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The Impact of Bioprocessing on Enhanced Oil Recovery

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J. S. Watson and C. D. Scott

ABSTRACT

Biotechnology can, and is likely to, play an important role in many aspects of microbial-enhanced oil recovery (MEOR). Most current research is directed toward in situ production of surfactants, polymers, and other materials that can enhance the recovery of oil by altering the water-oil interfacial properties or viscosities or the bulk flow patterns in the field. The mechanisms of MEOR are still not well understood, and better evaluations of the relative merits of in situ and surface production of these chemicals that enhance oil recovery are needed. Field tests of MEOR must be planned and executed to increase our understanding of MEOR results.

Other potential uses of biotechnology to enhance oil recovery have been identified and should be explored. This report reviews current MEOR studies and assesses the additional roles which biotechnology is likely to have in future oil recovery operations. For example, the use of microbial action to reduce environmental problems from release or reinjection of floodwaters could become very important if current exemptions of oil recovery operations from environmental regulations are not extended.

INTRODUCTION

Microorganisms can have a variety of important effects upon all forms of fossil fuels, on their precursors, and on products or wastes from their processing and use. These effects can be either beneficial or harmful. Although bioprocessing concepts already play a role in the processing and use of fossil fuels such as petroleum, natural gas, oil shale, and tar sands, that role has been limited to a few applications. Several potential additional applications of biological processes have been suggested for microbial enhanced oil recovery (MEOR), but these are still experimental concepts requiring considerable work for verification. This report reviews the research in MEOR, assesses the progress that has been made, considers additional concepts which have been suggested, and indicates areas that have received little attention but that hold potential for important applications.

Microorganisms can be used in MEOR to produce materials which enhance removal of oil during water floods, or they can be used to alter the oil itself. They can also be used to alter or degrade pollutants in waste streams from any enhanced oil recovery operation. Most attention has been devoted to the production of surfactants and polymers by microorganisms. Surfactants alter the oil-rock wetting properties and/or aid in dispersion of the oil so it can be more easily transported out of the field by water flooding. Polymers increase the viscosity of the water flood and promote more uniform flow through the field. In extreme cases, polymers and other biomass can be used selectively to plug portions of the field so that subsequent water floods can be diverted to the desired regions. Somewhat less attention has been devoted to the production of gases such as carbon dioxide or methane for gas flooding of oil fields. Microbes can produce the desired materials in surface facilities or within the field. The materials can be used separately or together; in situ production of the materials usually implies use of mixtures of all of the materials produced.

Microbial interactions with oil can be important in several ways. They could involve upgrading the oil, perhaps by reducing the sulfur and/or nitrogen, or they could degrade oil or oil components which are spilled or entrained in wastewaters. There are only limited reports of successful microbial upgrading of oil, but there are numerous successful uses of bioprocessing to clean up wastewaters from petroleum-, gas-, and coal-processing facilities.

Although not strictly a processing step, the role of aerobic organisms in degradation of petroleum in soils and waters is especially important in controlling the spread of pollution from both processing wastes and spills. Recent years have seen an especially strong interest in the environmental effects of oil spills and methods for cleanup of spills, especially those which have occurred near shorelines, where the effects were most visible. This interest is evident from the numerous papers which have appeared in the technical and scientific literature and from reports in the popular press. The degradation of petroleum in marine environments is another topic of intense interest. In addition to providing a means for limiting the consequences of major oil spills, the degradation illustrates one form of biological alteration of petroleum. Although several other mechanisms such as evaporation and solubilization play important roles in the behavior of oil spills, the role of microorganisms is both evident and important.

Since many organisms have been shown to interact with petroleum, the challenge is to select and to direct these organisms for useful change. The potential goes far beyond degradation of spilled oil and oil-contaminated process waters. Organisms could potentially be used as an initial (or immediate) step to release hydrocarbons from sands or rock, to alter physical properties such as viscosity or wettability, or to remove undesirable materials such as heteroatoms (sulfur, nitrogen, or metals). Potentially, changes could be achieved that would also assist in enhanced oil recovery (EOR).

REVIEW OF THE LITERATURE

BACKGROUND

New oil and gas fields can usually supply only a portion of their reserves by their own pressure or by conventional pumping. Very large portions of the oil in the formation either cannot be recovered by conventional methods or can only be recovered at very low rates. After primary oil production by direct pumping declines to unacceptable rates, secondary recovery methods may be used. New approaches are under development for secondary treatment or "enhanced oil recovery."[1] Some of these techniques are becoming more widely used, and new and more effective methods are showing some promise. Water flooding is the most common approach to secondary recovery. Thermal stimulation of oil fields has recently become relatively common (especially in California), and combinations of thermal treatments and flooding show considerable promise. Other, more innovative methods include the use of biological materials and chemicals such as carbon dioxide to aid in oil recovery. After the rate of oil recovery by secondary methods becomes marginally practical, perhaps more than half of the original amount may remain.

Biological techniques show promise for tertiary recovery and constitute a significant part of the overall U.S. effort for long-term development of advanced oil recovery methods.[2] Biological methods can involve injection of either organisms or materials produced by organisms into oil formations to increase the flow of oil from the formation.[3]

The injected materials can interact with the oil or the formation and can increase oil production by altering the oil itself, by changing physical transport properties such as viscosity or interfacial tension, by plugging selected regions of the formation, or by repressurizing the formation.

Because of the promise of MEOR, research and development (R&D) efforts have begun in numerous private, academic, and government laboratories. A large fraction of the reported work has been done outside the United States. Several MEOR field tests have occurred in actual petroleum formations. Some feel that petroleum companies take a rather conservative stand in regard to innovative EOR testing and implementation;[4] they prefer extensive laboratory tests and limit field tests to relatively poor oil formations of lesser potential value. In view of the damage that some enhancement methods can still produce, it is not likely that this attitude will change in the near future; perhaps it should not change. Since MEOR involves addition or growth of materials in the formations, there is serious potential for environmental insults by releases of materials to groundwater or other portions of the environment.[5] As long as our understanding of MEOR remains inadequate, a need for laboratory studies is evident.

TRADITIONAL RECOVERY METHODS

After production in an oil well has either ceased or slowed to uneconomic rates, the oil remaining in the formation is likely to exceed that produced, perhaps severalfold.[6] The decision to attempt further recovery and the method selected are likely to depend upon properties of the formation, but some secondary recovery will probably be attempted to recover at least a portion of the oil. Water flooding is the most commonly used method; in fact, it is relatively standard for many formations. Thermal stimulation is gaining favor and can be viewed as common practice, but other recovery methods are no more than experimental concepts that have had only limited field tests. A major problem with all well-tested recovery methods is the limited degree of recovery; large portions of the original oil remain in the field.

Several nonbiological methods are under development for tertiary recovery. They include (1) use of carbon dioxide to pressurize the formation and to mix with the oil to speed recovery, (2) use of polymers to increase the viscosity of floodwaters for more uniform flooding, (3) combustion of portions of the oil to generate heat and pressure to drive the remaining oil from the formation, and (4) use of surfactants to free the oil from the formation surfaces and form emulsions which can be more effectively flushed from the formation. Among the numerous difficulties and limitations for each of these methods is the lack of consistent or predictable results. Furthermore, the maximum rate of recovery may increase, rather than the total eventual recovery. The objective is to keep production rates high enough to remain economical while more oil is recovered.

Carbon dioxide methods can, in principle, recover relatively large portions of the petroleum. Gas costs can be a problem, but they depend upon the quantities of gas lost, or the fraction recovered. This in turn depends partly on the formation (soluble losses to water in the field, losses to remote regions of the field, etc.) as well as on the efficiency of the aboveground operations.

Another possible approach is partial combustion of the petroleum. The several variations in this approach usually involve using hot combustion gases to sweep the petroleum from the field. These approaches combine aspects of thermal stimulation with gas flooding. The recovery can be high from such operations, but considerable oil may still be left in the formation. "Fingering" can allow the combustion front to bypass significant quantities of oil. The impact of such operations on the formation would be quite severe, and future efforts to recover the remaining oil might not be possible.

The use of polymers to enhance flooding of formations can significantly increase the oil yield. Obviously, the polymers must be relatively inexpensive. Furthermore, the formation should not contain a large flow of water which could carry off significant amounts of polymers. Several of the more interesting polymers have been produced by biological processes, usually in laboratory- or small-scale quantities. Several polymers which have been considered, such as polysaccharides, are subject to degradation by microorganisms that may be present in the formation or in the water used to force oil from the formation. This can be a serious problem if stray organisms cannot be excluded from the formation. Furthermore, any operation which allows water and potential organisms into petroleum formations can do considerable damage by plugging the formation with bacteria or bacterial products.

Surfactants are also being studied for EOR from depleted wells and formations. Although the mechanisms for EOR using surfactants are quite different from that proposed for polymer addition, the operations and problems of the two approaches are similar. Both involve injecting water containing the chemical into the formation, but the interactions of the materials with the formation are different. The polymers act principally to increase the viscosity of the floodwater, while the surfactants disperse the oil and assist in freeing it from the formation surfaces. The two techniques can be used together. Biodegradation is a serious problem with both surfactants and polymers. Again, costly losses of either surfactants or polymers could occur if water flow through the formation were large.

DIRECT MODIFICATION OF THE OIL

The ability of biological materials to alter or degrade petroleum and other fossil fuels has been known for many years, and the interactions of biological materials with petroleum are important natural phenomena.[7-12] Atlas has provided an excellent review of microbial degradation of oil that focuses upon aerobic degradation and environmental processes, but also describes a wide body of literature showing that numerous common organisms can degrade petroleum in soils, seawater, and fresh water.[13] Most of the literature on degradation is concerned with environmental issues. Hydrocarbons are common substances which occur naturally throughout the world, and organisms have evolved which can degrade or decompose them. Microorganisms may have played important roles in the formation of petroleum, shale, and tar deposits, and they certainly play important roles in altering petroleum deposits after they are formed.

The composition of petroleum deposits is believed to be affected by microorganisms and is used as one indication of their age. However, this gauge of a deposit age has been questioned and may have limited merit. Organisms which occur in petroleum formations or reach formations usually react first with the polar compounds and then with the alkanes. They react less readily with alkenes and aromatics. Thus, by this standard, older deposits would be enriched in unsaturated compounds and asphaltenes.

Since petroleum exists in environments relatively free of oxygen, the organisms likely to have continuing effects on underground petroleum are likely to be anaerobic; changes which take place once the oil is aboveground are more likely to be aerobic. There are, however, questions about the role of anaerobic organisms in altering petroleum within formations. One review suggests that few or no anaerobic hydrocarbon transformations occur;[14] a supply of oxygen and aerobic conditions, however, permit a number of transformations. Schink studied methanogenic bacteria and their interactions with hydrocarbons and was not able to find clear indications of interactions with alkanes or alkenes, but he did find degradation of more complex molecules.[15] Most references to biological alterations of petroleum formations refer to "degradation" of the petroleum. Biodegradation usually refers to loss of n-alkanes and branched compounds.[11,14,16-20] Some reports indicate that biodegradation results in increased sulfur content, but others indicate that bacteria can reduce the sulfur content of oils. The effects of petroleum degradation should certainly be considered for the U.S. Strategic Oil Reserve.

Petroleum formation degradation can be discussed in two senses: before and after the petroleum formation is breached by drilling. Before drilling, the formation is more likely to be under anaerobic conditions. It has been speculated that the transformations which take place during the long geologic period may be beneficial and involve the formation of more light compounds and reductions of asphaltenes and sulfur. On the other hand, once the formation is breached and possibly flooded with water, changes occur which may be more likely to be harmful unless they are controlled. These changes can involve introduction of microorganisms, and the probability rises that regions of the formation may become aerobic.[21] These changes are likely to result in the degradation of branched and smaller alkanes first and thus enrich the petroleum in alkenes and aromatics, including asphaltenes. If these changes are relatively rapid, they could be very important because all the known petroleum reserve formations have been breached, and the undiscovered formations may be few in number. However, continuing degradation by aerobic processes would require a steady supply of oxygen to replace that being consumed.

It is well known that organic molecules can bind to cells in culture systems.[22] It has also been shown that microorganisms will grow on droplets or films of oil.[23] This attachment is an indication of the interactions of organisms with oil and oil products and probably an essential initial step in effective degradation of oil. However, attachment does not necessarily mean that interactions with hydrocarbon will occur.

Furthermore, some studies indicate that the water-soluble portion of petroleum mixtures is degraded more effectively than the insoluble portions;[24] heavy oils are usually less affected by biological changes.[25] Some have indicated that small droplets of oil in water are important to petroleum degradation, but it is not apparent how much of this is simply due to surface area effects. It is clear, however, that if petroleum is eventually totally degraded, all components must be susceptible to degradation by some organism(s) at some measurable rate.

PRODUCTION OF CHEMICALS FOR ENHANCED OIL RECOVERY

Chemicals for enhanced oil recovery may be produced in situ or in surface facilities. In situ processing does not necessarily refer to conversion of the entire field or even to any of the formation. It may mean in situ production of polymers or surfactants much like those which can be produced on the surface.

In Situ Production of Materials for Microbial Enhanced Oil Recovery

As noted earlier, microorganisms may be helpful through in situ formation of materials that enhance oil recovery or that directly interact with entrapped oil.[26-28] In situ growth of microorganisms and production of materials to enhance oil recovery is usually called MEOR. This is usually treated as a different method of EOR, but its relation to chemical flooding using surfactants, polymers, or other chemicals produced by microbial processes in surface facilities should be obvious. During in situ processing, the microbial action usually must be anaerobic and must take place under field conditions (temperature, pressure, and chemical environment). Anaerobic paths to surfactant and polymer formation are available, but the rates are not necessarily as high as those which can be obtained with aerobic systems.[29,30] A great deal of additional work will be required before such techniques are generally useful.

Surfactants can be produced under anaerobic conditions.[31] Any organism used in situ must be able to withstand all of the conditions in the formation, and these conditions are likely to be anaerobic. The organisms often must be tolerant to chlorides[32] and high osmotic pressures. Trace metals can be important to microbial growth and function; usually small concentrations favor growth, but excessive concentrations retard growth or even have a poisoning effect.[33] Nutrients are also important for microbial functions, and aerobic systems need a supply of oxygen. Considerable work has been done on injection and transport of organisms and nutrients for producing these materials within petroleum formations.

One factor important to any in situ operation is temperature because the activities of most organisms are limited to moderate temperatures. One report indicates that microbial activity stops at between 150 and 165°F.[34] At lower temperatures, the rate of microbial activity is likely to increase with increasing temperature, but then decline rapidly as the maximum temperature is approached. Organisms that are effective at one temperature may not be effective at significantly higher or lower temperatures.[35] Thermophilic organisms can function at higher temperatures than most organisms and are likely to be dominant in oil fields with high temperatures. Each organism has a different behavior in relation to temperature response; changes in the temperature can therefore alter microbial behavior qualitatively as well as quantitatively. One study of aerobic degradation of oil in soils showed that higher temperatures favored degradation of aromatic fractions.[36]

In situ organisms can grow and eventually plug a petroleum formation. Some see this as a serious potential problem for in situ use of microorganisms, but when used selectively, it can be beneficial. When certain portions of formations contain too much porosity, it may be difficult to flood the formation and sweep major portions of the petroleum to collection wells. For high recovery, the floodwater should penetrate essentially all parts of the formation so that large portions of the oil will not be left in "dead volume." Growing microorganisms may be selectively introduced into these porous regions to plug or reduce the porosity so more of the flood flow will go through other parts of the formation and increase the oil recovery.[31,37,38] Both cells and nutrients are transported selectively to regions of the field with the highest permeability, so it should not be difficult to achieve some concentration of organisms in regions which need to be plugged.[39,40] Adverse plugging usually occurs near the injection wells and often can be cleared by injecting hydrochloric acid.[41] Some consideration has also been given to using microorganisms to assist in increasing the permeability in regions near the well holes.[42]

The high porosity of the regions to be plugged is helpful in introducing organisms and nutrients to the formation. A sufficient flow of nutrients is required to keep the organisms growing until the desired degree of plugging has been achieved, but, fortunately, growth can continue well after the last injection and thus complete the flow obstruction. However, transport of organisms and nutrients into petroleum formations remains an important aspect of all in situ methods.[29,31,43-45] Another important aspect is competition between the injected and native microbial populations for nutrients, either added or naturally existing.[46] Desirable microbes can "lose out" to native cultures in this competition.

Another potential use of organisms in situ is to generate gas to repressurize the formation.[47,48] The gas generated could be methane, carbon dioxide, or a mixture of low molecular weight hydrocarbons. Repressurization could be a separate and specific action, or it could be favorable aspect of other in situ microbial activities.

Formation of Materials in Surface Facilities to Assist in Oil Recovery

Microbes can be used in surface facilities to produce materials such as surfactants, which assist in release of oil from the formation and control water-oil droplet behavior, or polymers, which increase the viscosity of floodwater.[49,50] These materials have potential uses in transporting oil droplets in pipelines as well as in EOR. Biosurfactants (bioemulsifiers) can be just as effective as synthetically produced surfactants, and, in some cases, even superior.[51] When produced in surface facilities, the nutrients can be either sugars supplied from external sources or part of the petroleum itself.[52] When petroleum is used as the nutrient, aerobic processes are more likely to be active than are anaerobic processes.

Biological Production of Surfactants. As was noted earlier, surfactants reduce the interfacial tension between the oil and water and alter the preferential wetting of the surrounding formation by the oil. This can make water flooding much more effective. The surfactants need to be relatively inexpensive, so surfactants produced by microbes are receiving considerable attention.[29,53-55] Several of these materials have been used in field tests. The nutrient could be sugar[56] or waste materials such as those from the paper and pulp industries.[57,58] Although the surfactants are produced by microbial action, microbial activity within the oil-producing formation can degrade them and reduce or eliminate their benefit.

Preparation of Biopolymers. One of the more promising technologies for increasing the yields from oil wells involves injecting polymeric materials which alter the viscosity of the petroleum so that more of the petroleum can be removed by gas injection. These polymers can be "biopolymers," such as xanthan gums, in which all or some portion of their preparation involved use of biological techniques.[59,60] Biopolymers, which can be produced either in surface facilities or in situ, are usually extracellular polysaccharides. Because of the greater range of conditions which can be specified in surface reactors, it is probably possible to produce a somewhat greater range of products on the surface.

Few details have been reported on methods for producing polymers, but it appears that many operations have used relatively simple batch fermenters. Xanthans have been produced commercially since 1964 by *Xanthomonas campestris* and consist of repeating chains of a pentasaccharide containing glucose, mannose, glucuronic acid, acetate, and pyruvate.[61] Seldom is a production rate given, but one patent reports production rates of 0.24 to 0.32 g of xanthan per gram of cells per hour.[62]

GASIFICATION TO METHANE (ANAEROBIC) OR CARBON DIOXIDE (AEROBIC)

The ability of anaerobic organisms to degrade or convert petroleum to methane has been questioned. Schink's study indicates that the bulk of the petroleum is not susceptible to conversion by methanogenic bacteria,[15] but this does not necessarily mean that no interactions with petroleum are possible. Most petroleum contains minor components which may be reacted more effectively. The use of methanogenic bacteria to convert all of the petroleum to methane does not look promising, but they may be useful in selective removal of some of the more complex molecules, perhaps with beneficial results. Some studies suggest that the bulk of the methane is produced from portions of the oil that have been oxidized by oxygen and aerobic organisms near the injection wells.

Aerobic organisms can probably convert all the components (all the carbon) to carbon dioxide, but the different components are degraded at different rates. The beneficial uses of degradation to carbon dioxide include degradation to prevent environmental damage (discussed in another section) and production of carbon dioxide for use in EOR. Microbial action is one source of carbon dioxide for EOR, and the carbon dioxide could be produced on the surface. Alternative nonmicrobial ways to obtain carbon dioxide from surface sources exist, but they may not be near the formation. The economics of carbon dioxide preparation from petroleum aboveground probably would be enhanced by recovery of energy from the process.

Production of carbon dioxide by microbial action in situ does have some benefits. First, it consumes oil before it is recovered. For EOR techniques that are less than totally efficient, this could reduce the cost of any petroleum consumed by an amount equivalent to the cost of MEOR. Second, forming the carbon dioxide in situ also pressurizes the formation, a step necessary for most EOR operations. The principal disadvantage is one common to all in situ operations — the difficulty in controlling the microbial processes.

Carbon dioxide is formed in several in situ operations discussed elsewhere in this report. The operations could be aimed at production of surfactants or biopolymers, or they could be directed toward pressurizing the formation. However, all of these phenomena occur simultaneously, making control especially difficult. The quantities and pressures of the gas formed may be much less than those needed for high-pressure carbon dioxide "flooding," but the carbon dioxide effects may still be important. In several such operations, it may not always be easy to assess the role of all the factors involved in a successful field test.

Local surface production of carbon dioxide has not been generally considered, but the option should not be ruled out without serious consideration. Unless the field happens to be located near a source of nutrients which can be used to produce the carbon dioxide, it will be necessary to transport the nutrient (grain or other biomass) to a point near the field, but these costs can be less than the cost of transporting the gas. In recent years, high-productivity bioreactors have been developed which have much higher throughput than conventional batch systems, and such developments should reduce the cost of producing gas onsite. Furthermore, the possible merits of producing the other products such as alcohols at the field should be considered in the assessment of onsite gas production. Also, the possible use of a portion of the oil itself, especially the least valuable portions, as the carbon source should be considered.

CURRENT ENVIRONMENTAL CONTROL TECHNOLOGY

Considerable concern has been expressed about environmental impacts of EOR methods, but much less has been said about actual environmental control practices. This is partly because of the developmental nature of most EOR approaches. Water flooding and thermal methods do not appear to add any new materials to the formation, but that is not necessarily true. Additional water is used in water flooding, and additional oil components may be released by thermal stimulation. Quantitative, if not qualitative, changes do occur. Foreign microorganisms are also introduced to the field via the water flood, and changes in field temperatures during thermal stimulation could change microbial populations. Another reason for the limited discussion of environmental control methods is the current exclusion of petroleum recovery operations from some of the detailed reporting procedures required for other industries under the Resource Conservation and Recovery Act.

Most current environmental control efforts are believed to be concerned with wastewaters removed from the field with the oil. In some water flood operations, this can be an appreciable volume in comparison with the volume of oil recovered. No survey shows how all companies handle this water, but the majority are believed to reinject the water into deep wells. Some ponding to allow settling of sludge may be used prior to injection. With water flood operations, it would be possible to reuse some portion of the water by reinjection into the petroleum field, but accumulation of materials such as salts could cause increased corrosion and other problems. Thus, reuse of the water is likely to be limited and a significant "purge" stream sent to deep well disposal.

The principal problem with deep well injection is the potential for contaminating water supplies. Of course, that is the rationale for the use of deep wells, and regulations exist for all deep well injection (for any waste). Such regulations are likely to become increasingly restrictive in the future.

TECHNICAL PROBLEMS

To evaluate biological approaches to EOR, it is necessary to consider the problems and limitations of the different approaches.

Conventional Techniques

Enhanced oil recovery does not currently constitute a large fraction of either the petroleum produced in this country or the effort devoted to oil production. Under these conditions, there may not be complete agreement on what constitutes "conventional" techniques. Water flooding and thermal (steam) methods are probably the techniques most likely to be considered "existing art." Since microbial techniques are usually among the least developed techniques, we will simply define all nonmicrobial techniques as "conventional." This also permits a focus on the differences between problems with microbial and nonmicrobial techniques.

Perhaps the most serious problem with all available techniques is poor recovery. Although the aim of EOR is to recover more of the available petroleum in the formation, current techniques often still leave large portions of the oil in the formation — as much as over one-half of the total oil. Yields from fields of very heavy oils can be especially low. One estimate of primary and secondary (water flood) recovery from the Lloydminster fields in Canada is only 8% of the initial oil present.

Care must be used in looking at yields because total yield and recovery rate can be confused. EOR programs usually increase the production rate significantly, which in turn usually increases the total yield that can be recovered practically. However, quantitative relations between the eventual yield and the increased flow are not necessarily obvious. Generally, thermal methods will increase the recovery rate manyfold, but the total recovery may not be that much larger. In situ combustion does promise total recoveries of up to 50%.

Carbon dioxide flooding can increase the yield significantly, especially for some formations. Hydrocarbons and even inert gases (nitrogen) are also alternative substances for flooding petroleum formations. Hydrocarbon flooding, although relatively effective, is expensive. For most formations, however, considerable petroleum will remain even after the use of the best available EOR techniques.

Another problem with conventional EOR methods, and probably with MEOR methods as well, is the lack of consistent increases in the yield. Although some projects will yield substantial and very profitable increases in oil production and yields, others will not. This probably results from differences in the formations and from inadequately characterized formations. Detailed characterization can be especially difficult. The inconsistencies could also reflect the state of our ability to model EOR processes. The hydrodynamics and chemical interactions which occur in EOR operations are complex and difficult to understand even when the characteristics of the formation are studied extensively.

"Fingering" or other forms of nonuniform flow in the formation can have important effects for any flooding operations. Large-scale fingering is likely to result from differences in the permeability within the formation. The flood will follow the path of least resistance and bypass some or most of the petroleum trapped in the less permeable regions of the formation. This is a problem which selective plugging by microorganisms seeks to address.

As long as petroleum remains inexpensive, it will be necessary to closely control the use of costly chemicals and materials in EOR operations, particularly because large quantities of materials are required to flood or treat a large petroleum formation. Carbon dioxide is not an expensive material, but very high recovery and reuse efficiencies are needed to maintain economic operations. In formations that have high water contents, the water can dissolve substantial amounts of carbon dioxide and increase the cost. Furthermore, water with substantial carbon dioxide concentrations can be corrosive and cause problems with pipes and other equipment in the well. Even the availability and supply of sufficient carbon dioxide for many operations are serious problems. The cost of transportation of carbon dioxide from sources tens to hundreds of miles away can be significant, particularly because the gas is corrosive to pipelines.

Other flooding materials such as surfactants and polymers can also have significant costs, but those costs are usually less well known because the approaches are often less well developed. Materials such as polymers and surfactants can also be degraded by organisms which are either native or introduced to the formation, causing significant losses.[73-76] Biodegradation often results in reduction in the polymer viscosity. Resistance to biological degradation is one important factor in selecting the polymers to be used,[63,64] and in many cases the biopolymers are especially susceptible to degradation. Some synthetic (nonbiological source) polymers are believed to be less susceptible to in situ microbial degradation. The recovery and reuse of polymers and surfactants is likely to be difficult, perhaps impractical.

Other gases have also been used or considered for flooding petroleum formations. Hydrocarbons such as methane can be especially effective, but their high cost appears to have reduced interest in them. Obviously, one cannot use such materials unless the oil yield is sufficient to pay for any losses. If a ready supply of methane or other hydrocarbon does not exist near the well, transportation costs or the cost of producing gas from the recovered oil must be included. Nitrogen, essentially an inert gas for this application, has also been considered for pressurizing and flooding formations, but again, cost is a serious problem.

Inefficiencies in the recovery of materials added to the EOR operation can mean a potential environmental control problem. If those materials are not decomposed in the operation, they will remain in the formation or be present in the oil or flood liquid. Either could result in environmental problems. The incorporation of the materials in flood water presents the most obvious problem and makes recycling the water more important. Removal of the materials from any water discharges could be necessary.

Since none of the conventional EOR methods recover all or even most of the available petroleum, there may be some merit in leaving the formation in a state suitable for additional recovery operations at some later date. Most EOR techniques probably leave the formation in such a state. Most also leave the formation filled with water, and in some cases new microorganisms will have been introduced to the formation either intentionally or accidentally. Thermal concepts which involve combustion of the petroleum probably result in the most serious long-term changes for the formation and may make subsequent EOR activities impossible or impractical.

Bioprocessing Concepts

Many of the problems of MEOR are similar to those just discussed for conventional techniques, but there can be important quantitative differences. Since MEOR techniques are generally less thoroughly studied, they present greater uncertainties. Generally, the degree of oil recovery expected for MEOR techniques is greater than those for the best understood approaches. This, of course, is an important reason that MEOR is so interesting. However, it is still too early to prove this widely held view.

A common problem with several MEOR concepts is getting the organism or biologically produced materials such as surfactants or polymers produced by the organisms into the formation. This is done by injecting aqueous suspensions through suitably located wells. A major difficulty is in getting the organism or material to penetrate the formation as desired and it has received considerable study. Microorganisms can penetrate some formations very effectively. Problems can result either because of low permeability of the formation, because the permeability of certain regions of the formation is too great, or because of adsorption of the organisms on solid surfaces. The permeability problem probably can be reduced by using spores rather than the full-size organisms. This has been suggested, but no record of spore use in field tests was found. Undesirably high permeability can be helped by using microorganisms (and their products) to plug those regions because it is easier for organisms to reach those regions prior to plugging.

If an organism is injected into the formation, it is usually necessary to continue to supply nutrients if the organisms are to function and grow in situ. It is also necessary to supply oxygen to aerobic organisms. Organisms which grow on petroleum alone without either additional nutrients or oxygen have not been found in formations, nor are they likely to be.

In situ MEOR approaches are limited to conditions under which organisms can grow. There are considerable variations in the temperatures and chemical environments under which organisms can survive and function, so there are opportunities to select organisms. However, temperature and environmental restrictions can rule out many options.[65] At sufficiently high temperatures, no organism can function or even survive. The temperature usually depends upon depth. MEOR which uses organisms in situ may only be effective for the more shallow or upper portions of the formation. The chemical environment can vary somewhat throughout a formation, but the temperature is more likely to vary. High concentrations of chlorides are often detrimental to growth and function of organisms; so the brine present in many fields could restrict the use of MEOR. Several studies on MEOR have looked for chloride-tolerant organisms.

Control of biological activity is an important aspect of any MEOR program. "Control" means the ability to activate and deactivate the organisms of interest for specific tasks, including suppression of organisms that produce undesirable effects. In many cases, suppression of "wild" strains would require sterilizing the formation and all nutrient or other streams fed to the formation. It is likely to be desirable in some programs to stop, slow, or reactivate organisms to control the pressure developed or to control the plugging in certain regions of the formation. Control of the flow of nutrients may be sufficient for some operations, but more aggressive actions such as sterilization or introduction of new organisms may sometimes be required.

Nutrients (or any chemical) added to the formation should not be allowed to enhance the growth of sulfate-reducing bacteria. These can compete with the more desirable microbes, lower the pH of the waters within the formation, and increase corrosion of well casings and other field structures. The potential problem is increased by the relative tolerance of some sulfate-reducing organisms for higher pressures and temperatures.[66] One recent study indicated that injected organisms can win out over sulfate reducers,[67] but those results came from a shallow field where neither the pressures nor the temperatures were very high.

BIOPROCESSING RESEARCH OPPORTUNITIES

As is evident from the limited literature review presented here, the opportunities for MEOR are great. The large number of options for using microbial actions require much R&D to even approach optimum operations. Advances in nonmicrobial EOR methods will compete with microbial methods, but it appears likely that eventually the low energy and chemical requirements will bring MEOR into common use. Much of the research needed for evaluating and developing MEOR has begun, but several potentially important areas have received little or no attention, largely because the available program funds cannot cover all options.

CONVENTIONAL AREAS OF MEOR RESEARCH

Screening and Testing of Organisms

An area of obvious importance is screening and selecting organisms that produce effective surfactants and biopolymers. These screening tests can be directed both at in situ operations using field conditions and at surface processing using optimum conditions. The "aboveground" operations offer opportunities for using carefully controlled conditions and thus growing pure cultures and even potentially difficult cultures. Although considerable work has been done in screening cultures, the variety of cultures and conditions which can be used justifies additional effort.

Separation of the surfactants and polymers of interest is an obvious supporting area of importance for surface processing. The entire processing system required to produce efficiently the large quantities of materials needed should be investigated. In their practical implementation, these could be large biochemical processing operations requiring considerable process and microbial development. Recent developments in bioprocessing include innovative bioreactors with outputs (capacities) many times greater than those of conventional stirred tank bioreactors. Clearly, similar innovative reactors are needed for surfactant and polymer production to supply the large quantities of materials required for large petroleum formations at low cost.

Preparation of surfactants and biopolymers in-situ offers fewer options. The materials must be grown in conditions that exist within the formation, and it can require considerable study to find organisms to match each of the field conditions.[68] Because it would be difficult to supply oxygen to oil fields, especially deep fields, anaerobic organisms are likely to be required. Furthermore, the temperature within the fields increases with depth, generally at a rate of approximately 0.027°C/m. The average temperature in most U.S. fields ranges from 49 to 90°C.[69] Control of in situ processes could be difficult, and it is impossible to use only the desired materials in the formation.

Everything produced in the formation is present after in situ operations, which could make these operations less specific. One advantage of in situ approaches is the ability to combine functions such as gas pressurization with surfactant and biopolymer formation. However, it may also be possible to add gas-generating organisms along with surfactants or biopolymers produced aboveground; thus, optimum organisms may be used for both functions, providing that the gas-generating organism does not degrade the surfactant as well as the nutrient.

Little is known about how organisms can chemically modify petroleum. It would be desirable to have organisms that would convert lesser value heavy crudes to light crudes or would selectively degrade undesirable compounds such as those with heteroatoms. Most organisms tend to interact with the lighter fractions of the crude and leave the heavier fractions. If organisms are found for effectively converting heavy crudes to more valuable products, they will probably be very specific and require sterilization of the formation prior to use to prevent or reduce unfavorable reactions from native organisms, which are likely to attack the lighter and more valuable fraction of the oil. Organisms which remove sulfur or nitrogen from the crude (either in situ or aboveground) would be desirable.

Although studies of pure cultures are still an appropriate area for expanded R&D, properly mixed cultures could be even more useful. Symbiotic effects could create mutually helpful physical changes. An example of near-term potential is the joint use of organisms which produce surfactants and/or biopolymers and gases to repressurize the formation. This type of additive effect has been studied. More complex interactions of tailored mixed cultures are also possible; different organisms could carry out desired reactions in two or more steps, one by each organism. Also, one organism could produce nutrients needed by other organisms.

Introduction and Transport of Organisms and Nutrients

Introduction of microorganisms into petroleum formations has been recognized as an important step in any in situ microbial technique. Several studies have addressed this problem, and additional studies should consider innovative techniques of introducing organisms. One such possible technique is the conversion of the organisms into spores, inactive states of organisms that are smaller than the normal organism. It may be easier to transport the spores into the formation or even into specific regions of the formation. The spores could then be activated and begin their desired functions.

A companion problem to introduction of organisms is the deactivation of organisms. It will often be just as important to stop the microbial action as it was to begin it, such as when using microbes to plug regions of petroleum formations selectively. The plug should extend no farther than the region needed. In using microbes to generate gas and repressurize the formation, it is desirable to control the buildup of pressure. Sufficient pressure is needed to force the petroleum to the well heads, but additional pressure could move the petroleum into other portions of the formation. It may also be desirable to have the capability to repressurize several times as the pressure declines. In some cases, control of the microbial action may involve little more than control of the rate at which nutrients are fed to the formation. In other cases, when the organisms can grow unaided in the formation, more forceful approaches may be needed.

It can also be important to eliminate or control the growth of organisms that either occur naturally or are unavoidably introduced during flooding or nutrient addition. This can be an important problem even when using conventional water flood methods. For instance, biological degradation of surfactants and viscosity-altering polymers has been a problem in several field tests. Control could involve killing existing organisms before introducing the polymer or surfactant or the organisms which produce them, and it could also require periodically killing the organisms that grow into the formation during operations. Elimination or control of undesirable organisms is an important aspect of any operation which attempts to use monocultures or controlled mixed cultures.

Field Characterization

It will seldom be possible to separate MEOR activities from field (formation) characterization. The hydrodynamics of the formations are, of course, important to all EOR approaches and even to primary recovery. However, MEOR can require additional hydrodynamic characterization. For instance, it is important that pores be large enough to transport the organisms or products being introduced. Most flow occurs through paths of least resistance, the more porous regions of the formation, but EOR activities often attempt to remove oil from the "tight" regions. When microorganisms are used to plug the undesirable porous regions, new flow patterns develop through the more porous portions of the unplugged regions. These flow paths may not be as well characterized for conventional EOR operations, so additional flow characterization may be needed after plugging operations. MEOR operations, as well as some conventional operations, need to introduce materials into specific regions of the formation, and that can require more information than would be needed only to predict and understand removal of the oil.

Perhaps the most important differences in the formation characterization needed for MEOR and conventional EOR are in the chemical and biological conditions throughout the formation. MEOR is often more sensitive to the presence of chlorides and other toxins that occur in the formation. Such materials may hinder or prevent the use of in situ MEOR approaches, or they may restrain the growth of wild organisms which can cause problems for biologically produced materials made on the surface (surfactants or polymers). Other chemicals of importance are oxygen, necessary for aerobic organisms, and nutrients, which are necessary for both aerobic and anaerobic organisms. Temperature can be a more important factor in MEOR operations since it affects microbial growth and metabolism as well as fluid viscosities. For MEOR approaches involving alterations or interactions with the oil or the surrounding rock, it is obviously important to understand the chemical nature of those solids as well as the surrounding fluids. The information needed may involve detailed chemical descriptions, or it may only be important to understand the wetting characteristics.

RESEARCH AND DEVELOPMENT AREAS OF SPECIAL IMPORTANCE

MODELING OF MEOR

Field characterization is necessary to select appropriate conditions for experimental testing (simulations with identical or very similar materials and conditions) as well as to evaluate and design field tests and actual MEOR operations. Evaluations also require realistic modeling of the formation and the MEOR operations within it. The experimental MEOR studies need to be accompanied by realistic models that can incorporate detailed characterization data from specific formations. Such modeling becomes a necessary bridge between laboratory experiments, field tests, and production operations. The behavior of microorganisms and materials they produce in petroleum formations will be too complex to predict from simple experimental data on individual steps or interactions. These models are the key to successful scale-up and extension of the technology to more and more formations.

The need for detailed understanding of such diverse phenomena as microbe production, growth, interactions with petroleum and surfaces, and behavior in complex petroleum-bearing formations requires a multidisciplinary effort among microbiologists, chemists, geologists, and engineers. The most successful programs are likely to occur in those organizations that have all these capabilities, can assemble them in cooperative efforts, and can maintain needed support in environmental science, computer science, and analytical chemistry.

SURFACE PROCESSING VERSUS IN SITU PROCESSING

In situ microbial processes have obvious advantages. They reduce the need for surface facilities and can generate gases within the field formation. The first advantage is significant, and the second could become so if MEOR approaches are adopted in which gas generation contributes significantly to the improved oil yields.

Two other advantages are not so obvious and can be challenged. First, in situ MEOR seems simple. If one injects the proper organisms into the field and provides the correct nutrients, good things may happen. Of course, the chemistry and other conditions in the field must be considered in the selection of organisms, but once such questions are decided, the operation of an MEOR system seems simple. In practice, however, in situ MEOR may be more complex. Growth of organisms and EOR activities from the products of the organisms can be very complicated operations, and we frequently have little knowledge or control over them.

Second, multiple effects of the numerous processes can take place in situ. There have been vague reports that in situ MEOR operations can give oil yields significantly greater than those that can be accounted for by the individual mechanisms believed to be involved. This implies that there can be synergistic effects with the multiple mechanisms involved in MEOR. However, it also implies that the improvements would be achieved by combining the individual products produced in situ with conventional chemical EOR. Our limited understanding of EOR certainly makes that assumption questionable. However, the very large increases are not sufficiently documented to determine if they result from individual processes in MEOR. If such large effects do prove to result from synergistic effects, it should be possible to duplicate the results by adding the proper mixture of surfactant, polymers, and other chemicals produced on the surface. In fact, surface processing affords the opportunity to add these same materials in different ratios and concentrations to seek more nearly optimum operations.

Comparison of Costs for Surface and In Situ Production of Chemicals

Because every material produced in situ could be produced in surface facilities, in situ methods could simply be judged on the basis of relative cost of producing and injecting the materials or organisms. Although surface facilities can be costly, they can also provide more efficient use of reagents (nutrients, etc.) and optimal conditions for the bioreactions of interest. Thus, surface production would not necessarily be more costly than in situ production. Further research should address the questions of possible "special benefits" of in situ methods. If special merits exist, they are likely to result from the exact location where the chemicals (surfactants, polymers, alcohols, acids, etc.) are produced. For instance, some organisms prefer to concentrate at the oil-water interface,[70] and the production of these materials at or near the interface could be more effective than introducing them with the bulk chemical flood. If a case is to be made for selecting in situ MEOR over surface production of chemicals, the research program should include an investigation of such mechanisms for establishing the merits or demerits of in situ production. No suitable studies of this sort are known to be in progress despite the rather obvious need. Because of the complexity of in situ operations, most mechanistic studies such as these should be made in laboratory equipment where conditions can be carefully controlled. The results of such studies would considerably increase our understanding of MEOR.

The principal reasons that surface processing should not be eliminated from consideration are its simplicity, its ease of control, and its great flexibility. Any material produced in situ could probably be produced on the surface, at some cost. Moreover, surface processing can use optimum temperatures and chemical environments that might not exist in situ. Different organisms and nutrients can be used, and the processes can be controlled. Furthermore, the materials injected into the fields after surface production can be limited to those that produce the desired results.

Controlling microbial activity usually means controlling population composition, metabolism, and growth, including initiating and stopping the microbial activity. Although surface equipment can add to capital expenses, it can also allow the introduction of pure strains or selected mixtures of microbial strains into sterile systems. The ability to know what is happening is far better in surface facilities than it is in situ. Any operation should be simpler in surface equipment, and some operations may only be possible in surface equipment.

Recent developments in bioprocessing have produced advanced bioreactors with much higher capacities per unit volume than conventional batch equipment. Some continuous bioreactor processing rates are more than ten times greater than those of conventional equipment. Because of their smaller volume they can be started or restarted more quickly and thus operate more efficiently. Such systems can reduce the capital and even operating costs greatly and thus reduce the capital disadvantages of surface processing when compared to in situ processing.

One recent assessment indicates that the nutrients used in in situ processing cost only 20 to 30% as much as purchasing the chemicals if produced elsewhere.[71] Such analyses constitute a reasonable start at comparison of in situ and surface processing. Next, the efficiencies of the two approaches in utilizing the nutrients must be compared. It would also be desirable to analyze the cost of the chemicals produced elsewhere to ensure that they do not include additional, unnecessary costs for use in EOR operations. Such costs could include concentration of the products for commercial sale, purification of the materials to levels not required for EOR, and unusual or unnecessary transportation costs. The efficiencies of in situ production of chemicals are likely to be significantly lower than those for surface processing. Inefficiencies will result from "wild" organisms that consume nutrients and from washout of nutrients from water movement in the field. Furthermore, the chemical environment and the temperature in the field may not result in optimal growth and metabolism from the organisms.

ENVIRONMENTAL CONTROL BIOTECHNOLOGY

A few studies have been made of the environmental effects of MEOR. There have been serious concerns with the addition of biologically active materials to any underground formation where they or their products can reach groundwater. The potentially large size of some EOR operations makes the need to understand the environmental impact of the operation especially important. However, there has been less consideration of the potential role of biotechnology in reducing or eliminating adverse environmental effects from any type of EOR operation. Even more conventional EOR approaches which introduce nothing but water or heat and move the oil through new parts of the formation can have an environmental impact. Any water removed from the field could be declared "hazardous" under future regulations and require treatment prior to discharge to surface waters or deep wells. Furthermore, water additions can introduce new microorganisms. When properly used, biotechnology can be used to degrade or eliminate materials that could reach groundwater. It is likely to be important in several roles such as the clean-up of water flushed from oil-bearing formations during EOR operations. It could even be considered for degrading or eliminating residual traces of oil left underground.

Cleanup of Spills and Residues

There has been considerable concern in recent years with the environmental consequences of oil spills from ocean tankers. Much less has been said about spills and residue from EOR operations, but there are enough similarities that all of the transportation spill work needs to be considered. The similarities are especially notable when MEOR is considered for offshore fields. Perhaps the major concern with any marine spill is that the petroleum or some components of it will persist and cause long-term, if not permanent, environmental damage. Studies of the natural degradation of petroleum are crucial to answering these questions.[72-82] Degradation of petroleum in an oil spill obviously occurs under primarily aerobic conditions and probably involves organisms that occur normally in seawaters. Smaller concentrations of hydrocarbons enter seawater by natural means, and organisms have evolved that can interact with such materials. After a large release of petroleum to seawater, the population of those organisms probably increases the rate of degradation.

Studies of petroleum degradation in laboratory samples of seawater indicate that the process proceeds in an order similar to that reported for aerobic degradation of petroleum deposits, in which alkanes are among the most easily degraded. However, additional factors are involved in oil spills at seas. Volatile components will be selectively removed by the air and winds, and the components that have significant solubilities in saltwater will be removed from the spill site and probably degraded over a much larger volume of water. Substantial acceleration of seawater degradation rates can be achieved if proper nutrients are supplied to the spill area. Nitrogen appears to be the most important nutrient,[83-85] phosphate may be less so,[86,87] and vitamins could also be important.[88]

Most studies of petroleum degradation in seawater have utilized organisms that normally reside in the seas and are effective in eventually degrading the spilled oils and returning the sea to its original condition. But selected organisms could be even more effective. Some success in searching for better organisms has been reported, but this technique has not been fully explored. Such organisms would either be stored for quick use soon after a spill or capable of rapid growth so they could be used quickly.

Wastewater Treatment

The other common use of microorganisms is in decomposing the small traces of oil and its products in the water effluents from refineries and other petroleum-handling and -processing facilities, often in fresh waters. The biological processes considered for EOR and MEOR are similar to wastewater treatment systems used in the petroleum industry or proposed for the coal conversion industries.[89,90] Many aspects and applications of biotechnology to other oil- and coal-based operations can apply to EOR and MEOR systems. The natural degradation of petroleum compounds in fresh waters is important to the ultimate control of environmental pollution and the recovery of ecological systems from normal releases and unexpected spills of petroleum and its products from fixed inland facilities or from inland transportation systems (barges, trucks, trains, or pipelines). Degradation in soils surrounding facilities or in soils where petroleum wastes have been intentionally added can also be important.[91-96]

Petroleum-processing facilities can include onsite facilities for biological treatment prior to release of wastewaters to the environment, and such facilities are common.[97-102] The degradation process can involve either the common organisms that tend to grow in such systems or special organisms such as PHENOBAC, which is particularly effective in degrading the ring compounds which many of the more common organisms degrade less effectively.[103,104] The degradation can occur under either anaerobic or aerobic conditions; both have been studied and found to be effective. The equipment used can resemble conventional sewerage equipment (activated sludge digestors, etc.) or can include new, more innovative equipment with organisms attached to solid surfaces. The equipment and techniques used in cleaning up petroleum wastewaters appear to be similar to those being tested and used in related shale oil and coal conversion facilities.

Off-gas Treatment

Control of off-gas from EOR operations has not received much attention, and for most EOR approaches, it is not likely to be a major problem when compared with other potential environmental issues. However, problems of significant magnitude could arise from some EOR approaches such as those using in situ partial combustion. Also, bioprocessing approaches for off-gas processing have not been used as frequently in other industries as for wastewater or solids processing. Thus, the potential uses of biological approaches are fewer for off-gas treatment. Nevertheless, there have been some investigations of microbe use with gaseous streams, and these should be followed.

In Situ Biotechnology for Environmental Control

Even less has been said about the potential to reduce environmental impacts from in situ operations through biotechnology. In most cases, this is not likely to be an important consideration since the petroleum left in the formation is probably no more hazardous than it was before the initial drilling and subsequent EOR operations began. However, penetration of the formation, introduction of water and organisms (even unintentionally), and modifications of underground water flow paths could in some cases result in altered environmental effects. There are probably two ways to use microorganisms to reduce environmental impacts: alter the water flow paths and biologically degrade or remove the residual oil, microbe residue, or chemicals.

Perhaps the most likely initial use of microbes for in situ environmental control would be to control flow through the formation, principally to selectively plug undesirable water inflow/outflow regions. This could be a permanent solution to the problem, a temporary solution requiring periodic upgrade, or a temporary solution to assist in other permanent solutions such as clay or grout injections.

Using biotechnology to destroy materials remaining in the formation may be less likely. Because decomposing any residual oil in the formation is not of interest unless the formation is essentially exhausted of its oil content, the most likely applications would be to selectively remove undesirable components such as heteroatoms or surfactants, polymers, or plugs injected or formed in the formation to assist in EOR. These could even include materials produced by MEOR operations. Such selective decomposition would require considerable control over the organisms, probably a difficult task.

FIELD TESTS AND EXPERIMENTS

Tests or experiments in actual oil fields are especially important and necessary to the development of MEOR, but they can be rather costly and consume significant portions of the available R&D budgets. Because of their importance and potential economic impact on the rest of the MEOR program, a few special comments are given on what can be learned from field experiments and how they should be planned.

Several experiments using MEOR have been made in actual oil fields, some in the United States, but most in other countries. The major interest has been in flooding, with surfactants and polymers produced in situ. Although considerable interest in a significant expansion of field "tests" has been noted, the merit and need for an expanded number of tests should be reconsidered; better tests, rather than more tests, are needed.

<u>Goals for Field Tests</u>

Tests or experiments in actual oil fields are certainly important and necessary. They can serve two important functions.

1. They can provide quantitative data under actual conditions which can not be simulated well in the laboratory. Such data confirm laboratory data and provide insight into new data needs. They allow reliable assessment of our ability to design MEOR tests and operations and predict (estimate) the results.

2. They can "demonstrate" the potential of MEOR and thus convince the public and those who would use the technology that it is a feasible and attractive way to increase oil production under suitable conditions.

Both types of field experiments are important and must be made for the eventual success of MEOR. However, it appears appropriate at the moment for most government R&D to focus upon the first type of field experiment rather than on "demonstration" tests. The potential for MEOR to enhance oil production appears to be reasonably well understood by those involved in the research and in funding the research. Reasonable mechanisms for increased production via MEOR are available. Surfactants and polymers work well in laboratory tests, and a few field tests indicate that under suitable conditions, similar results can be achieved in the field. There are even indications that the different effects produced by MEOR may combine to give greater production than the sum of the individual contributions would indicate. The problem with MEOR is that the results can be difficult to predict, either because important characteristics of the field are not well known or because the interactions of microbes or products with the rock or oil are not understood.

Demonstration Tests

Under present conditions, demonstration field tests do not appear to be as appropriate for significant governmental support. There are two potential outcomes from a field demonstration: the MEOR will either work well or poorly. Neither of these results is necessarily important in itself. An unfavorable result that is not general can have little meaning, but it could discourage the development and use of MEOR. On the other hand, a very favorable result that cannot be reproduced could actually mislead people and result in overly optimistic attempts to start many unsuccessful MEOR projects. Having enough successful tests may increase interest in MEOR sufficiently to attract private money for additional tests, but this could be of more importance to the promoters than to the industry as a whole.

Numerous field tests would produce some successful results and probably enhance interest in MEOR, and a sufficient number of tests would also provide a somewhat more reliable assessment of success probability if the tests were carried out in fields with a proper range of properties.

Collection of empirical data in that manner is not an effective way to approach problems as complex as MEOR, but some meaningful generalities from such a battery of field tests may be found. The complexity of MEOR appears to discourage some from trying to aim for rational bases for understanding the processes, although variations in the performance of MEOR should be a principal reason for searching for improved understanding.

Experiments in Petroleum Fields

Field experiments should be carefully planned, take place in a well-characterized field, and employ sufficient instrumentation and analysis to gain maximum information from the experiments. Further, the experiments should be carried out with specific goals. Normally, they should test models (eventually mathematical and quantitative models, but qualitative models or concepts can also be useful in early stages of development). The tests should have one or more parameters to measure and compare with expectations.

Field experiments should aim at constantly improving the predictability of MEOR operations as well as the level of performance. Thus, predictions are, or will become, a significant part of the MEOR development program. The predictions could begin as qualitative ones, but quantitative predictions should be the goal. It is unnecessary to formally advertise a predicted enhancement; only a basis for prediction is needed and ideas on what data (or calculations) would be helpful in improving the predictive capability. A suitable goal for a field experiment is to improve understanding of an important aspect of MEOR, and that does not always mean that the performance of the field experiment will be better than that of previous experiments.

Since field experiments (as opposed to tests or demonstrations) should have one or more specific goals, sufficient instrumentation and analytical procedures should be available to meet those goal(s). The objective is not to do more field experiments or even larger ones, but to perform the most meaningful field experiments. If careful characterization of the field is required, a smaller field (or closer well spacing) could be desirable since there is a greater chance of missing important geological features if the field is large. The cost of a good field experiment is likely to be larger than the cost of a simple test or demonstration because more information is desired from the experiment. Field characterization and installation of equipment could be more disruptive to an operating field, and smaller fields may be better able to tolerate such disruptions than larger ones.

Characterization Needed for Field Tests

One of the difficulties of any field experiment is that one cannot design the field to meet specific needs; one can only choose among the fields available. Furthermore, the characteristics of fields are never known in as much detail as one is likely to desire. The initial field selection must be made with limited knowledge, so undesirable selections will be made. In most cases, additional characterization will be needed once the field is chosen. The potential complexity of petroleum fields makes modeling difficult, but particularly important.

It is unlikely that all large fields where MEOR will be applied can be characterized as well as those used in the field experiments. The field experiments and models should first reduce the uncertainty for applications of MEOR enough so that variables in the field characteristics are more important than uncertainties about any aspect of MEOR. Next, the field experiments and models should identify the field characteristics most important to MEOR performance and develop the best ways to make those important characterizations. That is, the field experiments should provide the user with the most effective and practical ways to assess what MEOR can do for his field. Risk will remain as long as any aspect of field characterization is not completely evaluated, but those risks should be reduced to the lowest practical level. By identifying the field characteristics most important to MEOR and using models to evaluate those characteristics with the simplest and most practical measurements, the risk to the user of MEOR can be reduced at a minimal cost.

Field characterization and modeling of fields are covered in other EOR programs, so the MEOR program need not undertake the sole effort in these areas. It should only be necessary for the MEOR program to characterize fields used in its own experiments and to develop characterization methods that are uniquely important to MEOR. Of course, it may be better to use much simpler models, perhaps to customize simple EOR models, for some early MEOR field experiments when relatively little is known about the techniques, but the eventual goal is likely to involve incorporation of MEOR into the best field description models available. It will be desirable to make maximum use of information and techniques developed in the other programs and to conserve the available MEOR funds for use in areas of specific interest to MEOR.

The laboratory program and the availability of fields will help determine which field experiments are performed. However, a few generalizations are suggested. The first field experiments should involve simple and probably small fields, which are representative of a significant portion of the U.S. fields believed to be candidates for MEOR. The field should be relatively well characterized and available for further characterization as needed. As discussed earlier, each field experiment should have one or more specific objectives such as testing a prediction or measuring a phenomenon. The number of field experiments in progress at any one time should depend upon the specific questions that need addressing and the available funding. In general, the number of field tests should not go beyond the ability to assess and understand the results. New field tests should not be attempted until a new goal is established and suitable experimental techniques are available.

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