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Microbial enhanced oil recovery (MEOR)

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Two-thirds of the oil ever found is still in the ground even after primary and secondary production. Microbial enhanced oil recovery (MEOR) is one of the tertiary methods purported to increase oil recovery. Since 1946 more than 400 patents on MEOR have been issued, but none has gained acceptance by the oil industry. Most of the literature on MEOR is from laboratory experiments or from field trials of insufficient duration or that lack convincing proof of the process. Several authors have made recommendations required to establish MEOR as a viable method to enhance oil recovery, and until these tests are performed, MEOR will remain an unproven concept rather than a highly desirable reality.

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Introduction

The first production from an oil well is the result of the pressure of the earth's overburden on the oil-bearing formation or by pumping. As this primary production declines, some of the wells are converted to injector wells and either waterflooding or sometimes gas flooding are implemented. Even after this secondary production effort has reached its economic limit, two-thirds of the original oil in place is still left in the ground and tertiary measures may be employed. These include chemical enhanced oil recovery (EOR) methods such as polymer flooding, surfactant flooding, alkaline flooding, etc. or the use of thermal measures such as injection of steam or in situ combustion.

Another tertiary method of oil recovery is microbial enhanced oil recovery, commonly referred to as MEOR. Actually, there are several ways in which microorganisms can enhance oil recovery other than what is commonly referred to as MEOR. For example, microorganisms can be used to reduce the paraffin build-up in producing wells or they can be utilized to produce solvents or polymers above ground for pumping into the oil-bearing formation as in EOR. In reality, the only difference between EOR and some of the MEOR methods is the means by which the recovery-enhancing chemicals are introduced into the reservoir [1]. Normally, however, MEOR refers to the use of microorganisms in the oil-bearing formation itself to enhance oil recovery.

Review of MEOR

Beckman first proposed MEOR in 1926, but it was not until the work of ZoBell and Russian investigators in the 1940s that any serious consideration was given to the process [2–6]. It must be remembered that microbiology as a science was less than 100 years old at the time and the ability of microorganisms to use hydrocarbons was viewed as a biological curiosity. Most of the research was conducted in university laboratories and it was not until the 1940s that an oil company in the U.S. actually hired a microbiologist.

ZoBell's first patent [3] involved the injection of the bacterium *Desulfovibrio hydrocarbonoclasticus* along with oxidized sulfur compounds and a carbon source, such as lactose, but no field trials were performed. In a latter patent, ZoBell introduced the concept of adding oxygen-free hydrogen produced by the action of a *Clostridium* species on a carbohydrate [7]. In the same year, Updegraff and Wren [8] patented an MEOR method involving the injection of a species of *Desulfovibrio*, a symbiont bacterium, and molasses into the formation. Once again, however, no actual field tests were attempted.

Although some microorganisms can grow on oil, it must be remembered that during the early years of MEOR, it had not been conclusively proven that microorganisms could actually metabolize the hydrocarbons anaerobically, and virtually nothing was known about the microbiology of oil-bearing formations. As a matter of fact, it was not until recently that bacteria have been shown conclusively to metabolize hydrocarbons in oil anaerobically [9,10].

There is absolutely no question as to weather microorganisms have the capability of enhancing oil recovery by virtue of some of the products they can produce. For example, bacteria can produce acids from oil and other organic compounds which will dissolve carbonates, thereby increasing permeability as shown in Figure 1. They can also produce gases that increase pressure in the reservoir and decrease the viscosity of the oil by dissolving in it. Biosurfactants, emulsifiers, and solvents

Figure 1

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Cores obtained from North Blowhorn Creek Unit after treatment in the laboratory. Core on the left only had simulated production water pumped through it daily. Core on the right had simulated production water containing 0.12% (w/v) potassium nitrate passed through it on Mondays and 0.034% (w/v) sodium dihydrogen phosphate passed through it on Wednesdays and Fridays. On Tuesday, Thursday, Saturday, and Sunday, simulated production water only was pumped through this core. Note destruction of portions of the core on the right after treatment [31].

decrease the viscosity of oil making it easier to produce (as shown in Figure 2), or they can produce biopolymers that increase the viscosity of the water in waterflooding operations, making the operation more effective. By increasing in number, the bacteria will selectively plug the oil-bearing formation and alter the water injection profile in a waterflooding operation. Therefore, the question is not whether microorganisms can enhance oil recovery, but rather how to employ this ability in an economically practical and scientifically valid manner.

A majority of the MEOR processes, particularly the early methods, involved injecting microorganisms into the reservoir. Unfortunately, some operators have had bad experiences during normal waterflooding operations because microorganisms have caused the plugging of wells or they have contributed to corrosion problems by producing hydrogen sulfide. Interestingly enough, Beck [11] and O'Bryan and Ling [12] experienced some plugging by the injected bacteria in their laboratory studies of MEOR. It has been suggested that not only will the bacteria themselves cause plugging, but also the by-products of their metabolism, such as ferric hydroxide, will cause plugging [13].

It is obvious that injected microorganisms will have difficulty penetrating into the oil-bearing formation. This led Hitzman [14•] to propose using spores instead of vegetative cells because of their smaller size. Even so, spores also create plugging problems and Lapin-Scott *et al.* [15•] proposed using ultramicrobacteria (UMB) that have a diameter of less than 0.3 μm. Jack *et al.* [16] calculated that the microbes injected into oil sands needed to be small and spherical and less than 20% of the size of the pore throat in the formation. Even if the injected microorganisms meet the size criterion, they cannot be metabolically producing gases, polymers, or slime of any kind at the time of injection, since that would inhibit penetration through the formation. According to Davis and Updegraff, the pore entry diameter should be at least twice the diameter of the microbial cells being injected; otherwise serious plugging will occur [17].

The hazard exists that the injected bacteria themselves may cause the plugging of the oil-bearing reservoir. To prevent this from happening, Chang and Yen [18] suggest using a lysogenic strain of bacteria. They state 'It may be possible to use bacteria carrying inducible latent phage, potentially triggered by reduction of a specific substrate level, presence of a certain cell density, concentration of by-product, or application of some subsequent oil recovery agent.'

According to Yen [19] a wide variety of chemicals have been proposed to prevent bacterial activity in oil-bearing formations and Hitzman [20] even patented the concept of adding a biocide to the water in a waterflood to kill or inhibit sulfate-reducing bacteria because of the hydrogen sulfide they produce. In regard to MEOR, one suggestion is to use a bacterium resistant to the biocide being employed [19].

Nevertheless, research on MEOR continued and by 1990 there had been 133 U.S. patents issued in addition to a number of patents in other countries [19]. By 2003 more

Figure 2

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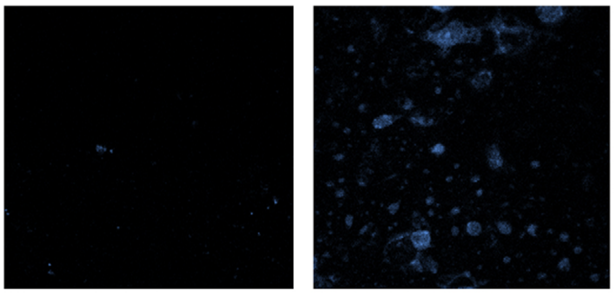
Cores obtained from North Blowhorn Creek Unit after treatment in the laboratory. Core on the left only had simulated production water pumped through it daily. Core on the right had simulated production water containing 0.12% (w/v) potassium nitrate passed through it on Mondays and 0.034% (w/v) sodium dihydrogen phosphate passed through it on Wednesdays and Fridays. On Tuesday, Thursday, Saturday, and Sunday, simulated production water only was pumped through this core. Note removal of oil from the core after treatment [31].

Figure 3



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Fluorescent images of crushed Cranfield core samples stained with DAPI (4,6-diamindino-2-phenylindole) and viewed using the confocal microscope. Photo on the left is the image of the crushed Cranfield Core, oil, production water and nutrients (K_2HPO_4 and KNO_3) before incubation. Photo on the right is the same materials as listed above but after incubation anaerobically at 115 °C for 60 days [23].

than 400 MEOR field tests had been conducted in the U.S. [21], in addition to others carried out in other countries, but the claims of the significant recovery of incremental oil is open to question.

In all cases, the microbes selected for use in MEOR had to have a maximum growth temperature below 80 °C until it was discovered that some microorganisms could actually grow at temperatures up to 121 °C [22]. In this regard it has been shown that viable microorganisms were present in an oil-bearing formation at a temperature of 118–124 °C as shown in Figure 3 [23]. There is even one patent on how to produce new modified microorganisms suitable for use in MEOR that are viable at extreme temperatures, pressures, pHs, and salinities [24].

Most of the MEOR literature is on laboratory data and it is difficult, if not totally impossible, to extrapolate laboratory results into what is to be expected in the field and, for that matter, to predict what will happen in a new field based upon the results from another field because of reservoir heterogeneity. It stands to reason that the injection of microbes into the reservoir will only penetrate a short distance beyond the wellbore, unless of course, there are cracks in the formation. Furthermore, using MEOR on a single well, rather than an MEOR process that treats multiple wells, only a fraction of the oil in the reservoir would be potentially available for recovery [25••]. In most cases in the literature, interpretation of field results is problematical because of the multiple variables that change during the recovery process [26].

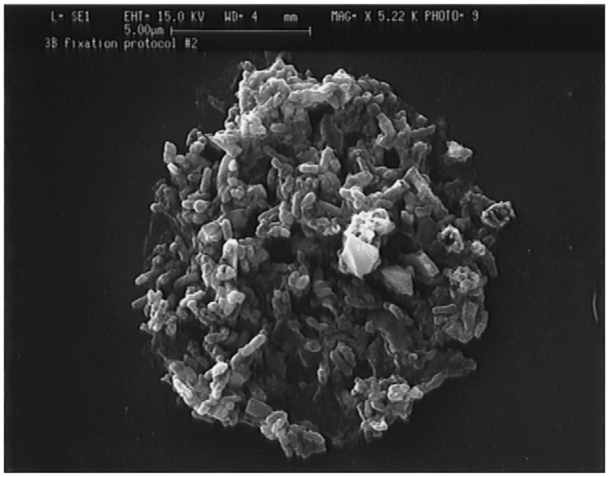
Ultimately, the value of MEOR can only be determined by the results of field trials. Davis [27] summarized the results of the first field trials and in 1991 Lazar [28] reported on nearly 30 MEOR field trials conducted between 1956 and 1991. Even more recently, Maudgalya *et al.* [29••] evaluated the MEOR field trials conducted over the past 50 years. Of the 407 examples they cite, 333 were concerned with repairing wellbore or formation damage and not considered MEOR as described earlier. Of the 44 single wells treated, 36 were considered successful and of the 26 waterflooding field tests, 20 were considered successful. Overall, however, the authors point out that few of the tests explain the mechanics of the oil recovery or presented post-treatment analyses or how the results were calculated. This helps explain why MEOR has not gained credibility in the oil industry.

Unfortunately, in many instances the effectiveness of the field trials was based on laboratory core tests and was proven to be totally unreliable. Furthermore, sometimes microbial performance in the laboratory is not the same as in the field and as a consequence laboratory experiments cannot predict the outcome expected in the field. This is another reason why MEOR has not been accepted by the oil industry. Furthermore, many of the successful single well tests were small and all of the microbial activity occurred in the immediate area adjacent to the wellbore making it unclear whether the results are well stimulation, not the tertiary oil recovery process referred to as MEOR. Most of the European field trials fall into this category [29••].

Moses [30] pointed out that most field trials were not followed for a long enough time to determine the long-term effects. He also pointed out that sufficient money and expertise are required for a satisfactory field trial. A field trial was funded by DOE under the direction of a vice president of an independent oil Co., a petroleum engineer, and a microbiologist and seemed to meet the requirements of Moses [25••]. The field (North Blowhorn Creek Unit, situated in Lamar Co., AL) had 20 injector wells and 32 producer wells and the MEOR process involved the addition of KNO_3 and NaH_2PO_4 to the waterflood. In 2001, DOE reported that the project had added reserves of 400,000–600,000 bbl, decreased the decline rate from 18.9%/year to 7–12%/year, and extended the economic life of the field by 5–11 years. Evidence of proliferation of microorganisms in the formation is shown in Figure 4. Also, the produced oil became more like the oil originally produced from the field and the produced gas was more like the gas produced earlier in the life of the field because of the increased propane content [25••]. While injection of nutrients stopped in January 2002, the field is still producing today (2009), even though it was scheduled to be abandoned in 1998.

Obviously, MEOR could substantially increase the world's supply of oil, and yet it has not gained acceptance

Figure 4



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Electron micrograph of a section of core from the North Blowhorn Creek Unit after the treatment of the field with KNO_3 and NaH_2PO_4 for 24 months [31].

by the oil industry. Recommendations to resolve both the economic and technical issues have been adequately addressed by Moses [30] and Maudgalya *et al.* [29••] and from an economic perspective, they agree it will be expensive. Technically, most single well treatments would best be categorized as well stimulation treatments rather than MEOR as stated earlier. This leaves the treatment of whole fields or a large portion thereof, available for MEOR treatment. Unfortunately, unless the field is unitized, both legal and economic issues become a serious problem. For example, if one owner treats his or her wells, it may result in increased profits for neighboring wells at his or her expense. Contrariwise, if the treatment results in increased hydrogen sulfide production or some plugging, it could result in lawsuits by neighboring well owners.

Another major problem is the cost of developing a given MEOR treatment. If a company spends a large amount of money developing a process, they justifiably would expect some protection of their investment, for example, a patent. This would obviate the availability of the process to the overall oil industry.

Conclusion

In conclusion, it can be stated that the potential to enhance oil recovery by MEOR is considerable, but if the problems surrounding its use are not resolved, it will remain an unproven concept rather than a highly desirable reality.

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References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Bryant S, Lockhart TP: **Reservoir engineering analysis of microbial enhanced oil recovery**. In *Proceedings of the SPE Annual Technical Conference and Exhibition*; *Dallas, TX: 2000*.
2. Zobell C: **Bacterial release of oil from sedimentary materials**. *Oil Gas J* 1947, **46**:62-65.
3. Zobell C: **Action of microorganisms on hydrocarbons**. *Bacteriol Rev* 1946, **10**:1-49.
4. Mogilevskii G: **The bacterial method of prospecting for oil and natural gases**. *Razvedka Nedr* 1940, **12**:32-43 (English Translation: Associated Technical Service, East Orange, NJ).
5. Bokova E, Kuznetsova VA, Kuznetsov SI: **Oxidation of gaseous hydrocarbons by bacteria as basis of microbiological prospecting for petroleum**. *Doklady Akad Nauk SSSR* 1947, **56**:755-757 (English Translation: Associated Technical Service, East Orange, NJ).
6. Nechaeva N: **Two species of methane oxidizing mycobacteria**. *Mikrobiologiya* 1949, **18**:310-317 (English Translation: Associated Technical Service, East Orange, NJ).
7. Zobell C: **Recovery of hydrocarbons**. US Patent 1953, 2,641,566.
8. Updegraff D, Wren GB: **Secondary recovery of petroleum oil by *Desulfovibrio***. US Patent 1953, 2,660,550.
9. Kropp K, Davidova IA, Suflita JM: **Anaerobic oxidation of *n*-dodecane by an addition reaction in a sulfate-reducing bacterial enrichment culture**. *Appl Environ Microbiol* 2000, **66**:5393-5398.
10. Aiken C, Jones DM, Larter SR: **Anaerobic hydrocarbon biodegradation in deep subsurface oil reservoirs**. *Nature* 2004, **431**:291-294.
11. Beck J: **Penn grade progress on use of bacteria for releasing oil from sands**. *Producers Mon* 1947, **11**:13-19.
12. O'Bryan O, Ling TD: **The effect of the bacteria. *Vibrio desulfuricans* on the permeability of limestone cores**. *Tex J Sci* 1949, **1**:117-128.
13. Updegraff D: **Plugging and penetration of petroleum reservoir by microorganisms**. In *Proceedings of the International Conference on Microbial Enhancement of Oil Recovery*. 1983:80-85.
14. • Hitzman D: **Microbiological secondary recovery**. US Patent 1962, 3,032,472.
15. • Lappin-Scott H, Cusack F, Costerton JW: **Nutrient resuscitation and growth of starved cells in sandstone cores: a novel approach to enhanced oil recovery**. *Appl Environ Microbiol* 1988, **54**:1373-1382.
16. Jack T, Stehmeier LG, Islam MR, Ferris FG: **Microbial selective plugging to control water channeling**. *Microbial Enhancement of Oil Recovery—Recent Advances*. Elsevier Publishing Company; 1991:. 433–446.
17. Davis J, Updegraff DM: **Microbiology in the petroleum industry**. *Bact Rev* 1954, **18**:215-238.
18. Chang P, Yen TF: **Interaction of *Escherichia coli* B and B/4 and bacteriophage T4D with berea sandstone rock in relationship to enhanced oil recovery**. *Appl Environ Microbiol* 1984, **47**:544-550.
19. Yen T: *Microbial Enhanced Oil Recovery: Principle and Practice* Boca Raton, FL: CRC Press, Inc.; 1990.
20. Hitzman D: **Bactericidal composition comprising tetra alkyl quaternary ammonium halide and hydrogen peroxide**. US Patent 1959, 2,917,428.

21. Van Hamme J, Singh A, Ward OP: **Recent advances in petroleum microbiology**. *Microbiol Mol Biol* 2003, **67**:503-549.

22. Kashefi K, Lovley DR: **Extending the upper temperature limit for life**. *Science* 2003, **301**:934.

23. Schmitz D, Brown LR, Lynch F, Kirkland BL, Collins K, Funderburk W: *Improvement of Carbon Dioxide Sweep Efficiency by Utilization of Microbial Permeability Profile Modification to Reduce the Amount of Oil Bypassed During Carbon Dioxide Flood*. Mississippi State University, Department of Energy; 2005:. Contract No. DEFC2605NT15458 05090806.

24. Premuzic E, Lin M: **Process for producing modified microorganisms for oil treatment at high temperatures, pressures and salinity**. US Patent 1996, 5,492,828.

25. Brown L, Vadie AA, Stephens JO: **Slowing production decline and extending the economic life of an oil field: New MEOR technology**. *SPE Reserv Eval Eng* 2002, **5(1)**:33-41.
••

26. Ollivier B, Magot M: *Petroleum Microbiology*. Washington, DC: ASM Press; 2005.

27. Davis J: *Petroleum Microbiology*. Amsterdam (New York, NY): Elsevier Publishing Company; 1967.

28. Lazar I: **MEOR field trials carried out over the world during the last 35 years**. *Microbial Enhancement of Oil Recovery—Recent Advances*. Elsevier Publishing Company; 1991.

29. Maudgalya S, Knapp RM, McInerney MJ: **Microbial enhanced-oil-recovery technologies: a review of the past, present, and future**. *SPE Production and Operations Symposium*; *Oklahoma City, OK: 2007*.
••

30. Moses V: **MEOR in the field: why so little?** *Microbial Enhancement of Oil Recovery—Recent Advances*. 1991:. 21–28.

31. Stephens J, Brown LR, Vadie AA: *The Utilization of Microflora Indigenous to and Present in Oil-Bearing Formations to Selectively Plug the More Porous Zones Thereby Increasing Oil Recovery During Waterflooding*. Mississippi State University, Department of Energy; 1996:. Contract No DE-FC22-94BC14962.