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Microbial Enhanced Oil Recovery (MEOR)

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Abstract: Microbial enhanced oil recovery (MEOR) represents the use of microorganisms to extract the remaining oil from reservoirs. This technique has the potential to be cost-efficient in the extraction of oil remained trapped in capillary pores of the formation rock or in areas not swept by the classical or modern enhanced oil recovery (EOR) methods, such as combustion, steams, miscible displacement, caustic surfactant-polymers flooding, etc. Thus, MEOR was developed as an alternative method for the secondary and tertiary extraction of oil from reservoirs, since after the petroleum crises in 1973, the EOR methods became less profitable. Starting even from the pioneering stage of MEOR (1950s) studies were run on three broad areas, namely, injection, dispersion, and propagation of microorganisms in petroleum reservoirs; selective degradation of oil components to improve flow characteristics; and metabolites production by microorganisms and their effects.

Keywords: advanced enhanced oil recovery, alternative tertiary oil recovery, improved oil recovery, in situ surfactant production, microbial enhancement of petroleum recovery, petroleum reservoir microbiology

INTRODUCTION: HISTORY OF MICROBIAL ENHANCED OIL RECOVERY (MEOR)

In 1926, Beckman suggested for the first time that microorganisms could be used to release oil from porous media. Between 1926 and 1940, little was done on this topic. Then, in the 1940s, ZoBell and his research group (1947) started a series of systematic laboratory investigations. Their results marked

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the beginning of a new era of research in petroleum microbiology with application for oil recovery. ZoBell explained the main mechanisms responsible for oil release from porous media involving processes such as dissolution of inorganic carbonates by bacterial metabolites; production of bacterial gases which decrease the viscosity of oil, thereby promoting its flow; production of surface-active substances or wetting agents by some bacteria; as well as the high affinity of bacteria for solids, later attached to crowd off the oil films (see also Tables 1 and 2). ZoBell (1947) described and patented processes by which bacterial products such as gases, acids, solvents, surface-active agents, and cell biomass, released oil from sandpack columns in laboratory tests. ZoBell's experiments were later repeated (Updegraff and Wren, 1954; Davis and Updegraff, 1954), resulting in the Updegraff's patent (1957) based on the use of underground injected microorganisms which can convert cheap substrates like molasses into agents of oil recovery such as gases, acids, solvents, and biosurfactants. The first field test was carried out in the Lisbon field, Union County, AR, in 1954 (Yarbrough and Coty, 1983). From the USSR, Kuznetsov concluded that oil deposits contain bacteria capable of anaerobically destroying oil to form gaseous products (CH_4, H_2, CO_2, N). Kuznetsov's work substantiated the technology of activation of reservoirs microbiota, later developed by Ivanov and his research group (1983). In the 1960s and 1970s, significant research activity took place in some European countries such as former Czechoslovakia, Hungary, and Poland (Dostalek and Spurny, 1958; Yaranyi, 1968; Dienes and Yaranyi, 1973; Karaskiewicz, 1974; Senyukov et al., 1970; Lazar, 1978). The field trials developed in these countries were based on the injection of mixed anaerobic or facultative anaerobic bacteria (*Clostridium*, *Bacillus*, *Pseudomonas*, *Arthrobacterium*, *Micrococcus*, *Peptococcus*, *Mycobacterium*, etc.) selected on their ability to generate high quantities of gases, acids, solvents, polymers, surfactants, and cell-biomass. Details about such activities are also in the diagrams of Lazar's review papers (1991, 1998). At the same time, Heinningen et al. (1958) suggested a new technology (selective plugging recovery) based on the idea of improving oil recovery from water floods by producing polysaccharide slime in situ from an injected microbial system based on molasses. This technology has been recognized as an important additional mechanism of oil release from reservoir rocks. Very important efforts were put into producing biopolymers of xanthan or scleroglucan types as viscosifying agents for EOR (Hitzman, 1988; Lazar, 1991, 1998). Investigations carried out in the period 1970–2000 have established the basic nature and existence of indigenous microbiota in oil reservoirs, as well as reservoir characteristics essential to a successful MEOR application. All these investigations proved that cyclic microbial recovery (single well stimulation), microbial flooding recovery, and selective plugging recovery are feasible to applications, as well as the technology based on activation of stratal microbiota successfully developed in former Soviet Union (Ivanov et al., 1983, 1993). In conclusion, MEOR research was boosted by the petroleum crisis (1970s) and later became a scientific substantiated EOR method,

Table 1. Microbial products, their role in enhanced oil recovery, and some of the effects to solve production problems[a]

Microbial product	Role in enhanced oil recovery	Some of the effects
Gases (H_2, N_2, CH_4, CO_2)	• Reduce oil viscosity and improve flow characteristics • Displace immobile • Sweep oil in place	• Improved oil recovery by gases • Miscible CO_2 flooding
Acids (low molecular weight acids, primarily low molecular weight fatty acids)	• Improve effective permeability by dissolving carbonate precipitates from pores throat. Significant improvement of permeability and porosity • CO_2 produced from chemical reactions between acids and carbonate reduce oil viscosity and causes oil droplet to sweel	• Enhanced oil flooding
Solvents (alcohols and ketones that are typical cosurfactants)	• Dissolve in oil reduce viscosity • Dissolve and remove heavy, long chain hydrocarbons from pore throat (increase effective permeability) • Involved in stabilizing and lowering interf. tension that promotes emulsification • Reduce interfacial tension	• Emulsification promotion for increased miscibility
Biosurfactants	• Reduce interfacial tension between oil and rock/water surface which causes emulsification; improving pore scale displacement • Alter wettability	• Microbial surfactant • Flooding
Biopolymers	• Improve the viscosity of water in waterflooding and direct reservoir fluids to previously unswept areas of the reservoir • Improve the sweep efficiency of waterflood by plugging high permeability zones or water-invaded zones • Control of water mobility	• Microbial permeability modification (selective plugging)
Biomass (microbial cells)	• Physically displace oil by growing between oil and rock/water surface • Reversing wettability by microbial growth • Can plug high permeability zones • Selective partial degradation of whole crude oil • Act as selective and nonselective plugging agents in wetting, alteration of oil viscosity, oil power point, desulfuration	• Same biopolymers

[a] Formation damage; low oil relative permeability; trapped oil due to capillary forces; poor sweep efficiency channeling; unfavorable mobility ratio; low sweep efficiency; water or gas coning.

Table 2. Key mechanisms for enhanced oil recovery in MEOR

- porosity and permeability modification
- wettability alteration
- oil solubilization
- emulsification
- interfacial forces alteration
- lowering oil mobility ratio
- microbial metabolic pathways alteration by sodium bicarbonate

supported by research projects carried out all over the world in countries such as the U.S., Canada, Australia, China, Russia, Romania, Poland, Hungary, Czech Republic, Great Britain, Germany, Norway, and Bulgaria. Many international meetings were periodically organized on the MEOR topic (Table 3) and proceedings volumes with the advances in the knowledge and practice of MEOR have been published. It is important to recognize and acknowledge the role of the U.S. Department of Energy (DOE), which sponsored MEOR basic research and field trials, as well as periodically organizing international meetings. Several books on MEOR were also published (Zajic et al., 1983; Yen, 1986, 1990; Donaldson et al., 1989). By the end of the 1990s, MEOR was already a scientific and interdisciplinary method for the increase of oil recovery. Today, MEOR technologies are well suited for application, whenever

Table 3. MEOR meetings organized after 1979

Meeting location	Year	No. of titled papers	No. of papers reporting field trials
San Diego	1979	7	1
Vancouver	1981	16	0
Afton, OK	1982	26	2
Fountainhead, OK	1984	30	2
Abilene, TX	1986	13	2
Bartlesville, OK	1988	19	6
Norman, OK	1990	34	8
Brookhaven, NY	1992	40	9
Dallas, TX	1995	41	11
Austin, TX	1996	10	7
MEOR sections at biohydrometallurgical technologies meetings			
Islamabad, Pakistan	1990	6	1
Jackson Hall, WY	1993	6	2
Vina del Mar, Chile	1995	3	—
Big Sky, MN	1996	3	—

the need for oil rises at a rate of 3 to 4%/year, while oil production constantly decreases. It is of interest to mention that the abandonment of stripper wells has increased to 175% since 1980 (Hitzman, 1991). Taking into account this rate, within 15–25 years, the U.S. could have access to less than 25% of its remaining oil resources. However, in spite of the long history of MEOR activities, MEOR technologies were very slowly recognized by industry. This may be due to the lack of published data especially in widely available journals, as well as to little cooperation between microbiologists, reservoirs engineers, geologists, economists, and owner operators.

MEOR RESEARCH AREAS

A complete MEOR system (Lazar, 1991, 1998) should be represented by four main components, namely, reservoir, bacterial system, nutrients, and protocol of well injection. According to Jack (1993), any such MEOR system is faced with some common problems, namely:

A) Repair of lost injectivity due to wellbore plugging—to avoid wellbore plugging, there are necessary activities such as filtration before injection, nonproduction of biopolymers during solution injection, or microbial adsorption to rock surface (using of dormant cell forms, spores, or ultra microbacteria).

B) Dispersion/transport of all necessary components to the target—there are a series of papers and patents concerning proposals for complex injection protocols (Stehmeir et al., 1990; Clark and Jenneman, 1992; Silver and Bunting, 1992). For this reason, reservoirs of less than 50–75 mD are not recommended for MEOR field trials (Knapp et al., 1990).

C) Promotion of desired metabolic activity in situ—factors such as pH, temperature, salinity, pressure seem to be the main constraints for promotion of desired metabolic activity in situ for any MEOR application. Premuzic and Lin (1991) suggested that development of thermophiles could significantly extend the limit temperatures. It is also known that injection of huge volumes of surface water can reduce temperatures of formation at least near injector wells and that salinity and pH proved to be less restricted. Experiments already proved (Sperl et al., 1993) that with minimal supplementation, growth of naturally occurring microorganisms can be guided to produce viscosifying agents to help in oil recovery.

D) Preclusion of competition or undesirable secondary activity—secondary activity, mainly of the sulfate-reducing bacteria (SRB), in many cases seem to be a problem. Nitrate at a low level suppresses hydrogen sulfide production. For this reason, nitrate could be included in the nutrient support (Knapp et al., 1990) and the injection of sulfide tolerant *Thiobacillus denitrificans* strains recommended (Sperl and Sperl, 1991; Lazar, 1998).

RECENT ADVANCES IN MEOR

In the U.S., the field tests run by the National Institute for Petroleum and Energy Research at the Mink Unit in the Delaware-Chivers in Nowata County, OK, were finalized with incremental oil production from flood water treated with a proprietary microbial system at a minimal cost (Bryant and Burchfield, 1990). Also, hundreds of single well treatments aimed at the control of paraffin deposition were undertaken commercially (Nelson and Launt, 1991; Brown, 1992). In 1986–1990, MICRO-BAC International Inc. (Austin, TX), started a very fruitful activity concerning the control of paraffin depositions and oily sludge in tank bottoms, which became of great interest after 1990 (Schneider, 1993; MICRO-BAC-International, 1992–1994). In Russia, Belyaev and Ivanov (1990) and Ivanov et al. (1993) successfully established their method based on stimulation of indigenous microbiota by introducing oxygen and some salts with water injection. In China, Wang (1991) came with very documented results concerning the production and application in China oil fields of biopolymers produced by *Leuconostoc mesenteroides* and *Pseudomonas aeruginosa* strains, as well as by *Brevibacterium viscogenes*, *Corynebacterium gumiform*, and *Xanthomonas campestris*—the last three species using hydrocarbons for biopolymer production. During the last 15–20 years, China was very active in MEOR method and today is still active in this field and could be considered one of the leaders in this field (Y. X. Wang, 1999; W. D. Wang, 1999; Z. He et al., 2000). Dewax method by microorganisms has been demonstrated (He et al., 2003). In Canada, Stehmeir et al. (1990) carried out a field test of a *Leuconostoc* based on a plugging system and also a new concept for selective plugging was reported by Cusak et al. (1992). This new concept is based on using ultra microbacteria formed by selective starvation. Another new concept in selective plugging is based on the idea of using biomineralization to form calcite cements capable of sand consolidation and fracture closure in carbonate formations (Ferris et al., 1991). Also, in Canada, Jack (1993) concluded that selective plugging strategies remain the most promising (Lazar, 1998). In Germany, Wagner (1991) and Wagner et al. (1993) reported the successful enhancement of oil production from a carbonate reservoir where *Clostridia* species, such as inoculum and molasses as the main nutrient support, have been used. Wagner's experience was then used for some MEOR applications in Tataryia oil fields in Russia (Lazar, 1998). In Australia, a new concept for enhanced oil production has been developed (Sheehy, 1991, 1992). This concept consists of using ultra microbacteria generated from indigenous reservoir microbiota through nutrient manipulation. The outer cell layers of such ultra microbacteria have surface-active properties. Such a microbial system was successfully demonstrated in increasing oil production in the Alton oil field in Queensland, Australia. In Romania, Lazar (1991, 1996, 1997) and Lazar et al. (1993) have reported successful results of MEOR field trials both in single-well stimulation and microbial flooding recovery technologies at several Romanian oil fields, where

Table 4. World experience on MEOR field trials (last 40 years)

Country	Acronyms of MEOR technology	Microbial systems	Nutrients	Incremental of oil production	References
1	2	3	4	5	6
USA	CMR, MFR, MSPR, ASMR, MCSC, MSDR, MPR	• Pure or mixed cultures of *Bacillus*, *Clostridium*, *Pseudomonas*, gram-negative rods • Mixed cultures of hydrocarbon degrading bacteria • Mixed cultures of marine source bacteria • Spore suspension of *Clostridium* • Indigenous stratal microflora • Slime-forming bacteria • Ultra microbacteria	• Molasses 2–4% • Molasses and ammonium nitrate addition • Free corn syrup + mineral salts • Maltodextrine and organic phosphate esters (OPE) • Salt solution • Sucrose 10% + Peptone 1% + NaCl 0.5–30% • Brine supplemented with nitrogen and phosphorous sources and nitrate • Biodegradable paraffinic fractions + mineral salts • Naturally contain inorganic and organic materials + N, P sources	+	Hitzman, 1983; Grula et al., 1985; Bryant et al., 1987, 1990, 1993; Zajic, 1987; MICRO-BAC brochures 1992–1994; Coates et al., 1993; Nelson et al., 1993; Jenneman et al., 1993, 1995
Russia	MFR, ASMR, MSPR, MNFR	• Pure cultures of *Clostridium tyrobutiricum* • Bacteria mixed cultures • Indigenous microflora of water injection and water formation • Activated sludge bacteria • Naturally occurring microbiota of industrial (food) wastes	• Molasses 2–6% with nitrogen and phosphorous salt addition • Water injection with nitrogen and phosphorous salt and air addition • Waste waters with addition of biostimulators and chemical additives • Industrial wastes with salts addition • Dry milk 0.04%	+	Senjucov et al., 1971; Ivanov et al., 1993; Belyaev et al., 1991; Nazina et al., 1994; Svarovskaya et al., 1995; Wagner et al., 1995
China	CMR, MFR, MSPR	• Mixed enriched bacterial cultures of *Bacillus*, *Pseudomonas*, *Eurobacterium*, *Fusobacterium*, *Bacteroides* • Slime-forming bacteria: *Xanthomonas campestris*, *Brevibacterium viscogenes*, *Corynebacterium gumiform* • Microbial products as biopolymers, biosurfactans	• Molasses 4–6% • Molasses 5% + • Residue sugar 4% + • Crude oil 5% • Xanthan 3% in waterflooding	+	Wang et al., 1991, 1995, 1999; Zhengguo et al., 2000
Australia	BOS system	• Ultra microbacteria with surface active properties	• Formulate suitable base media	+	Sheehy, 1991

(*continued*)

Table 4. (*Continued*)

Country	Acronyms of MEOR technology	Microbial systems	Nutrients	Incremental of oil production	References
1	2	3	4	5	6
Bulgaria	CMR, ASMR	• Indigenous oil-oxidizing bacteria from water injection and water formation	• Water containing air + ammonium and phosphate ions • Molasses 2%	+	Groudeva et al., 1993
Canada	MSPR	• Pure culture of *Leuconostoc mesenteroides*	• Dry sucrose + sugar beet molasses dissolved in water	−	Jack and Stehmeier, 1988; Jack et al., 1991
Former Czechoslovakia	CMR, MFR, ASMR	• Hydrocarbon oxidizing bacteria (predominant *Pseudomonas* sp.) • Sulfate-reducing bacteria	• Molasses	+	Dostalek and Spuny, 1957, 1958
England	MHAF, MSPR	• Naturally occurring anaerobic strain, high generator of acids • Special starved bacteria, good producers of exopolymers	• Soluble carbohydrate sources • Suitable growth media (type E and G)	±	Moses et al., 1993
Former East Germany	MFR, ASMR	• Mixed cultures of thermophilic: *Bacillus* and *Clostridium* • Indigenous brine microflora	• Molasses 2–4% with addition of nitrogen and phosphorous sources	+	Wagner et al., 1987, 1993
Hungary	MFR	• Mixed sewage-sludge bacteria cultures (predominant: *Clostridium*, *Pseudomonas*, *Desulfovibrio*)	• Molasses 2–4% with addition of sugar and nitrogen and phosphorous sources	+	Yaranyi, 1968; Diennes et al., 1973
Norway	MWPC	• Nitrate-reducing bacteria naturally occuring in North Sea water	• Nitrate and 1% carbohydrates addition to injected sea water	−	
Poland	MFR	• Mixed bacteria cultures (*Arthrobacter*, *Clostridium*, *Mycobacterium*, *Pseudomonas*, *Peptococcus*)	• Molasses 2%	+	Karaskiewich, 1973
Romania	CMF, MFR	• Adapted mixed enrichment cultures (predominant: *Clostridium*, *Bacillus*, *Pseudomonas*, and other gram-negative rods)	• Molasses 2–4%	+	Lazar and Constantinescu, 1985; Lazar et al., 1991, 1998
Saudi Arabia	CMF as well as other adequate MEOR technologies	• Adequate bacterial inoculum according to requirements of each technology	• Adequate nutrients for each technology	−	
The Netherlands	MSPR	• Slime-forming bacteria (*Betacoccus dextranicus*)	• Sucrose-molasses 10%	−	
Trinidad-Tobago	CMF	• Fac. anaerobic bacteria high producers of gases	• Molasses 2–4%	−	
Venezuela	MFR	• Adapted mixed enrichment cultures	• Molasses	−	

+ = yes; ± = not yet reported; − = not reported.

Table 5. Some advantages of MEOR technologies

1. The injected bacteria and nutrient are inexpensive and easy to obtain and handle in the field.
2. Economically attractive for marginally producing oil fields; a suitable alternative before the abandonment of marginal wells.
3. According to a statistical evaluation (1995 in U.S.), 81% of all MEOR projects demonstrated a positive incremental increase in oil production and *no* decrease in oil production as a result of MEOR processes.
4. The implementation of the process needs only minor modifications of the existing field facilities. It is less expensive to install and more easily applied than another EOR method.
5. The costs of the injected fluids are not dependent on oil prices.
6. MEOR processes are particularly suited for carbonate oil reservoirs where some EOR technologies cannot be applied with good efficiency.
7. The effects of bacterial activity within the reservoir are magnified by their growth whole, while in EOR technologies the effects of the additives tend to decrease with time and distance.
8. MEOR products are all biodegradable and will not be accumulated in the environment, so environmentally friendly.

adapted mixed enrichment cultures (AMEC) and molasses were injected into reservoirs after an improved protocol of injection (Lazar, 1991, 1998).

With almost a century of research and various field trials (Table 4), MEOR has proven great potential in oil extraction as well as certain advantages (Table 5). After 1990, the activity of MEOR field trials is running on the basis of conclusions that successful MEOR applications should be focused on water floods, where a continuous water phase enables the introduction of the technology or single-well stimulation (including skin damage removal), where its low cost makes it a preferable choice. At the same time, selective plugging strategies and activation of stratal microbiota remain the most promising and should be developed. Technologies such as microbial paraffin removal, microbial skin damage removal, microbial control souring and clogging, and those based on using ultra microbacteria remain of interest for the further development of the MEOR method.

MEOR APPLICATIONS IN ENVIRONMENTAL REMEDIATION

Some of the research prior to these MEOR projects were successful in the field of hydrocarbon-polluted environmental sites. Thus, the use of biosurfactants in pipeline heavy oil as an oil in water emulsion and cleaning out tank sludges, the use of bacterial cells as de-emulsifiers, desulfurization, and production of biopolymers is an effect of using products and processes arising from MEOR into other applications.

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