

c) **Selection of microbial formulation and compatibility tests:** These tests are one of the important factors of testing. From these tests information regarding the "Residence time vs Reaction time" and their compatibility with a certain reservoir under different conditions can be studied. After the injection of microbes a waiting time is required so that the microbes can act on various areas of the reservoir and produce the required results. Thus shut-in time should also be formulated using predetermined laboratory tests.

d) **Base line determination of producing wells:** In the base line determination of the producing wells frequent production measurements are made of the producing wells for a specific period, prior to injection.

e) **Growth of microbial formulation and injection of microbes and nutrients:** In this method microbial formulation according certain standards is done and then final inoculation is done at site.

f) **Shut-in period**: After the injection of bacteria and required nutrients, the well is shut in for specific period to allow for the growth of bacteria in the oil-producing formation.

g) **Productions Follow Up:** After completing the shut-in period the well is put back in operation and the increase in production is recorded or the production follow up period is the period in which testing is conducted again after a certain specific period of time. With this the pilot testing is completed. The tests help to determine:

- Changes in physical properties of oil such as viscosity
- Microbial count in the reservoir and are they acting in the right manner
- Changes in the oil composition
- Are the nutrients nourishing bacteria and are causing them to produce the right bacteria
- Changes in the reservoir and study of harmful effects such as stimulation of sulfur reducing bacteria
- Are the microbes corroding or promoting corrosion in the tubulars
- Should we continue with the microbial injection and MEOR process?

- What would be the frequency of microbial batch injection?
- Study of residence time vs injection time
- Expansion of injection program if required
- Microbial analysis
- Are the wells being injected transport them to the required places or should we change the site of injection
- Study of huff-n-puff tests
- Is there stimulation of any in-situe flora due to nutrients injection and what is the effect of stimulation of these in-situ microbes?

Some Real Results of MEOR Field Applications Around the World

MEOR has been successfully applied to various fields around the world. A few of these are presented here to support the whole disscussion.

1) Dostalek and Spurney (1957), in Czechoslovakia, conducted field tests by injecting a mixed culture of sulfate-reducing (Desulfovibrio) bacteria and paraffin-exidizing bacteria (Pseudomonas) with a molasses base nutrient solution. They stated that the daily average oil production increased by approximately 7% during the 6-month period.
2) Jaranyi et al. (1963), working in Hungary, used a mixture of anaerobic, thermophilic bacteria that fermented molasses in a field containing naphthenic-type crude oil. In later field triels, they used raw sewage as the inoculum (1 litre of sewage mixed in 300 litres of 2-3% molasses). The deepest reservoir treated was 2500m (8200 ft). They reported beneficial results to oil production in 7 out of 10 reservoirs that were treated, but the specific increases of production were not given.
3) In Northwest Peru20, in the Talara basin the Providencia and Lobitos fields of Block Z-2 in 2003, produced 95,000 BOPD while consuming 163,000 B/D. seven producing wells were selected to evaluate MEOR for enhanced oil recovery. The MEOR resulted in average 13,907 to 19,410 bbl of incremental oil. After this test it was concluded that, MEOR is equally feasible for single or commingled production.
4) Karaskiewicz (1962) conducted 18 field trials in Poland between 1961 and 1969 with microbial cultures obtained from soil and water samples taken in the vicinity of the oil fields and from sugar factory waste-waters. The cultures were grown in 10-litre bottles containing formation water plus 4% molasses at 32C. The wells that were treated ranged in depth from 500 to 1525m (1650 to 5000 ft). According to Hitzman (1983), Karaskiewicz reported increases of oil production rates that ranged from 20 to 200% over the original rate of production.
5) During the period 1977-1981, Johnson (1979) inoculated approximately 150 stripper wells in the United States with a mixed culture of Bacillus-clostridium. The carbonate reservoir depths ranged from 60 to 300 m and porosity from 10 to 30%. Johnson injected the inoculum into the production wells, shut the wells in for 10-14 days, and then opened them once more for production. Production increases of 20-30% were obtained when the API gravity of ranged from 15 to 30 and the formation water contained less than 100,000 ppm salt.
6) Hitzman (1983) reported that Petrogen, Inc., tested the Johnson method in 24 wells ranging in depth from 90 to 1400m (300 to 4600 ft). the production rates of four of the wells doubled for a period of 6 months, and 12 of the wells showed a 3-month production increase of 50%.

During the last 10 years of research studies in the Arabic area it was found that some of the Saudi, Iraqi and Egyptian oil fields can be very good candidates for MEOR processes. Also, depleted or marginal oil fields in Egypt and Syria can be activated by injection of microorganisms, which can be beneficial in producing more oil. Recently a state of the art of the MEOR process was presented at the 6th international conference of MPM held in Cairo University. It was concluded that more extensive laboratory and field research should be carried out in order to develop a technology in the area of MEOR under reservoir conditions of temperature, pressure, permeability and formation water salinity.

Current Research Areas

The processes that facilitate oil production are complex and usually involve multiple biochemical processes. MEOR systems represent high-risk processes to oil producers looking for efficient and predictable oil recovery. Microbial biomass or biopolymers might: plug high-permeability zones and lead to a redirection of the waterflood; produce surfactants, leading to increased mobilization of residual oil; increase gas pressure by producing CO_2 or methane; or reduce oil viscosity due to digestion of large molecules.

While methanogenic bacteria have been shown to be active in oil and coal-bed methane reservoirs, they must function as part of a reaction chain to effectively produce methane. This includes breaking down the large chain hydrocarbon, converting the molecules to simple acids and alcohols, and then finally converting the simple molecules to methane. Each part of the chain is processed by different microbial consortia. All of these consortia are sensitive to environmental changes, such as the introduction of oxygen, which could sterilize the population, break the chain, and shut down the entire process.

Biogenesis is being looked at for converting coal, shale and residual oil to methane in commercial quantities. This in-situ microbial conversion to methane has the potential to create significant amounts of natural gas in days rather than millions of years. In experiments administered on Dietz coals of the Powder River basin, tested samples of coal and unamended formation water resulted in a steady increase in methane in the headspace, slightly exceeding 3% by 135 days. However, when a nutritional enhancer was added, methane levels reached nearly 9% in a comparable time-frame, with methane representing nearly 100% of the newly generated gas.

Researchers are working to create strains of bacteria that are better able to survive harsh environmental conditions in oil wells but still retain the ability to carry out the chemistry needed for MEOR. Genetic engineering is being used to develop microorganisms that not only live in high temperatures, but can also subsist on inexpensive nutrients, remain chemically active and produce substantial amounts of biosurfactants. Some researchers are developing bacteria that can be grown on inexpensive agricultural waste material, which is abundant in supply and is environmentally friendly.

Conclusions

Almost a decade ago MEOR might have been considered as a technology in its fantacy but the current oil crisis has established this cost-effective technology as a viable candidate for further research and application. At the moment emphasis has been shifted towards producing marginal and by passed oil by the application of new effective and economic techniques. MEOR is one such effective solution that has seen increasing applications in the oil industry. The successful application of this technology as an oil recovery process is evolving and being readily accepted. Marginal, by-passed and mature assets have taken the centre stage, shrinking oil reserves and limited new discoveries have now prompted the global oil industry to improve recovery factors from the existing oil fields. Since conventional EOR methods are cost intensive and not suitable for marginal and mature assets, so MEOR has stepped in as a suitable alternative.

Microbial enhanced oil recovery (MEOR) projects are being applied worldwide and it is predicted that this technology would save the industry's millions of dollars by increasing the amount of recoverable oil within a shorter time frame. But in order to keep this technology rosy there is a constant need to innovate and develop the existing technology.

Nomenclature

API = American Petroleum Institute
bbl = barrels
B/D = Barrels per day
BOPD = Barrels of oil per day
EOR = Enhanced Oil Recovery
IOR = Improved Oil Recovery
MEOR = Microbial Enhanced Oil Recovery
MPPM = Microbial Permeability Profile Modification
Rm = Radial extent of bioreactor

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Table 1: MEOR Design Options

Design Feature	Design Options
Reactor Type	Fixed Growing Mobile
Carbon Source	In-situ Ex-situ
Microbe Provenance	Indigenous Exogenous

Table 2: Microbial Products and Their Contribution to Enhanced Oil Recovery

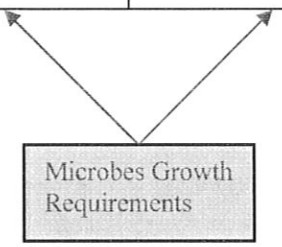
Microbial	Effect
Acids	Modification of reservoir rock Improvement of porosity and permeability Reaction with calcareous CO2 production
Biomass	Selective or nonselective plugging Emulsification through adherence to hydrocarbons Modification of solid surfaces, e.g., wetting Degradation and alteration of oil Reduction of oil viscosity and oil pour point Desulfurization of oil
Gases (CO_2, CH_4, H_2)	Reservoir repressurization Oil swelling Viscosity reduction Increase of permeability due to solubilization of carbonate rocks by CO2
Solvents	Dissolving of oil
Surface active agents	Lowering of interfacial tension Emulsification
Plymers	Mobility control Selective or nonselective plugging

Table 3: Types of Microbial Processes for Oil Recovery

Process	Production problem	Types of activity or product needed
Well bore cleanup (improve oil drainage into well bore)	Paraffin and scale deposits	Emulsifiers, Biosurfactants, solvents, acids, hydrocarbon degradation
Well stimulation (stimulate release of oil entrapped by capillaries and brine)	Formation damage, pore damage High water production	Gas, acids, solvents, Biosurfactants, Biomass and polymer production
Enhanced waterfloods (reduce permeability variation and block water channels)	Poor displacement efficiency Poor sweep efficiency Scouring	Biosurfactants, solvents, polymers, Biomass and polymer production, Nitrate reduction

Table 4: Reservoir properties necessary for microbes growth

Friendly Reservoir	Suitable Temperature for Microbes Survival
Porosity, Permeability	Oxiants Availibility



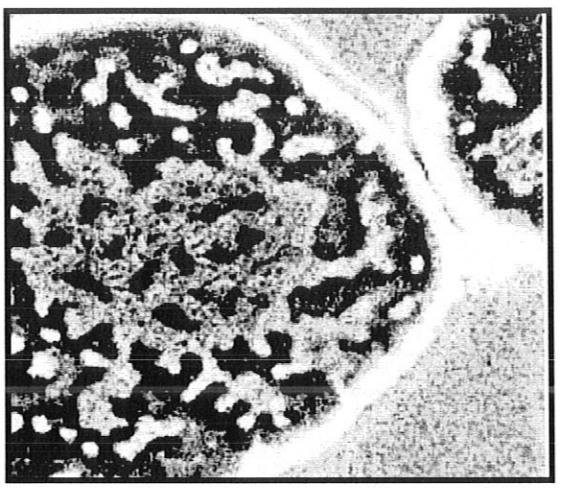


Figure 1: Microbes within an oil droplet (Sources: U.S Department of Energy)

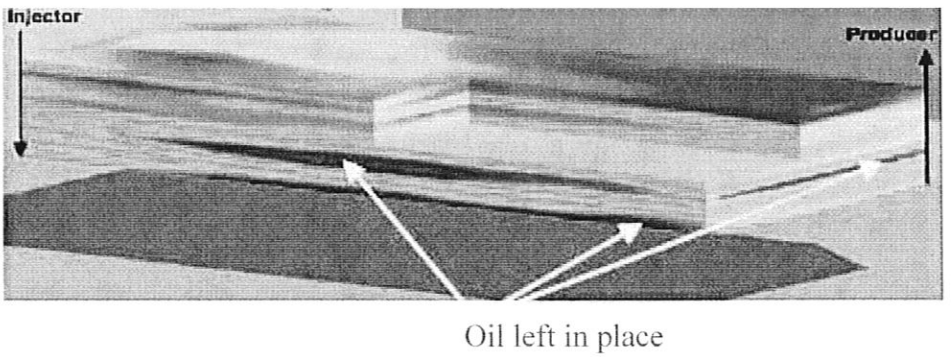


Figure 2: Illustration of bypassed oil and position of injection and production wells

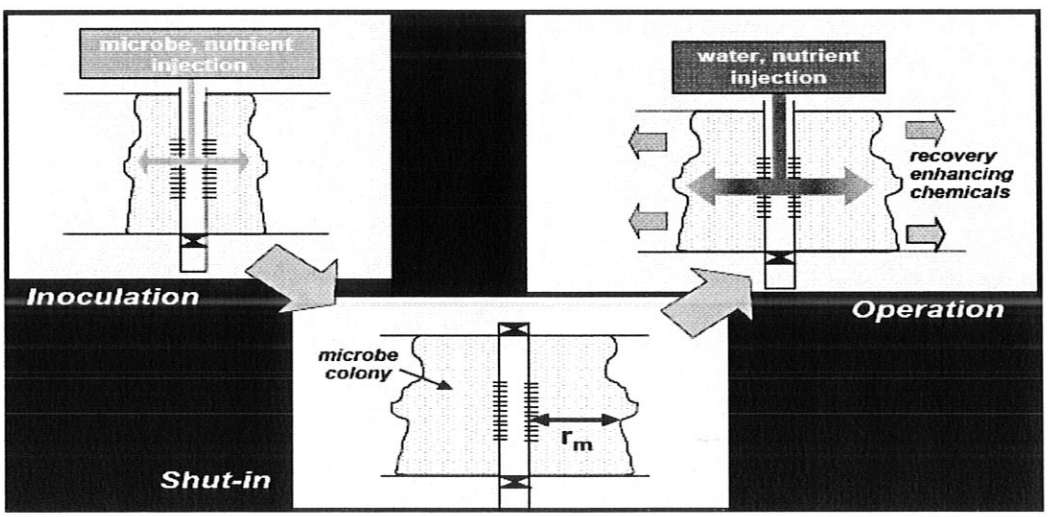


Figure 3: Base case implementaion of MEOR

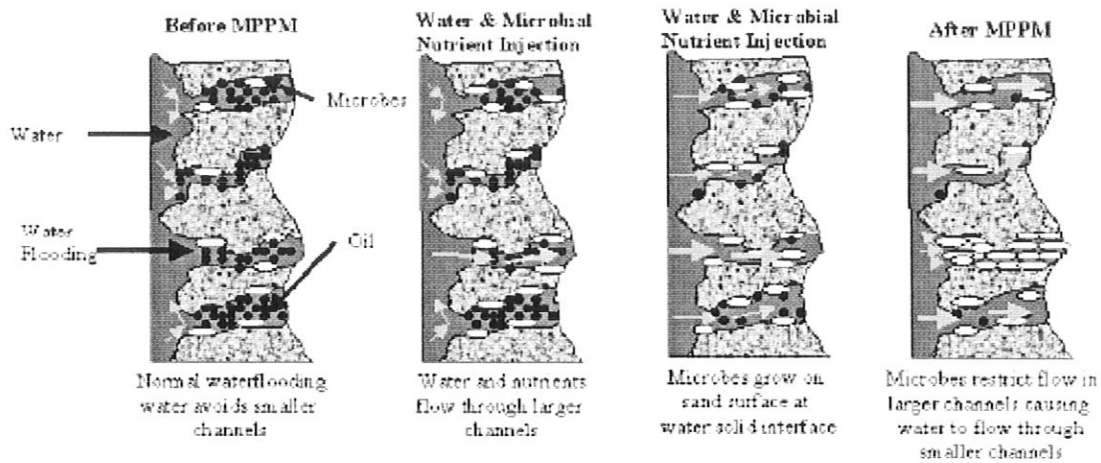


Figure 4: Mechanism of microbial enhanced oil recovery (MEOR) using in situ microbial permeability profile modification (MPPM) to enhance oil recovery

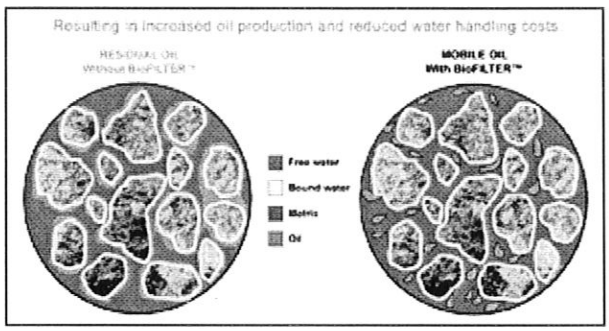


Figure 5: Fluid distribution in the reservoir with and without BioFILTER™