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International MEOR Applications For Marginal Wells

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ABSTRACT

The paper presents a review of MEOR field trials carried out during the last 40 years in several countries from Europe, America, Asia and Australia, with special reference to microbial systems used as well as to nutrients, protocol of well treatment and the effects on oil production.

GENERAL CONSIDERATIONS

As it is well known, after secondary recovery of oil from reservoir rocks, significant quantities of oil remain trapped in capillary pores of the formation rock or in areas not swept by the classical enhanced oil recovery methods such as water and gas floods. Among the modern EOR methods such as thermal and chemical ones (combustion, steams, miscible displacement, caustic surfactant-polymers floodings, etc.) which have been designed and applied to extract this trapped oil, Microbial Enhanced Oil Recovery (MEOR) method is an alternative to these methods developed during the last 35 -45 years. The history of this method starting from Beckman's idea (1926) that bacterial and their metabolites would assist in the release and transport of oil in geological structures. Later, ZoBell (1946, 1953) described and patented processes by which bacterial products, such as CO_2, solvents, acids and cell biomass released oil from sandpacks in laboratory tests. All these can act as potential mechanisms for dissolution of sulphate minerals and carbonate rocks, which will pressurize and push oil out of pore spaces. Viscosity reduction related to oil modification or gas dissolution effects, as well as biofilm development on solid surfaces physically displace oil. These ZoBell's investigations highlighted the parcel of compounds used to improve waterflood efficiency in chemical and miscible EOR processes and the products of microbial fermentation of carbohydrates. At the same time phenomena such as plugging and souring although they are desirable, could be considered direct and definitive evidence of the potential for microorganisms to proliferate in the reservoir environment and produce significant effects.

Starting even from the pioneering stage of MEOR (1950s), studies were run on three broad areas, namely:

- processes for the injection, dispersion and propagation of microorganisms in petroleum reservoirs;
- selective degradation of oil components to improve flow characteristics;
- production of products by microorganisms and their effects similar to those described for chemical and miscible EOR.

Later the activation by several ways of stratal microflora was added. On the basis of these early ideas, a first field test was carried out in the Lisbon field Union County, Arkansas, in 1954 (Yarbrough and Caty, 1983). In 1957, Updegraff introduced under a US Patent the use of injected microorganisms as factories underground to convert a cheap injected substrate as molasses into agents of oil recovery (gases, acids, solvents and biosurfactants). This strategy proved to be suitable as a production enhancement tool within the context of an ongoing waterflood operation in an appropriate target reservoir. After 1960s a large variety of studies carried out over the world have established many aspects connected to microbial production of acids, gases, solvents, biosurfactants, biopolymers and biomass, and their role and the oil production problems solved by these products and their effects as well as the key mechanisms for enhanced oil recovery by microbial systems (see tables and annexes). On the basis of these efforts, MEOR has advanced internationally overtaking the pioneering and empirical stage, especially after 1975-1980 as a stimulation generated by petroleum crises in 1973. MEOR method proved as an alternative to the EOR technologies by its advantages summarized in the Annex 1. However, the experience accumulated in time both in US and internationally, proved that MEOR technologies are well suited to be applied in today's economic situation, when the need for oil is rising at a rate of three to four percent/year, while oil production is constantly decreasing. Now it is considered that 40-45 % of the reservoirs are potential for microbial treatment and that only in an insignificant number of these reservoirs, MEOR was tested. Another important aspect is that about 50 % of the world's oil reserve lie in carbonate rock beds from which EOR technologies as polymer, biosurfactant and alkali flooding haven't a good efficiency compared to MEOR technologies suitable for such reservoirs.

All these general considerations become of great interest if we take into account that the abandonment of stripper wells has increased to 175 % since 1980 Hitzman (1991). If this rate is appreciated that within 15-25 years, the US could have access to less than 25 % of its remaining known oil resources. At this time MEOR could be the answer to oil industry needs for a cost-effective oil recovery method, at

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least for MEOR technologies mentioned in Tables 1 and 2 which are demonstrating that MEOR as a broader method can be designed selectively for applications. Even the classical MEOR technologies based on the use of inexpensive carbohydrates with addition of some mineral salts to stimulate: a) naturally occurring microflora and b) specially selected and then injected bacteria can be amplified due to the effects in a large diversity of options. But, in spite of the long history of MEOR activities, the development of the MEOR technologies have gone very slowly in recognizing by the industry due to two main reasons, namely:

- the results, mainly those from the field trials have been presented partly, often not in large circulation publications;
- insufficient cooperation and different views between microbiologists, reservoir engineers, geologists, owner operators and economists.

However, finally it has been accepted that after placing or stimulating the indigenous bacteria downhole, one of the following can be achieved:

- channel blocking / profile improvements, the control of water movement either to improve the sweep of waterflood to control coning or for a number of other special applications:
- polymer and surfactant flooding;
- matrix (and possible fractures) acidizing;
- single well stimulation by convection in various types of reservoir damaged, as it is partly summarized in some of the tables and annexes, as well as in the diagrams of this presentation.

DEVELOPING OF MEOR TECHNOLOGIES AND THE HISTORY OF MEOR FIELD TRIALS EVOLUTION

After ZoBell's investigations period, for about two decades, work on microbial enhanced oil recovery continued in the former Soviet Union and in several countries of Central and Eastern Europe (Dostalek and Spurny, 1957, 1958; Yaranyi, 1968; Dienes and Yaranyi, 1973; Karaskiewicz, 1974; Senjukov et al., 1970; Lazar, 1978), where field trials proceeded mainly based on the injection of mixed anaerobic or facultative anaerobic cultures including *Clostridium* type, which were selected on their ability to produce those types of metabolites mentioned in the earlier work in US from the fermentation of molasses. Many of the tests carried out that time in the mentioned countries involved injection of the microbial systems, a period of shut-in, followed by back production from the same injected wells as well as other wells around. Details about these activities are in diagrams of Lazar's paper (1991).

In 1958, Heiningen Van et al. suggested another target for microbial enhanced oil recovery, based on the idea of improving the recovery from waterfloods by producing polysaccharide slimes in situ from an injected microbial system based on molasses. This work initiated the microbial selective plugging technology, which has now been recognized as an important additional mechanism of oil displacement. But, after that time, for more than ten years no further work in this area was carried out, although very important efforts were put into producing biopolymers of Xanthan or Scleroglucan type as viscosifying agents for EOR. The early work as well as that by the end of 1970-1975s was nicely reviewed by Davis (1967) and then by Hitzman (1983, 1988), Updegraff (1990) and Lazar (1991). The strategy of using mixed or pure bacterial cultures as "factories" underground to convert cheap injected nutrients into products of oil release had been identified. Investigations carried out in this period have established the basic nature and existence of indigenous microbiota in oil reservoirs as well as the reservoir characteristics as essential to a successful MEOR application has been demonstrated. Also it has been proved that single well stimulation, enhanced performance in waterflooding and selective plugging were feasible field applications. At that time, after petroleum crisis in 1973 with unstable oil prices, it has registered an exploding interest in biotechnology which generally promoted a new round of creative activity. Thus, after 1980 an intensification and stimulation of the activity in the field of MEOR took place in many countries on many themes with varying degrees of secrecy and success. This could be demonstrated by the papers presented at several MEOR International Workshops, Symposia and Conferences finalized with important and useful publications (Donaldson and Clark Ed., 1983; Zajic and Donaldson Ed., 1985; King and Stevens Ed., 1987; Burchfield and Bryant Ed., 1988; Donaldson Ed., 1991; Premuzic and Woodhead Ed., 1993; Bryant Ed., 1995). It is important to recognize and acknowledge the role of Department of Energy (DOE) which in USA sponsored MEOR basic research and field trials as well as organized periodical international meetings (Table 3). In this period the anaerobic use of oil by microorganisms was reported in two independent studies which concluded that oil degradation occurred in the virtual absence of oxygene, but that the process is very slow (Moses et al., 1983, Jack et al., 1985). These studies as well as many others on similar topic had an immediate effect on the bioremediation of subsurface hydrocarbon and may be have long term implications for MEOR.

A complete MEOR system should be represented by four main components or factors, namely: the reservoir, bacterial system, nutrients and protocol of well injection (Diagram 1). According to Jack (1993) any such MEOR system is faced with some common problems such as:

Repair of Last Injectivity due to Wellbore Plugging

Repair of last injectivity due to wellbore plugging can compromise the ability to introduce further microbial systems into the reservoir. Under this aspect, a successful injection involves activities as: filtration before injection to remove particulate from the injection solution, selection of the appropriate size, non-production of polymers during solution injection or microbial absorption to rock surface. In some cases dormant cell forms such as spores and ultramicrobacteria should be used. Many papers of this

Table 1. World experience on MEOR field trials (Last 40 years).

Country	Acronyms of MEOR Technology	Microbial systems	Nutrients	Incremental of oil production	References
USA	CMF, 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 • Ultramicrobacteria	• 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 broshures 1992-1994 Pelger, 1991 Coates et al., 1993 Speol et al., 1993 Nelson et al., 1993 Jenneman et al., 1993, 1995 Stepp et al., 1995 Brown et al., 1995 Giangiacomo et al., 1995 Schneider, 1993
RUSSIA	MFR, ASMR, MSPR, MNFR	• Pure cultures of *Clostridium tyrobutiricum* • Bacterial 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%	+	Senjukov et al., 1971 Yulbarisov et al., 1989 Ivanov et al., 1993 Belyaev et al., 1991 Nazina et al., 1994 Muriygina et al., 1995 Svarovskaya et al., 1995 Wagner et al., 1995
CHINA	CMR, MFR, MSPR	• Mixed enriched bacterial cultures of : *Bacillus*, *Pseudomonas*, *Eubacterium*, *Fusobacterium*, *Bacteroides* • Slime forming bacteria: *Xanthomonas campestris*, *Brevibacterium viscogenes*, *Corynebacterium gumiform* • Microbial products as: biopolymers,	• Molasses 4-6 % • Molasses 5 % + Residue sugar 4 % + Crude oil 5 % • Xanthan 3 % in waterflooding	+	Xin Yuan Wang et al., 1991 Xiu Yuan Wang et al., 1995 Chung Ying Zhang et al., 1993

Country	Acronyms of MEOR Technology	Microbial systems	Nutrients	Incremental of oil production	References
		biosurfactants			
AUSTRALIA	BOS system	• Ultramicrobacteria with surface active properties	• Formulate suitable base media	+	Sheehy, 1991
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 CZECHO-SLOVAKIA	CMR, MFR, ASMR	• Hydrocarbon oxidizing bacteria (predominant *Pseudomonas* sp.) • Sulphate 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 carbohydrates sources • Suitable growth media (type E and G)	+_	Moses et al., 1993 Davey and Scott, 1995
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	+	Yarany, 1968 Diennes et al., 1973
NORWAY	MWPC	• Nitrate reducing bacteria naturally occurring in North Sea water	• Nitrate and 1 % carbohydrates addition to injected sea water	-	Paulsen, 1995
POLAND	MFR	• Mixed bacterial cultures (*Arthrobacter*, *Clostridium*, *Mycobacterium*, *Pseudomonas*, *Peptococcus*)	• Molasses 2 %	+	Karaskiewich, 1973
	CMF,	• Adapted Mixed Enrichment Cultures			Lazăr and

Country	Acronyms of MEOR Technology	Microbial systems	Nutrients	Incremental of oil production	References
ROMANIA	MFR	(predominant: *Clostridium*, *Bacillus*, *Pseudomonas* and other Gram-negative rods	• Molasses 2-4 %	+	Constantinescu, 1985 Lazăr et al., 1991
SOUTH ARABIA	CMF as well as other adequate MEOR technologies	• Adequate bacterial inoculum according to requirements of each technology	• Adequate nutrients for each technology	-	Sayyouh and Al Blehed, 1993
NETHERLAND	MSPR	• Slime forming bacteria (*Betacoccus dextranicus*)	• Sucrose - molasses 10 %	-	Heiningen et al., 1958
TRINIDAD-TOBAGO	CMF	• Fac. Anaerobic bacteria high producers of gases	• Molasses 2-4 %	-	Maharaj et al., 1993
VENEZUELA	MFR	• Adapted Mixed Enrichment Cultures	• Molasses	-	

Legend: + = yes;
+_ = not yet reported;
_ = not reported

Table 2 . MEOR processes and suitable type of microorganisms.

MEOR Process	Suitable Type of Microorganisms
• Well stimulation	• Generally surfactants, gases, acids and alcohol producers
• Wellbore clean up	- same -
• Water flooding	• Polymers and/or copious amount of biomass producers
• Permeability modification	• Emulsifiers, surfactants, acids and hydrocarbons degraders producers
• Polymer flooding	• Polymers producers
• Mitigation of coning	• Polymers and/or copious amount of biomass producers

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	1996	10	7
MEOR Sections at Biohydrometallurgical Technologies Meetings			
Islamabad, Pak.	1990	6	1
Jackson Hall, Wy	1993	6	2
Vina del Mar, Chile	1995	3	-
Big Sky, Mn	1996	3	-

period deal with finding a way to prevent or control the loss of injectivity.

Dispersion / Transport of All Necessary Components to the Target

It is well known that after all the components of an injected MEOR system are inside the reservoir, they must travel through the formation to reach the target site more or less at the same time. While such a phenomenon is not a problem for near well applications such as paraffin removal, for deep formation treatments could be, and rate of travel for nutrients, requires carefully timed injection sequences. Some papers and patents came with proposals for complex injection protocols (Stehmeier et al., 1990; Clark and Jenneman, 1992; Silver and Tsunting, 1992). For this reason, formations of less than 50-75 mD are not recommended for MEOR applications, except probably single dispersed cocci, spores, ultramicrobacteria and indigenous microorganisms (Knapp et al., 1990; Stehmeier et al., 1990), although field test results suggest much more facile transport of injected bacteria through the formation than laboratory studies (Hitzman, 1988).

Promotion of Desired Metabolic Activity in Situ

For promotion of desired metabolic activity in situ, several factors such as pH, temperature, salinity, pressure seem to be the main constrains in MEOR applications. Although limiting temperatures are required for bacterial metabolism before prohibitive pressures, it is suggested that development of thermophiles could significantly extend the limit temperatures (Premuzic and Lin, 1991). On the other hand it is known that injection of huge volumes of surface water can reduce temperatures of formation significantly, at least near injector wells. Salinity and pH proved to be less restricted.

Preclusion of Competition or Undesirable Secondary Activity

Preclusion of competition or undesirable secondary activity by indigenous bacteria, including sulphate - reducing bacteria (SRB). Secondary activity, mainly of the SRB in many cases seem to be more of a problem. The data of Jack et al. (1985) and Jenneman et al. (1986) demonstrated that nitrate at low level suppresses hydrogen sulphide production. This is the reason why the nitrate could be included in the nutrient support for field tests (Knapp et al., 1990). Also, the injection of sulphide tolerant *Thiobacillus denitrificans* strains were recommended as a means to control the net production of sulphide (Sublette et al., 1989), because in such case the presence of nitrate, sulphide is oxidized to sulphate.

The MEOR field trials carried out over the world during the last 40 years could be grouped in three "generations" namely: first up to 1970-1975 which due to the pioneering time, had often an empirical character, second between 1975-1990, which is less empirical since the scientific character is predominating and third after 1990, which has better coordination between microbiologists, geologists, reservoir engineers, owner operators and economists.

In countries such as USA, Canada, Great Britain, Romania, formers East Germany, Soviet Union, China and Australia in the period of MEOR field trials second "generation", a wide range of MEOR projects were carried out. Also International scientific meetings on MEOR in this period contributed substantially to the development of MEOR field trials, which generally became more ambitious and much better designed and documented. This fruitful activity of 1980s-1990s period, provided a context for developing new ideas and refined approaches in the field of MEOR.

Thus in the US the field tests run by the National Institute for Petroleum and Energy Research at the Mink Unit in the Delaware - Chivers in Nowata County, Oklahoma finalized with incremental oil production from a waterflood treated with a proprietary microbial system at a minimal cost (Bryant, 1990). Also hundreds of single well treatments aimed at control of paraffin deposition were undertaken commercially (Nelson and Launt, 1991; Brown, 1992). In this time MICRO-BAC International Inc., Austin, Texas, started a very fruitful activity connected to control of paraffin depositions and oily sludges in tank bottoms which after 1990 became of great interest due to the success both in the US and other countries (Schneider, 1993; MICRO-BAC Int. brochures, 1992-1994).

A very interesting new concept is concerning the use of *Thiobacillus denitrificans* to generate acids and dissolve formation carbonates through the oxidation of reduced sulphur species in the presence of nitrate (Sperl and Sperl, 1991). This concept will have an extension to the activity after 1990, and this can be noticed in Diagrams 2, 9, 24 of this paper.

In Russia, Belyaev and Ivanov (1990) and Ivanov et al. (1993) established successfully their method based on stimulation of indigenous microflora by introducing oxygen and some salts along with water injection. This methods avoids many application problems and costs.

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.

In Canada, Stehmeier et al. (1990) carried out a field test of a *Leuconostoc* - based on plugging system and also a new concept for selective plugging was reported by Cusak et al. (1992). This new concept is based on using ultramicrobacteria formed by selective starvation. Such kind of bacteria are very effective, because they offer the chance to treat tight formations to form deep plugs. In this case ultramicrobacteria being a dormant stage, field inocula would be easily shipped and handled and would have a long shelf-life.

Another new concept in selective plugging is based on the idea to use biomineralization to form calcite cements capable of sand consolidation and fracture closure in carbonate formations (Ferris et al., 1991). According to this concept the action of a urease producing bacteria species causes the hydrolysis of injected urea to shift the pH of a saturated calcium bicarbonate solution from neutral to 9 value.

In one of his papers Jack (1993) concluded that selective plugging strategies remain the most promising (and this is confirmed by data of Diagrams 2, 3, 4, 5, 17, 18, 24 of this review) in terms of significantly changing the economics of the oil production, because while stimulation cleaning treatments and enhanced waterflooding can improve economics and extend production life, flow diversion and control of coning problems have the potential to radically alter producible reserves in flowed reservoirs.

In Germany, Wagner (1991) and Wagner et al. (1993, 1995) reported the successful enhancement of oil production from a carbonate reservoir where *Clostridia* species as inoculum and molasses as the main nutrient support have been used. Wagner's experience was used for some MEOR applications in Tataryia oil fields in Russia in 1990 (Diagram 10).

In Romania, Lazar and Constantinescu (1985) and Lazar et al. (1991, 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 adapted mixed enrichment cultures and molasses were injected into reservoir after an improved protocol of injection (see diagrams in Lazar's papers 1991, 1993).

In Australia a new concept for oil enhanced production has been developed, according to the papers of Sheehy (1991, 1992). The concept is presented in Diagram 20 of this review and consists of using ultramicrobacteria generated from indigenous reservoir bacteria through nutrient manipulation. The outer cell layers of such ultramicrobacteria have surface active properties. This microbial system was successfully demonstrated to increase oil production in the Alton oil field in Queensland, Australia. The wettability of these cells resulted in oil release and formation of emulsions in the reservoir promoted by the cells themselves.

CONCLUSIONS

After 1990 - in so called the third "generation" of MEOR field trials the activity is running on the basis of conclusions that successful MEOR applications remain and should be focused on waterfloods where a continuous water phase enables us to introduce the technology or on single well stimulation where its low cost makes it a method of choice, as well as that selective plugging strategies remain the most promising and should be developed.

Most of the research teams very successfully involved in MEOR projects in the very active and fruitful period of 1980-1990s have a continuation after 1990 of their activity in improved and more sophisticated MEOR projects, mainly, as mentioned above, concerning single well stimulation-well bore area cleaning, microbial waterflooding recovery, and selective plugging of high permeability zones (see several of the Diagrams 2-25).

Because petroleum microbiology and recovery have much to offer in designing and performing bioremediation operations for industrial sites, some of the research before involved in MEOR projects, turned successfully to this field of hydrocarbons polluted environmental sites (oily sludges, soils, paraffin depositions, corrosion, souring, well bore plugging and chemical additives degradation). Thus, the use of biosurfactants to pipeline heavy oil as an oil in water emulsion, clean 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 spin off into other applications. So, microbially enhanced oil recovery has provided a challenging and stimulating field of study of a range of technologies and matters related to oil production and environmental biotechnology. Because all these aspects are not the subject of this presentation, in continuation we present in Diagrams 2 to 25 the most representative field trials, those results published after 1990. In Tables 1-4 and Annexes 1-8 there are outlined several aspects of MEOR method as it was developed during the last 40 years. All these make a very useful quick reference to the MEOR processes that have been used in the field.

As it is resulting from the Diagrams 1-25, a real future seems to have technologies as microbial selective plugging recovery, cyclic microbial recovery or single well stimulation (including skin damages removal) and activation of stratal microflora with its large varieties of applications. The last one being of great interest in today situation when waste product (such as molasses, corn syrup etc.) costs are in a large increase.

An interesting idea is that of Sperl et al. (1993) concerning that oil reservoir containing inorganic and organic materials which can be exploited through simple supplementation to support growth of microorganisms that can aid in releasing oil from the rock matrix. In this respect it is known that other compounds such as: sulphate, nitrate, carbonate, volatile fatty acids, nitrogen containing corrosion inhibitors, phosphorous containing scale inhibitors and trace elements, may serve as nutritional sources for microorganisms, and are added to reservoirs during production and operation of oil fields. Experiments demonstrated that with minimal supplementation, growth of naturally occurring microorganisms can be guided to produce viscosifying agents to aid oil recovery.

Also, it has been demonstrated that in the reservoirs with available nutrients the introduction of nitrate will produce effects as: heterotrophic denitrifying bacteria will rapidly become predominant and inhibit the growth of SRB, so no more new sulfide would be formed.

Table 4. Microbial products, their role in enhanced oil recovery and some of the effects to solve production problems.*

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 oil • Sweel oil in place	• Improved oil recovery by gases • Miscible CO_2 flooding
ACIDS (low mollecular weight acids, primarly low mollecular 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 which are typical cosurfactants)	• Dissolves in oil to reduce viscosity • Dissolves and remove heavy, long chain hydrocarbons from pore throat (increase effective permeability) • Involved in stabilizing and lowering interf. Tension, which promote 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 non selective plugging agents, in wetting, alteration of oil viscosity, oil power point, desulfuration	• Same biopolymers

Legend: * • 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

Diagram 1

MAIN COMPONENTS OF MEOR TECHNOLOGIES OUTLINED IN THE DIAGRAMS 2-25

RIGHT RESERVOIR
- Suitable characteristics of:
  - solid rock
  - aqueous phase
  - organic phase
  - gas phase

RIGHT MICROORGANISMS
- Suitable pure or mixt cultures for *IN SITU* or *EX SITU* activities
- Special naturally occurring selected bacteria, fac. Anaerobic, good producers of metabolites involved in residual oil recovery
- Activation of indigenous microbiota by several mechanisms

RIGHT NUTRIENTS
- Organic nutrients (i.e. molasses, corn siroup)
- Inorganic growth stimulants and biocatalysts (nitrogen, potassium, phosphorous sources and trace elements)
- In situ organic and inorganic materials, including hydrocarbons

RIGHT PROTOCOL TREATMENT OF WELLS
- Suitable to each MEOR technology as those mentioned in Annex 2

EFFECTS OR GENERATION OF
- Acids, gases, solvents, surfactants, polymers, biomass, etc. involved in residual oil recovery, control of skin damage etc.

Diagram 2

MICROBIAL FLOODING RECOVERY (MFR)

(Bryant et al., 1991, 1993 - USA)

RESERVOIR
- MINK UNIT of Delaware - Childers, field in Nowata County, OK
  - 15 producing wells
  - 4 from the 21 water injection wells treated with NIPER BAC-1
- MINK UNIT "Phoenix" Project
  - 47 producing wells
  - 19 injectors

BACTERIA
- NIPER BAC-1 represented by mixed cultures of:
  - a *Clostridium*
  - two *Bacillus*
  - a gram negative rod

fac. Anaerobes, good producers of acids, gases, surfactants

NUTRIENTS
- Molasses 2-4 %

- To each injection well: 26 gallons of NIPER BAC-1 and 20 gallons of undiluted molasses and finally diluted with injection water to 4 %
- Bacteria were injected only at one set of the project while nutrient daily for 2.5 years

RESULTS
- Increase of oil production by at least 13 % for MINK UNIT of Delaware and 11 % for Phoenix project in the first stage
- No problems with injectivity and corrosion
- Decrease water / oil ratios up to 35 %

Diagram 3

MICROBIAL SELECTIVE PLUGGING RECOVERY (MSPR)

(Coates, D.J. et al., 1993 - USA)

RESERVOIR
- Southeast Vassar Vertz Sand Unit, OK
- Problem: Areas with high permeability
- Purpose: Improve water flooding sweep efficiency
- Maximum recovery of oil from the swept portion of the field = 60 %

BACTERIA
- Reservoir indigenous nitrate utilizing bacteria

NUTRIENTS
- Molasses and ammonium nitrate

- Over a period of four months were injected:
  - 56.2 tons of molasses
  - 18.8 tons of ammonium nitrate

RESULTS
- Decrease of 50 % in the sulphide levels in the coproduced brine
- The quantity of nitrate injected with molasses wasn't sufficient
- Resulted a more homogenous distribution of permeability throughout the pilot area
- The alkalinity changes due to CO_2 production
- No significant additional of oil production due to the high recovery of oil (60 % of the original oil) in place

Diagram 4

MICROBIAL SELECTIVE PLUGGING RECOVERY (MSPR)

(Jenneman, E.G. et al., 1995 - USA)

RESERVOIR
- North Burbank Unit, Shidler, Osage County, OK with high permeability zones (up to 3000 mD), depth 3000 ft, t^0 45^{0}C, brine 10-20 total dissolved solids
- Pilot site considered of 4 producing wells surrounding a single injector

BACTERIA
- Stimulating of indigenous bacteria good producers of bioblocking agents (i.e. biopolymers, biomass)

NUTRIENTS
- Corn starch Polymers (maltodextrine) + Organic Phosphate Esters (OPE)

- Injection into reservoir to stimulate indigenous bacteria to generate cells and polymers

RESULTS
- Experiments on cores proved that corn starch dextrins or maltodextrins are suitables for stimulating the biosynthesis of exopolymers in environment such as oil field reservoir brines
- The field test is under progress, not published data available

Diagram 5

MICROBIAL SELECTIVE PLUGGING - RECOVERY (MSPR)

(Brawn, R.L. et al., 1995 - USA)

RESERVOIR
- Lamar County, Alabama
- Four field tests
  - Each including an injector with 4-5 producers
  - A comparable control injector with 4-5 producers

BACTERIA
- Stimulation of the brine
  - indigenous microflora with abilities of blocking the more permeable zones

NUTRIENTS
- Salt solution (grams):
  - $CaCl_2$ --- 10.90
  - $MgCl_2$ --- 2.71
  - $BaCl_2$ --- 4.56
  - $NaSO_4$ --- 1.84
  - $NaHCO_3$ --- 34.86
  - Na Cl --- 147.90
  - Injection water - 50 l
  - pH adjusted to 7.0 using 10 % (v/v) HCl
- In the core flood tests the above salts were added to 50 l of distilled water

- Depending upon the feeding regime nutrient addition to core plugs resulted in one or more of the following:
  - increased microbial population
  - decreased pH
  - reduction of the flow through the core due to microbial growth
  - increased flow through the core due to acid production
  - increased permeability, porosity and gas production
  - increased oil recovery

RESULTS
- Field trials started in Nov. 1994
- It is expected a restriction of the wider microchannals of the formation and an increase of sweep efficiency of the water flooding operation

Diagram 6

MICROBIAL SELECTIVE PLUGGING RECOVERY (MSPR)

(Stepp, K.A. et al., 1995 - USA)

RESERVOIR
- Reservoirs with high permeability zones

BACTERIA
- *Leuconostoc mesenteroides*
- *Bacillus licheniformis*

NUTRIENTS
- Sucrose --- 10 %
  Peptone --- 1 %
  NaCl --- 0.5 to 30 %

- Experiments on core flooding and flask, to evaluate the effectiveness of this system for:
  - improved sweep efficiency
  - permeability modification
  - reservoir conformance

  function of: temperature, salinity and pH

RESULTS
- This system can cause blockage of high permeability zones and fluid diversion
- Probably field test under progress

Diagram 7

MICROBIAL PARAFFIN REMOVAL (MPR)

(Pelger, W.J., 1991 - USA)

RESERVOIR
- Wells with skin damage problems (paraffin, emulsion, scale, corrosion); depth 500 to 13,500 ft

BACTERIA
- Commercially microbes products (MICRO-BAC INTERN. Inc. products) containing naturally occurring selected bacteria, non-pathogenic, non-toxic, not genetically altered, environmentally safe, with ability to selectivelly degrade saturated paraffins

NUTRIENTS
- Biodegradable paraffinic fractions of the treated situs
- Fertilizers as nitrogen and phosphorous sources

- Bio Tech Inc. has treated over 400 wells in six U.S. States

RESULTS
- More than 51 % of the treated wells have had significant increases in oil production

Diagram 8

MICROBIAL PARAFFIN REMOVAL (MPR)

(Nelson, L. and Schneider, R.D., 1993; Scientific and commercial broshures of MICRO-BAC INTERN. Inc. Austin, Tx. 1992-1994 - USA)

RESERVOIR
- Individual producing wells with skin damage problems (mainly paraffin) in the major producing formations of North America
- Water injection wells, flow lines, tanks

BACTERIA
- Naturally occurring selective isolated bacteria (CONSORTIA)
  - heterotroph fac. Anaerobic
  - non-pathogenic and not genetically altered
  - contain no sulphate-reducing or slime forming bacteria
  - environmentally safe
- Obtained by appropiate strategies to detect and recover the microorganisms with the desired features from nature, including polluted sites

NUTRIENTS
- Organic pollutants of the treated situs
- Fertilizers (nitrogen and phosphorous sources)
- Several substances of microbial metabolism that have chelating, antiprecipitation, filming activities (control of scale and corrosion)

Adequate protocol treatment, depending of the situs damage problems (paraffin, emulsion, scale, corrosion)

RESULTS
- From hundreds of case studies, exciting results, (i.e. Microbial Removal Paraffins treatments reported increase of oil production between 10 and 1700 % for 1-4 years due to:
  - decreased viscosity
  - reduced pour point
  - elevation in API gravity and in transport fluid fractions, etc.)

Diagram 9

MICROBIAL PARAFFIN REMOVAL (MPR)

(Giangiacomo, L. and Khatib, A., 1995 - USA)

RESERVOIR
- 4 wells with severe paraffin problems at Naval Petroleum Reserve No.3, Wyoming were selected to be treated

BACTERIA
- Commercial available microbial products containing naturally occurring selected bacteria non-pathogenic, non-toxic, non genetical manipulated, environmentally safe

NUTRIENTS
- Brine supplemented with mineral sources of nitrogen and phosphorous
- Biodegradable paraffin fractions of the treated situs

- Wells prepared by perforating a 10 bbl (1.6 m^3) treatment with 5 % HCl to clean any scale from the pump and tubulars. After 7 days each well treated with an initial 16 m^3 of bacteria and nutrients
- Shut in the well for 3 days, then return to production
- Additional hot oiling is required to aid the clean up process
- Monthly, 0.8 m^3 of bacteria and nutrients followed for the next 10-12 months

RESULTS
- Three wells have a positive incremental cash flow with additional oil

Diagram 10

MICROBIAL CONTROL OF SOURING AND WELLBORE CLOGGING (MCSC)

(Sperl, T.G. et al., 1993 - USA)

RESERVOIR
- Oil reservoirs naturally contain inorganic and organic material

BACTERIA
- Stimulation of naturally occurring nitrifying bacteria (*Thiobacillus denitrificans*)

NUTRIENTS
- To reservoirs naturally contain inorganic and organic materials, **supplementation** with nitrate and some mineral nutrients

- **Mechanism** - In souring carbonate containing reservoirs, a mutually microbial population is developed; heterotrophic nitrifying bacteria will become predominant and inhibit the growth of SRB
  - When *T. denitrificans* became established, formation of highly viscous solutions took place

RESULTS
- Positive results for MEOR processes
- Biological control of SRB growth
- Avoid wellbore clogging by microorganisms

Diagram 11

MICROBIAL FLOODING RECOVERY (MFR)

(Nazina, N.T. et al., 1994; Wagner, M. et al., 1995 - RUSSIA)

REZERVOIR
- Romashkinskoe oil field - Tatariya
  - depth = 493-575 m, t^0 = 17-32 ^{0}C, pressure = 5.4 Mpa, average porosity = 9.8%, water content = 68%, containing sulphates and H_2S (100-300 mg/l), paraffinic heavy oil reach in S^0.
  - In pilot area 5 injector wells and 23 producer wells.

BACTERIA
- ***Clostridium tyrobutyricum*** Isolated from indigenous brine microflora, good producers of organic acids, alcohols and gases (CO_2, H_2), surface active compounds, polymers
- **Field fermentors**:
  - 2.5 m^3 with 900 l of 6 % molasses sol. 0.3 % NH_4Cl, 0.4 % polyphosphate, pH = 11

NUTRIENTS
- Molasses 6% + Nitrogen and phosphorus salts

- Daily volume of injection: 100 to 500 m^3. Ratio of 1 : 10 to 1 : 50 inoculum-molasses solution.
- During 1992 (Nov.) - 1994 there were injected more than 18,000 m^3 of molasses solution and bacteria

RESULTS
- Decrease of oil density and viscosity
- Increased content of dissolved carbonates and calcium in the brine
- Increase of well production rate between 50-65 %
- Decrease of water cut from 80% to 60%
- Depress the growth of SR Bacteria

Diagram 12

ACTIVATION OF STRATAL MICROFLORA RECOVERY (ASMR)

(Belyaev, S.S. et al., 1991; Ivanov, V.M. et al., 1993 - RUSSIA)

RESERVOIR
- Bonduzhskoye oil field - Tatariya (Tertiary recovery stage)
- Romasckino oil field - Tatariya (Tertiary recovery stage) with temperature = 30 - 40 ^{0}C, permeability 500 mD, porosity 21.7 %, depth = 1500-1700 m

BACTERIA
- Reservoir and water injection indigenous microflora

NUTRIENTS
- Injection water with addition of:
  - nitrogen and phosphorous sources
  - air

- After the injection into reservoir two stages are developing, namely:
  First - by activation of microbial activity in the well bore area, the hydrocarbon-oxidising bacteria (10^4 - 10^5 cells/ml) are generating CO_2, fatty acids, aliphatic alcohols and biosurfactants.
  Second - stopping air addition lead deep into formation the activation of metanogens that generate supplementary amounts of CH_4 and CO_2.

RESULTS
- **Bonduzhskoye oil field**
  - oil production increased 20-100 %
  - water content decreased 20-30 %
  - during 5 years, 47,000 tons of supplementary oil production
- **Romasckino oil field**
  - oil production increased 32,9 %

Remarks: Between 1982-1990 this technology applied with positive results at 7 oil field area of Russian Federation.

Diagram 13

ACTIVATION OF STRATAL MICROFLORA RECOVERY (ASMR)

(Svarovskaya, I.L. et al., 1995 - RUSSIA)

RESERVOIR
- West Siberia oil fields with temperature of 45-95^0 and brine with rich microflora (2 x 10^7 cells/ml)

BACTERIA
- Stimulation of indigenous microflora represented by: *Pseudomonas*, *Bacillus*, *Actinomyces*, *Micrococcus*, *Mycobacterium*, *Sarcina*, *Mycococcus*, *Pseudobacterium*, *Thermodesulfobacterium*, etc.

NUTRIENTS
- To injection water addition of:
  - nitrogen and phosphorous sources
  - air

- Field applications based on the idea of increasing oil production by stimulating indigenous microflora in two stages:
  - **first** corresponds to oil displacement by injection of water with addition of mineral salts and air
  - **second** correspond to stimulated indigenous methanogenic microflora by stopping air addition
- By now probably field trials under progress

Diagram 14

MICROBIAL NUTRITIONAL FLOODING RECOVERY (MNFR)

(Murygina, A.A. et al., 1995 - RUSSIA)

RESERVOIR
- Vyngapour West Siberia oil field

BACTERIA

a) Indigenous occurring microflora of brine and food industry wastes

b) Industrial inoculum of lactobacteria (3 l / 100 m^3 of nutrient solution)

NUTRIENTS

a) Local industry wastes +
- Nitrogen and phosphorous salts 0.5-1.5 and 1.0-1.5 g l^{-1} respectively
- KCl - 0.001 %
- $(NH_4)_2HPO_4$ - 0.4 %

b) Dry milk 0.04 % instead of wastes

- During 1993 and 1994 summers there have been injected 722 m^3 of nutrient solution

RESULTS
- After 8 weeks to 7 months positive response
- By July 1994, supplementary 2,267 tons of oil were produced
- Coproduced water reduced by 33,902 m^3 as compared to base variant

Diagram 15

CYCLIC MICROBIAL RECOVERY (Single well stimulation) (CMR)

(Chun Ying Zhang and Jing Chun Zhang, 1993 - CHINA)

RESERVOIR
- Daquing oil field, China
- Two wells submited to MEOR treatment after huff and puff system

BACTERIA
- *Pseudomonas aeruginosa*
- *Bacillus licheniformis*
- Strain 5 GA, like *Bacteroides*

NUTRIENTS
- Molasses . . . . 5 %
- Residual sugar . . . 4 %
- Crude oil . . . . 5 %

- Injection in two wells: No.1 and No.2
- Shut in the well for 40 days (No.1) and for 64 days (No.2)

RESULTS

Well No. 1
- water cut decreased by 5 %
- oil production increased from 3-5 t/d to 5.5 t/d with a incremental of oil production of 480t for 8 months.

Well No. 2
- oil production increased from 7.6 t/d to 10-11 t/d with a incremental of oil production of 988 t for 18 months.

Diagram 16

CYCLIC MICROBIAL RECOVERY (Single well stimulation) (CMR)

(Xiu-Yuan Wang et al, 1995 - CHINA)

RESERVOIR
- Jilin oil field, Fuyn oil area, China
- 44 wells in pilot area subjected to Bio huff 'n' puff system

BACTERIA
- An enriched culture of 48 h, containing at least 4 species of *Eubacterium*, *Fusobacterium* and *Bacteroides*, adapted to reservoir conditions and anaerobically fermenting molasses with gases and acids production

NUTRIENTS
- Molasses . . . . 4-6 % (v/v)

- 44 wells have been injected at Fuyu oil area of Jilin oil field (1992)
- Shut in the wells for 15-21 days

RESULTS
- From the 44 wells treated, only 2 wells showed no response
- Water cut decreased from 78.5 % to 65.8 %
- Oil viscosity dropped by 5-14 cP
- Average oil production increased from 0.64 to 5.35 t/well/day up to the end of 1994 - for 250 days the incremental oil from 42 wells, was 9,943 tons (226 t/well/day average)
- Carbonate content of the oil bearing formation has an important role
- Increase of molasses content in fluid injected is favorable

Diagram 17

MICROBIAL SELECTIVE PLUGGING RECOVERY (MSPR)

(Xin-Yuan Wang, 1991 - CHINA)

RESERVOIR
- Yumen oil field, China

MICROBIAL SYSTEM

A.
- A thermally generated agent produced by *Ps. Aeruginosa* YA-144 as plugging agent
- Xanthan solution as an adjusting agent of the injection profile

B.
- Biopolymer production from hydrocarbons by:
  - *Brevibacterium viscogenes*
  - *Corynebacterium gumiform*
  - *Xanthomonas campestris*

- **Field trials** with cross-linked Xanthan L4 gel, as agent for improving the injection profile
- Xanthan contents 3 % in waterflood
- Total injection volume: 400 m^3

RESULTS
candidates for field trials in the North Sea as plugging
- Watercut decreased 1200 m^3
- Supplementary oil production: 845 tons for 4 months

Diagram 18

MICROBIAL SELECTIVE PLUGGING RECOVERY (MSPR)

(Davey, A.R. and Scott, L.H., 1995 - GREAT BRITAIN)

RESERVOIR
- North Sea oil reservoir with high temperature, salinity, pressure and absence of oxigen

BACTERIA
- Special starved bacteria selected from naturally occurring microflora of North Sea brine, good producers of exo-polymers and growing and surviving in the presence of saline formation waters at temperatures above 50 ^{0}C in fac. Anaerobic conditions

NUTRIENTS
- Suitable growth media (type E and G)

RESULTS
- Experiments on sandpacks and cores proved:
  - Two bacterial isolated selected, showed suitable starvation /revival/ plugging characteristics
  - Reduction of permeability of 88 %
  - Bacteria can survive nutrient starvation, which improve penetration through rock till new nutrients are added
  - The two starved bacteria selected show potential agents for flow diversion
- Field trials are under progress

Diagram 19

MICROBIAL HYDRAULIC ACID FRACTURING (MHAF)

(Moses, V. et al., 1993 - ENGLAND)

RESERVOIR
- Carbonate reservoir in Southern England
- Purpose: to get a significant dissolution of carbonate matrix and improve permeability for good drenage into wellbores

BACTERIA
- Naturally occurring anaerobic strain capable of generating organic acids from suitable carbohydrates sources

NUTRIENTS
- Suitable carbohydrates sources or other feedstock which by anaerobic conversion generate organic acids

Injection of 1,350 bbl of stimulation fluid containing water-nutrients-bacteria mixed with 250 bbl of fresh water

Shut in the well for 7 days, then for 30 days extensive monitoring program

RESULTS
- An ability to dissolve rock at a considerable greater distance from the wellbore than mineral acids can do
- No corrosive or hazardous effects of the components of the injection fluid
- Reduced costs of equipment and personnel

Diagram 20

BIOLOGICAL STIMULATION OF OIL RECOVERY (BOS SYSTEM)

(Sheehy, J.A., 1991 - AUSTRALIA)

RESERVOIR
- Alton oil field in Queensland, Australia
- High pressure and other extreme conditions as: the redox potential, pH, salinity, temperature, nutrient availability

BACTERIA
- Ultramicrobacteria generated from indigenous reservoir bacteria through nutrient manipulation
- The outer cell layers of such ultramicrobacteria with surface active properties

NUTRIENTS
- Formulate suitable base media

- Generation in situ of ultramicrocells with surface active abilities after the suitable base media formulate was injected into reservoir

RESULTS
- Increase in oil production mentained for 16 months after the BOS system was injected
- Increase oil output by 70 %
- An estimation that MEOR technology could unlock as much as 300 billion barrels of Australian oil left in place after conventional EOR technologies

Diagram 21

ACTIVATION OF STRATAL MICROFLORA RECOVERY (ASMR)

(Groudev, I.V. et al., 1993 - BULGARIA)

RESERVOIR
- Rock - claysh dolomitized limestone
- 2 wells with skin damage problems
  - No.1 - indigenous stimulating microflora
  - No.2 - Molasses injection

BACTERIA
- Stimulation of oil-oxidizing bacteria naturally occurring in the reservoir

NUTRIENTS
- Water containing air + ammonium and phosphate ions
- Molasses

- **Well No.1** = 60 m^3 of brine + NH_4NO_3 0.5 g/l + $(NH_4)_3PO_4$ 0.5 g/l + 120 m^3 air
  - Two stage process
- **Well No.2** = 200 m^3 of brine + Molasses 20 g/l + NH_4NO_3 0.5 g/l + $(NH_4)_3PO_4$ 0.5 g/l

Shut in the wells for about 12 weeks

RESULTS

Well No.1 = Increased oil production eight times for 30 days, decrease water cut

Well No.2 = Increased oil production three times for about 30 days, decrease water cut

Diagram 22

CYCLIC MICROBIAL RECOVERY (CMR)

(Lazăr et al., 1993; *tefănescu, M., 1996 - ROMANIA)

RESERVOIR
- Wells needed to be clean up in wellbore area, located in calcarous sandstone or calcarous marl with intercalations of sand, content in $CaCO_3$ at least 10-20%
- Subjected to MEOR treatment
  - 4 production wells
  - 2 water injection wells

BACTERIA
- Adapted Mixed Enrichment Cultures (AMEC) selected from the naturally occurring bacteria of brine and scum good producers of gases, acids, solvents and biosurfactants

NUTRIENTS
* Brine with 2-4% molasses

- Injection into the well 30 m^3/m of pay zone; rate of injection 150 l/min

- Shut in the well for 15-21 days

RESULTS
- At the water injection wells a decrease of pressure injection water from 5-6 to 2.5 Mpa for nearly two years
- At the production wells an increase of oil production with 200-500% up to 10-24 weeks

Diagram 23

CYCLIC MICROBIAL RECOVERY (Single well stimulation) (CMR)

(Maharaj, U. et al. 1993 - TRINIDAD and TOBAGO)

RESERVOIR
- 10 % (about 130 stripper wells) of the total wells of Trinidad and Tobago oil fields, considered suitable for single well stimulation

BACTERIA
Fac. Anaerobic bacteria, high producing gases

NUTRIENTS
Molasses

MEOR Applications probably under progress

Diagram 24

MICROBIAL WATER PROFILE CONTROL (MWPC)

(Paulsen, E.J., 1995 - NORWAY)

RESERVOIR
- Low temperature sandstone reservoirs in the North Sea

BACTERIA
- Nitrate reducing bacteria, naturally occurring in North Sea water at 50-70 m depth

NUTRIENTS
- Nitrate and 1 % carbohydrates addition to injected sea water

- Experiments on sandpacks, core models and pore micromodels for the fundamentation of the technology for reservoirs with temperature less than 40°C

RESULTS
- Nitrate reducing bacteria mixed population proved to produce extracellular material
- Sulphidogenic conditions seem to be discouraged, when NO_3^- or other oxyanions of nitrogen are utilized as electron receptors
- Temperature seem to be an important factor
- Field tests probably under progress

Diagram 25

CONCERNING POTENTIAL ARAB OIL FIELDS FOR MEOR

(Sayyouh, H.M. and Al Blehed , S.M., 1993 - SAUDI ARABIA)

PROSPECTING STUDY

- Residual oil in place = 700 billion barrels from which only 250 billion barrels (35 %) can be produced by conventional EOR methods. So, for MEOR method good opportunity.
- There were investigated by a laborious study based on data from 300 formations in Saudi Arabia, Egypt, Kuweit, Qatar, United Arab Emirates, Iraq and Syria.
- It is concluded that the Saudi Arabia, Qatar, Kuweit and Syria have some potential for MEOR technologies

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Annex 1

SOME ADVANTAGES OF MEOR TECHNOLOGIES

1. The injected bacteria and nutrients are inexpensive and easy to obtain and handle in the field.
2. Economically atractive for marginally producing oil fields; a suitable alternative before the abandonment of marginal wells.
3. According to a statistical evaluation (1995 in US), 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 is not dependent of 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.

Annex 2

ACRONYMS FOR MICROBIAL ENHANCED OIL RECOVERY METHOD

- MEOR = Microbial Enhanced Oil Recovery
- MORE = Microbial Oil Recovery Enhancement
- MIOR = Microbial Increased Oil Recovery
- MEHR = Microbial Enhanced Hydrocarbon Recovery

Annex 3

ACRONYMS FOR MEOR TECHNOLOGIES

1. CMR (SWS) = Cyclic Microbial Recovery (Single Well Stimulation)
2. MFR = Microbial Flooding Recovery
3. MSPR = Microbial Selective Plugging Recovery
4. ASMR = Activation of Stratal Microflora Recovery
5. MSDR = Microbial Skin Damages Removal
6. MPR = Microbial Paraffin Removal
7. MNFR = Microbial Nutritional Flooding Recovery
8. BOS System = Biological Stimulation of Oil Recovery
9. MWPC = Microbial Water Profile Control
10. MCSC = Microbial Control Souring and Clogging
11. MHAF = Microbial Hydraulic Acid Fracturing
12. MFFR = Microbial Fracturing Fluids Recovery

Annex 4

WHY ARE BACTERIA SUITABLE FOR MEOR APPLICATIONS

- They are small
- They grow exponentially
- They produce metabolic compounds involved in residual oil recovery (gases, acids, solvents, biosurfactants, biopolymers, biomass)
- They tolerate harsh environments, high formation water salinity, high pressure and temperature etc.

Annex 5

(Bryant et al., 1991)

KEY MECHANISMS FOR ENHANCED OIL RECOVERY IN MEOR

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

Annex 6

SOURCES FOR THE RIGHT BACTERIA NEEDED IN MEOR APPLICATIONS

- Natural - several ecological sites
- Defined - Culture Collections, such as ATCC
- Genetically engineered

Practically it has been used - natural source only

Screening for metabolic products as:

1 - Acids
2 - Gases
3 - Solvents
4 - Surfactants
5 - Polymers
6 - Sulphate reduction
7 - Residual oil release
8 - Oil degradation
9 - Toxicity or pathogenicity

— by calitative or cantitative tests specific to each left component (Lazăr, 1996)

Annex 7

NEEDS FOR IMPROVING THE MICROBIAL SCREENING AND SELECTION FOR MEOR APPLICATION

1. Simple, rapid analytical procedures for screening and monitoring microbial activity both for batch screening and field monitoring
2. Development of well-deffined modeling systems (radial flow model for evaluating the capability of bacteria with reservoir environment)
3. To define the effects of micronutrients on bacterial metabolism
4. Standard methods for metabolite assay and monitoring of microbial activity
5. To develop an adequate methodology for toxicity and pathogenicity testing
6. Cooperative research on genetically engineered microorganisms for MEOR while regulatory affairs will likely dictate the use of such microorganisms in the environment, MEOR specialists should be familiarised with potential applications
7. A glossary of terminology to allow to several field specialists to communicate

Annex 8

SOME OF THE THINGS CLEARLY PROVED BY MEOR FIELD TESTS

- Microorganisms can grow and migrate under normal reservoir conditions
- Microbial growth and their products involved in enhanced oil recovery respond to: nutrient availability, type of bacteria, reservoir conditions and protocol of well injection
- Each reservoir requires adequate design, elaborated by the participation of microbiologists, geologists, reservoir engineers and operators. Ecellent results when the projects were correctly designed and engineered.
- Reservoir characteristics such as: permeability, porosity, fractures, water quality and microbial system seem to be governing factors in MEOR applications.