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Using Bacteria to Improve Oil Recovery from Arabian Fields

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Abstract

Large quantities of residual oil remain in Arab oil reservoirs after the primary recovery and waterflooding stages. Because of the large area of the Saudi oil fields, the amount of residual oil is enormous. According to the latest publications, the original oil in place in Saudi Arabia is about 700 billion barrels. Only around 250 billion barrels, 35% of the total oil in place, can be produced by conventional methods. More than 90 billion barrels, as much as twice the proven reserve of the United States and Canada combined, could be added to Saudi Arabia's proven reserve if only 20% out of the 450 billion barrels left in place was produced through methods for enhanced oil recovery. Any method that can recover a significant part of this residual oil would be of great importance and should be investigated. Microbial Enhanced Oil Recovery (MEOR) has been recognized as a potentially cost-effective method of recovery.

This paper investigates the applicability of MEOR for recovering more of the oil under the Arab oil fields. Based on the analysis of data from more than 300 formations in seven Arab countries (Saudi Arabia, Egypt, Kuwait, Qatar, United Arab Emirates, Iraq, and Syria), we studied the possibility of applying MEOR to the Arabian area. The basic parameters studied include the permeability of the formation, reservoir pressure and temperature, crude oil viscosity and API gravity, and connate-water saturation in the formation and its salinity. We found that the Saudi, Iraqi, and Egyptian oil fields are very good candidates for MEOR processes; Qatar, Kuwait, and Syria have some potential for MEOR. However, because of the conditions of its reservoirs, the oil fields of the United Arab Emirates have no potential for MEOR.

MEOR is expected to recover up to 30% of the residual oil under present conditions in the Arab reservoirs. However, the actual recovery can only be determined through laboratory and pilot tests under field conditions. A new technology should be developed so that MEOR can be applied successfully.

1. INTRODUCTION

Bacteria are the only microorganisms that have been proposed for use in enhanced oil-recovery processes. They are small, grow exponentially, and they produce metabolic compounds, such as gases, acids, surfactants, and polymers. Bacteria can tolerate harsh environments, such as high formation-water salinity, high pressure, and high temperature. In 1983, Bubela [1] found that the optimum metabolic temperature and rate of growth of rod-shaped bacteria increased with an increase in pressure. Moses and Springham [2] observed that bacteria are catalytically active at high pressure. Grula et al. [3] readily grew *Clostridium* sp. in salt concentrations up to 75000 ppm.

The earliest realization that bacteria are beneficial to the production of oil was made by Backman in 1926 [4]. ZoBell in 1946 presented a process for secondary oil recovery, using anaerobic, sulfate-reducing bacteria *in situ* [5]. Earlier, this investigator had used other types of bacteria to enhance oil recovery in laboratory tests [6].

In 1963, Kuznetsov et al. found that bacteria discovered in some oil reservoirs in the Soviet Union produced 2 gm of CO_2 per day per ton of rock [7]. Later, Synyukov et al. [8] employed microorganisms to aid in the recovery of oil.

Laboratory studies have been made with specific microorganisms either for the surface production of various compounds, or by injecting the cells into a reservoir for *in situ* metabolic production. Both methods enhance oil recovery. Grula et al. isolated salt-tolerant strains of some types of bacteria in the laboratory and then conducted field tests with them [9]. Donaldson and Grula [10] found that some species of bacteria produce emulsifiers in salt concentrations up to 75,000 ppm. Laboratory results by Torbati et al. [11] showed that the larger pores of Berea sandstone are plugged by bacteria, which reduced its permeability, thus increasing oil recovery by improving the mobility ratio. Other laboratory researches conducted by Bryant and Douglas [12] demonstrated the mechanisms of crude oil displacement by microorganisms.

Bryant et al. [13] reviewed many field applications of MEOR. Bryant [14] found that MEOR screening criteria fit 27% of U.S. oil reservoirs. Recently, MEOR field applications were presented in the proceedings of an international conference on MEOR edited by Donaldson [15]. Hitzman [16] also recently reviewed MEOR field testing.

2. MECHANISMS

Many species of microorganisms produce carbon dioxide and other gases, such as nitrogen (N_2), hydrogen (H_2), and methane (CH_4) that could improve oil recovery by increasing pressure and by reducing the viscosity of crude oil that improves the mobility ratio.

Because many types of microorganisms produce polymers, they have been used to plug high-permeability zones in petroleum-saturated sandstones to improve sweep efficiency and displace bypassed oil. However, these microorganisms also have been shown to reduce the permeability of rock [13,14,17-19]. Work in the Netherlands [20] involving selective plugging experiments with *Betacoccus dextranicus* reported a significant increase in oil production.

Recently, research in China generated novel microorganisms that produce polymers [21] and researchers at the University of Calgary, Canada have reported a methodology for using ultra microbacteria to selectively plug a subterranean formation [22].

The evaporation of volatile hydrocarbons and the destruction of paraffinic compounds by microorganisms generates large amounts of polynuclear aromatic compounds that degrade asphaltic material [23].

Microbes also produce low molecular-weight acids, primarily low molecular-weight fatty acids, that can improve permeability of limestone and sandstone rocks with carbonaceous cementation, and thus, improve oil recovery.

A potentially useful group of microorganisms produce alcohols and ketones. These compounds are typical co-surfactants that are used in microemulsion solutions for stabilizing and lowering interfacial tensions which promote emulsification.

Microorganisms produce bio-surfactants that can decrease surface and oil-water interfacial tensions as low as 5 x 10^{-3} dyne/cm which causes emulsification [24]. Several types of microorganisms that produce bio-surfactants have been identified and isolated [25-28].

Microbes have been shown to alter the wettability of glass micro-models in Berea sandstone [12]. In 1986, Kianipay et al. [29] found that *in-situ* microbial growth mobilized residual oil by reversing wettability. Table 1 summarizes the different mechanisms of microbial-enhanced recovery.

2.1. Miscibility in oil reservoirs due to the production of natural gases and surfactants by bacteria

To mobilize the residual oil droplets, miscibility or a high pressure gradient is required. It is recognized that the efficiency of a given process to recover this amount of residual oil depends upon capillary and interfacial forces. The miscible process consists of displacing oil by injecting microorganisms that produce a solvent which is completely soluble in oil.

2.1.1. Natural gas

Figure 1 shows a phase diagram of a solvent/hydrocarbon system, assuming that the solvent (produced gas) consists entirely of the light component (G) [30]. Point O represents the composition of the crude oil, which must be rich in intermediate components. The displacement process is not first-contact miscible because the dilution path, OC_1, passes through the two-phase region.

The crude oil (O) and the gas produced (G) are not in thermodynamic equilibrium. Phase exchange takes place, and, as a result, generates the overall composition, M_1. The mixture splits into two phases, a gas G_1, and a liquid L_1, determined by the tie lines. The gas G_1 has a much higher mobility than L_1 and comes into contact with the newly formed residual oil of composition O. Phase exchange takes place to form mixture M_2, which splits into gas G_2 and liquid L_2; G_2 flows to form mixture M_3, and so the process goes on.

This process continues until the composition of the gas in contact with the oil becomes G_t (i.e., the gas phase will no longer form two phases on mixing with the crude). At this stage, the process has developed miscibility. The formation of the miscible bank is schematically shown in Figure 2; it is extremely stable. The design of a miscible process by injecting bacteria needs extensive laboratory studies and pilot tests. The parameters involved in the design encounter both the physical properties of crude oil viscosity and the characteristics of the reservoir, such as depth, temperature, pressure, and permeability.

2.1.2. Carbon dioxide

There is increasing interest in using carbon dioxide (CO_2) to displace oil from porous media. When carbon dioxide is produced from microorganisms injected into a reservoir, the gas dissolves in the crude oil and water under reservoir conditions and reduces the oil's viscosity, causing it to swell. In miscible carbon-dioxide flooding, liquid CO_2 mixes with oil, and through a mechanism of multicontact-phase equilibrium, eventually achieves miscibility, which increases the efficiency of recovery. Miscibility conditions are required to mobilize the trapped oil droplets.

Another principal effect of carbon dioxide is the action of carbonic acid, formed in solution with water [31]:

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

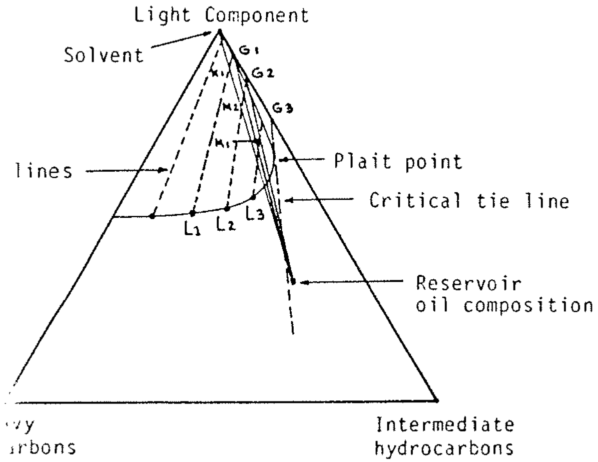
Its effect on calcareous rocks is to increase injectivity by partially dissolving the rock according to the following equations [31]:

$$H_2CO_3 + CaCO_3 \leftrightarrow Ca(HCO_3)_2$$

$$H_2CO_3 + MgCO_3 \leftrightarrow Mg(HCO_3)_2$$

Ta
Me isms of enhanced oil recovery

rocess	Type of microorganism used and displacement mechanism
E d waterflooding	Microorganisms that produce low molecular-weight acids (improve formation permeability)
Im d oil recovery by gases	Microorganisms that produce gases such as CO_2, N_2, H_2, and CH_4 (improve mobility and miscibility)
Mi l permeability m ation	Microorganisms that produce polymer and/or copious amounts of biomass (improve sweep efficiency)
Mi l polymer flooding	Microorganisms that produce polymers (improve mobility)
Mi l surfactant flooding	Microorganisms that produce surfactants and alcohols (improve miscibility and reduce capillary forces)



Fi 1. Schematic of the vaporizing gas drive process [30].

These biocarbonates formed are soluble in water, and so may increase the absolute permeability of the carbonate rock. Bubela [32] found that the porosity and permeability of calcite were increased by the presence of bacteria from 17% to 45% and from 2 darcy to 47 darcy, respectively, while those of the dolomite were increased from 24% to 27% and from 2 darcy to 14 darcy, respectively. These increases are due to the biological production of fatty acids and CO_2. Cementation resulting from the diagenesis of carbonates, due to an alteration of the CO_2 level in the interstitial fluids, decreased the permeability of the simulated sediments quite considerably.

The residual oil saturation obtained by producing CO_2 from bacteria is lower than that obtained by producing natural gases, which will improve the oil recovery factor.

2.1.3. Surfactants

Information on the phase equilibrium of the surfactant-oil-water systems is needed to formulate systems that exhibit small, two-phase regions. At low concentrations of surfactants, the contribution of phase equilibrium to oil recovery comes from the changes in phase volumes. Changes in the system's conditions, such as salinity, temperature, and the molecular weight of surfactant, tend to alter the phase behavior of these systems [33].

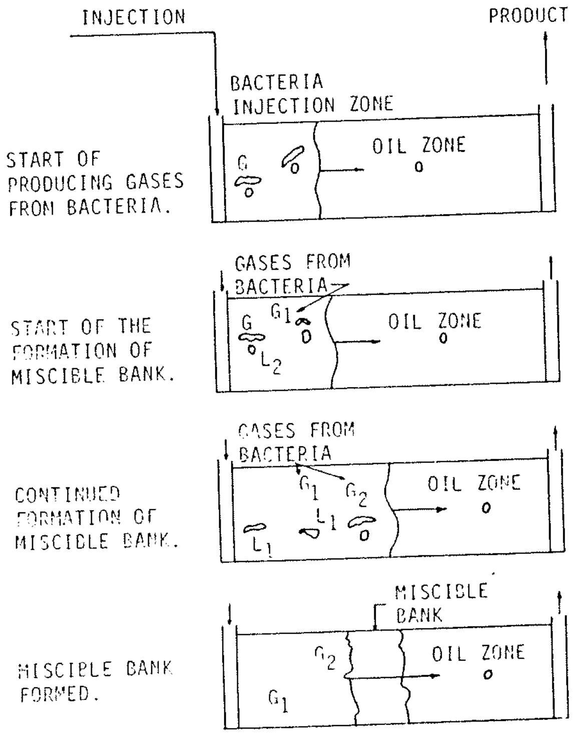
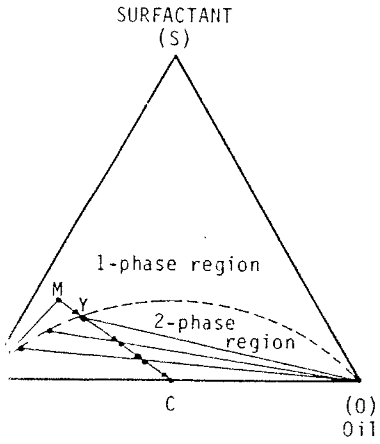


Figure 2. Formation of miscible bank by gases from bacteria.

hase-diagram studies, under reservoir conditions, provide a powerful way to p ict the formation of different phases in the reservoir as a function of c sition. Figure 3 is a ternary diagram of a surfactant-crude-brine system. T inodal curve (dashed line) divides the diagram into a single-phase region a and a multiphase region below. Surfactant concentrations in excess of 15 p t are of no interest to tertiary oil recovery for economical c erations. Therefore, the composition of the injection for practical s tant flooding is bounded from below by the binodal line, and from above by e c restrictions on the concentration of the slug. Based on the phase d ms, some investigators [34] defined the displacement process by surfactant a cally miscible displacement (along MY and MW in the phase diagram). If it i locally miscible, it is an immiscible displacement (along YC). In other w miscibility is a property of pairs of compositional points. Decomposition o surfactant slug always implies associated changes in sulfonate c tration, viscosity, and interfacial properties. This behavior can be p ted using ternary diagrams.

2. Economics of MEOR

he end of 1990, the world had 1015 billion barrels of proven reserves of c il. This amount is available through conventional production technology. T maining oil in place, however, can reach up to three times as much, so, t least 3000 billion barrels of oil are targeted for enhanced oil recovery t logy. In Saudi Arabia alone, there will be more than 500 billion barrels left in place after depleting its proved reserves by conventional recovery (ing to 260 billion at the end of 1990). The ever-increasing world demand f calls for new recovery technology to economically produce the oil left i ce. One of the emerging EOR technologies which holds promise as a c fective method for producing more oil is Microbial Enhanced Oil Recovery



F 3. Surfactant-water-oil phase diagram.

2.2.1. Economic advantages of MEOR

Several publications have shown that MEOR is potentially a cost-effective technology for increasing oil production [13]. Many advantages of using MEOR can be cited; some of the most important are the following [13,35]:

1. The injected microorganisms and nutrients are inexpensive and easy to obtain and handle in the field.
2. MEOR is economically attractive for marginally producing fields.
3. The cost of the injected fluid is not dependent on oil prices.
4. The implementation of the process needs only minor modifications to existing field facilities, which reduces cost.
5. The method is easily applied with typical surface equipment for waterflooding.
6. MEOR is less expensive to install and more easily applied than any other EOR technique.
7. MEOR products are all biodegradable and will not accumulate in the environment.

2.3. Results of an improvement in recovery using MEOR

The following section summarizes some reports of improvements in recovery using MEOR.

The *Journal of Petroleum Technology* reported in its Technology Digest (September 1991) that tests at the Alton field in Queensland, Australia, showed that Biological Oil Stimulation (BOS) increased oil output by 70% [36]. The same study estimated that MEOR technology could unlock as much as 300 billion barrels of Australian oil left in place after conventional technology.

Injection of microorganisms and molasses improved the rate of oil production at the Mink Unit project by about 13% [37]. In the same application, Water-Oil Ratio (WOR) was reduced in producing wells by as much as 35%. Bryant et al. [12] showed that microorganisms and molasses nutrient can recover an average of 32% more of a light crude oil (Delaware-Childers) from Berea sandstone cores than after laboratory-simulated waterflood. Kianipey et al. [29] reported that the *in situ* growth metabolism of injected bacteria decreased residual oil saturation in the unconsolidated, thin reservoir flow cells by 9-24%. Another study [38] showed that a field core produced 28% more residual Mink crude oil than the waterflood process. Richard et al. [39] demonstrated that between 10 and 39% of the oil left behind in the cores after waterflood could be recovered.

3. SCREENING CRITERIA

The data from the Middle East oil fields provide the characteristics of oil reservoirs that can be used for MEOR field projects (see Table 2). Extensive research is going on today to develop new technologies in bio-technological processes that can be used under actual reservoir conditions of temperature, pressure, rock permeability, and water salinity.

The reservoirs of the Arabian Gulf area are characterized by the relatively high salinity of the formation waters that puts a serious limitation on the use of MEOR. Most screening criteria used a TDS upper limit of 100,000 ppm. Rock permeability ranges of 1-1000 md have been reported for MEOR field projects [14]. No MEOR field projects have been carried out where pressures and temperatures were too high for microbial growth. The usual biological limitation for temperature is about 160°F, and for pressure, it is about 20,000 psi. In Saudi reservoirs, the temperature and pressure ranges from 140 to 240°F and from 2000 to 5500 psi, respectively, which means that MEOR processes can be applied. The

2
ning criteria [14]

Parameter	Range suggested
voir rock permeability	>75 md, unless highly fractured
oir depth	<8000 ft
oil type	>15° API; as yet, not enough information available for heavier crude oils
voir temperature	<170°F
ity of reservoir formation	<10% sodium chloride; total TDS may be higher

eability of the formation rock in Saudi oil reservoirs ranges from 100 to) md, which is a wide range for MEOR application. Sayyouh and Al-Blehed .41] studied on the screening criteria for enhanced recovery of Saudi crude including thermal and non-thermal processes; however, MEOR was not included he non-thermal methods.

FIELD DATA AND POSSIBLE APPLICATIONS

ble 3 summarizes the literature on field tests made using microorganisms. e conditions in the oil fields in more than 300 petroleum formations in the world were surveyed, and a summary for each country is presented in Table igure 4 shows the variations in rock permeability for six Arab countries. average rock permeability ranges from less than 10 md to 3000 md, which des permeabilities suitable for MEOR applications in Saudi Arabia, Qatar, and in some Egyptian oil reservoirs.

e average depth for all reservoirs in the Arabian area ranges from 1000 to ft (Figure 5). The UAE is not suitable for MEOR due to the large average of the oil fields (i.e., from about 8000 to 12000 ft), as shown in Figure wever, Syria has a range of formation depth between 2000 to 6000 ft, which itable for many types and species of bacteria. Apparently this range is ficial, because the optimum rate of growth of microorganisms is higher. re 5 also shows that Saudi, Egyptian, Kuwaiti, and Iraqi oil fields have some tion depths within the range of MEOR application.

igure 6 shows the API gravity ranges of the different crude oils; all the API ity of the Middle East crudes are within the range of MEOR applications, ugh some Iraqi crude oils are not.

lthough the oil production in Saudi Arabia, Kuwait, Qatar, and UAE is tially still in the primary and secondary phase, the production of oil in , Syria, and Iraq is mostly in the secondary phase because of the relatively il fields. The waterflooding of the older oil fields is becoming less ctive. The oil left in place is trapped by capillary forces and needs more to be displaced. The technology of microorganisms has improved so that it ssible to determine their nutrient requirements, metabolic products, such

Table 3
Some field applications on MEOR [16,20]

Location	Geology and lithology	Injected Bacteria	Response	Depth	Temperature °C	Permeability	Oil viscosity	Density or API
Romanian Field, Romania	Sand with a high content of marls and clays	*Bacillus* *Clostridium* *Pseudomonas* *Escherichia* *Arthrobacater* *Mycobacaterium* *Peptococcus* Bacteria accounts: $4x10^8$-$9x10^9$/ml	Bacteria produce gases and acids Increase in CO_2 in the produced water Increase in oil production: - Baicoi Reservoir: +2633 tons - Vata Reservoir: +32-1 tons (from 1977 to 1983) Increase in oil viscosity and density and light fractions increased in oil	336-1559m	27-55	100-1500 mD	6-53 cp	0.85-0.91 kg/dm^3

Salinity: 5-180 g/li

Some field applications on MEOR (cont.)

Location	Geology and lithology	Injected Bacteria	Response	Depth	Temperature °C	Permeability	Oil viscosity	Density or API
Lloyd-minister Field Canada	Unconsolidated sand	*Leuconostoc mesenteroides*	Bacteria produce acids and alcohols	650 m (5.4 m pay thickness)	21	1500 mD (porosity= 30%)	heavy	API=15° 973.8 Kg/m^3 at 150°C
		Bacteria accounts: 10^2-10^3/ml for aerobes and 10^4/ml for anaerobic	Decrease in pH and surface tension					
		11.6 m^3 Molasses in 120 m^3 water						

Salinity: 6% brine

Table 3
Some field applications on MEOR (cont.)

Location	Geology and lithology	Injected Bacteria	Response	Depth	Temperature °C	Permeability	Oil viscosity	Density or API
Lisbon Field, Union County Arkansas, U.S.A.	Nacatoch sand; a loosely unconsoilidated sand with 8% carbonate content	Beet molasses was added to injected water (4000 gal of 2% by wt.)	Bacteria produce gases (mainly CO_2 and H_2) and acids	1920 ft (30 ft net pay) thickness	90-105 (current 96°F)	5770 mD (porosity = 30.5%) (air permeability = 408 mD)	4.48 cp @100°F 8 cp @ 60°F	API=36° @ 60°
		Clostridium acetobutylicum suspensions	CO_2 content of the gas produced varied between 39-82% (air free)					
			Methane CH_4 (80% increase) was produced (Some CO_2 and H_2 was converted to methane)					
			Oil production increased from 0.6 to 2.1 BOPD in some wells					
			Maximum increase in production rate was 250%					

Salinity: 42000 ppm

Location	and lithology	Bacteria	Response	Depth	ature °C	bility	viscos-ity	or API
Okmulgee Field, Oklahoma, U.S.A.	Sandstone (gas drive reservoir)	*Clostridium* (counts 10^7/ml)	Produced water contained ethanol, acetone, n-butanol, and CO_2	1750 ft	-	-	-	-
	(Gas composition: O_2, N_2, CH_4, CO_2, H_2S, and H_2).	Molasses (8.6%) in salt water (3% NaCl)	Oil viscosity increased, indicating oxidation and loss of dissolved CO_2 CO_2 considered important for increasing oil recovery					
Mineiuz-Rockdale Field, U.S.A. Micro-Bac Gulf Coast Inc., USA	Fine silty sandy shale - highly laminated from sand shale to shaley sand	-	Oil production increased from 1.5 to 4 BOPD	908-1022 ft	-	-	-	-

Table 3
Some field applications on MEOR (cont.)

Location	Geology and lithology	Injected Bacteria	Response	Depth	Temperature °F	Permeability	Oil viscosity	Density or API
Delaware, Childers, OK, U.S.A.	Sandstone	*Bacillus* *Clostridium* Nutrient - molasses 22 gal/ injection well	Bacteria produce gases (mainly CO_2), acids, and surfactants. Produced gas composition: Methane 60% CO_2 25.8% Butane 2.8% Pentane 2.6% Octane 3% About 19% increase in recovery	600 ft (porosity - 20%)	80	52 mD	7 cp	35°
West Germany Dutch I Dutch II	Limestone	-	-	4068 ft	150	10-50 mD	-	30.6°
USSR	Sandstone porosity - 20-23%	Bacteria in molasses (from 6 wells)	3% CO_2 produced Oil viscosity increased. Oil recovery - 37-40 m ton/d for 4 months	(1000-1200 m) 5577 ft	90	500-1000 mD	-	Heavy oil (asphalt)

Salinity: <0.02% - Delaware, Childers, OK
Salinity: 23% TDS - West Germany, Dutch I and Dutch II
Salinity: 0.02% TDS - USSR

Location	Geology and lithology	Injected Bacteria	Response	Depth	Temperature °F	Permeability	Oil viscosity	Density or API
Australia	-	-	-	-	-	260 mD	-	-
Hungary	Sandstone and Limestone	Anaerobic thermopiles in molasses (from 10 wells)	Recovery - 126% yield from 12 wells	650-8061 ft	207	10-700 mD	-	-
Poland	Porosity - 13-25%	*Clostridium* in molasses (from 17 wells)	CO_2 produced increased Recovery - 20 - 200%	1325-3753 ft	-	-	-	-
Czechoslovakia	Porosity - 22-36%	*Desulfouibric Pseudomonas* in molasses.	Oil viscosity decreased Recovery - 50% (from 7 wells)	164-230 ft	-	3000-8100 mD	-	-

Table 4
Oil reservoir data for different Arab countries

	Saudi Arabia		Qatar		Kuwait		
Property of Reservoir	Northern Area	Southern Area	On-Shore	Off-Shore	Northern Area	Southern Area	Neutral Zone
Depth (ft)	4100-6800	5200-8000	5600-6600	7000	8300-8600	4800-10000	1100-1700
Lithology	Sandstone (Wasia)	Carbonate (Arab D)	Limestone	Limestone	Sandstone and carbonate	Carbonate, except Burgan	Sandstone and carbonate
Thickness (ft)	20-200	100-300	200-400	80-400	200-1400		100-250
Porosity (%)	20-29	14-22	18		18-24		20-35
Permeability (MD)	1000-3000	100-500	65-150	100-500			
Oil gravity (°API)	27-34	37-42	38	28-33	26-34	18-23	

Oil reservoir data for different Arab countries (cont.)

	Iraq		UAE			Syria	Egypt
Property of Reservoir	Northern Area	Southern Area	On-Shore	Off-Shore	Dubai		
Depth (ft)	2800-6500	10000-11000	7500-7900	8500-9150	7500-12900	2000-6000	2105-11900
Lithology	Carbonate	Sandstone	U. Thamana Limestone	U. Thamana Limestone	Limestone	-	Sandstone and carbonate
Thickness (ft)	-	200-300	81-170	100	-	-	-
Porosity (%)	20	20-25	25-30	19-29	-	-	-
Permeability (MD)	200	400-1000	15-80	1.5-30	3-70	5.3-3000	-
Oil gravity (°API)	Shallow heavy oil 10 deeper light oil 34-42		41-44	37-39	30-50	-	20-38

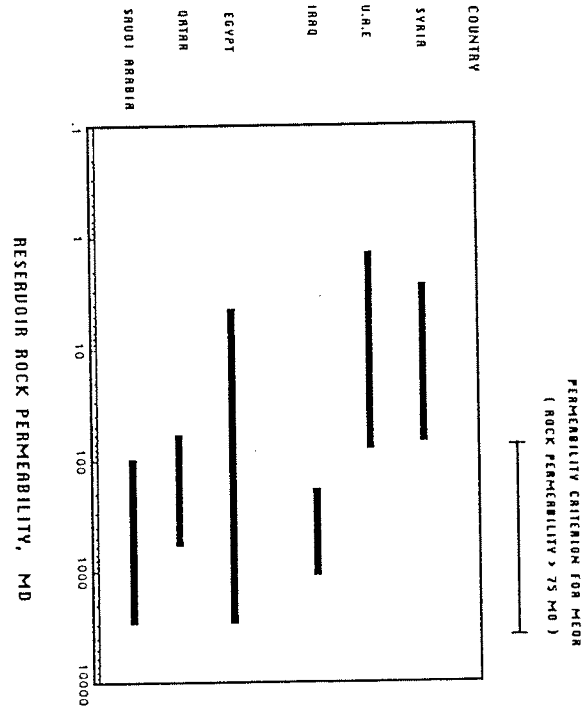


Figure 4. Rock permeability for different crude oil reservoirs.

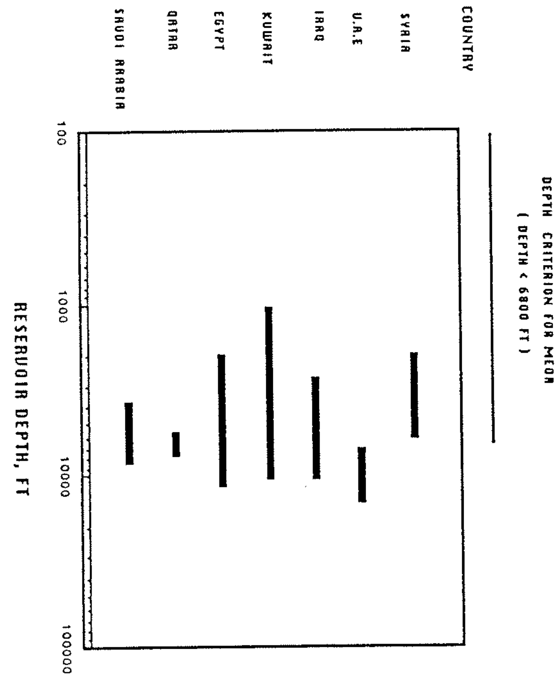


Figure 5. Depth for different Arab oil reservoirs.

as gases (methane, hydrogen, nitrogen, and carbon dioxide), polymers (polysaccharides and proteins), solvents and surfactants, and their environmental limits. There may be many undiscovered microbial systems that either already exist in deep reservoirs or are capable of existence there.

The data in Table 4 gives the characteristics of the Arab oil reservoirs used for possible MEOR field projects. The application of MEOR methods to improve oil recovery in depleted Egyptian and Syrian oil fields is very well suited to today's economic climate. The recent increase in interest in MEOR is attributed to its low cost compared to other EOR methods. Thus, with the present low oil prices and the high cost of other EOR methods, considering MEOR is justified.

5. CONCLUSIONS

From the analysis discussed in this study, we reached the following conclusions:

1. Extensive laboratory and field research should be carried out to develop new technologies for microbial enhanced oil recovery under reservoir conditions of temperature, pressure, permeability, and formation-water salinity.
2. Saudi, Iraqi, and Egyptian oil fields are good candidates for MEOR, while Qatar, Kuwait, and Syria have some potential. However, the reservoirs in the UAE have no potential for this process.
3. Depleted oil fields in Egypt, Syria, and Iraq could be activated by injection of microorganisms and produce more oil.
4. Although the application of MEOR may be limited due to the high formation salinity in the Arabian Gulf area, new bio-technology may solve this problem.

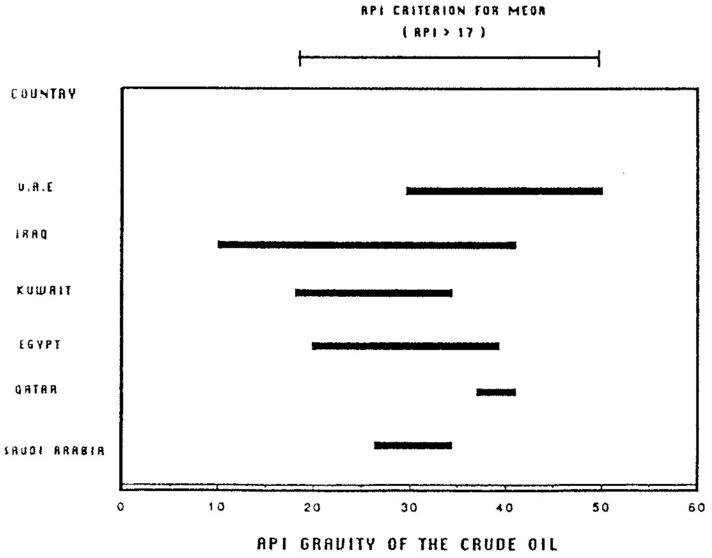


Figure 6. API gravity for different Arab crude oils.

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On Towards the Real World

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Abstract

Converting an interesting research idea into a profitable technology requires three principal components: a sound scientific base, proper integration with the relevant engineering, and a good marketing strategy. Some people would add luck. Underlying all this is high quality management at every stage of the process. But however favorable the initial signs, not all good ideas will be successful in the marketplace; for many techniques, their time will come (and go) as the economics of their competitors deteriorate (and improve). Applying these concepts to petroleum microbiology in a broad sense, how have some of the major projects in the field measured up? Look at three cases:

Single-cell protein was certainly based on elegant science combined, in the course of time, with impressive engineering. Yet it has largely failed in the marketplace - economic conditions changed over a long incubation period as they so often do and the world view of food priorities was by no means the same in 1985 as it had been in the 1960s. Were managements at fault? Could they have done better?

Or, consider the control of sulfate-reducing bacteria. Their biochemistry and physiology have been studied for decades and no doubt their genetics will soon be equally well mapped. The problems they pose are believed to be widespread in oil production, even critical to some operations. Biocides galore have been marketed. Yet still the problems are said to persist, more readily acknowledged by some operators than by others, preventative measures preferred in one case, remedial procedures, when necessary, in another. The market appears obvious and the science seems to be ready - but has it neglected to acquire a convincing engineering dimension? Have economic cost-benefits not been properly assessed? Have managements failed to take the steps needed actually to control souring? Or is the whole problem not really acute enough to be worth bothering about in the light, perhaps, of more serious difficulties confronted by producers?

And what of MEOR? For close on half a century a band of stalwarts, now centered on one side of the Atlantic, now on the other, with offshoots at the ends of the earth, have battled away with very limited success to get their ideas adopted by the industry. The science is neither revolutionary nor contentious. But the engineering links are weak: few scientists working on MEOR seem to have been able to integrate well with qualified and experienced engineers. And of commercialization, there is hardly a breath: just a trace here and there. Is this, too, a management problem? Is dependence on government funding inevitable? Why does MEOR progress so slowly when some forms of innovation rapidly succeed by their own efforts?

Questions like this have certainly been asked before [1] - perhaps some of the answers will emerge in this volume.