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Investigating the Bio-corrosion Problem of MEOR in Oil Fields

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Abstract

An Egyptian Microbial Enhanced Oil Recovery (MEOR) project evaluated the degree of corrosion action which may result, on the production tube and casing and surface equipment, during the using of bacteria to improve the ultimate recovery in oil fields.

The high resolution metal loss technique and several standard coupons of the carbon steel were used to evaluate the level of corrosion of the bioproduct of these bacteria. The coupons were chosen to have the same material as that of the casing, the production tubes and the other surface facilities that may be used during the different phases of the MEOR project.

Four solutions that are used during the project phases were examined. The first solution is the sea water solution, which is used to preflush the reservoir. The second is a mixture of the nutrient and the sea water, which is used to incubate the bacteria inside the reservoir. The third one is the bacterial solution (a mixture of sea water, nutrient and the bacteria) that is injected into the reservoir in case of the incubation of bacteria outside the reservoir. The fourth solution is the effluent fluid that comes out from displacement tests on a pilot model which simulates the process of the MEOR. This effluent solution includes bacteria and its metabolism, nutrient, formation water, sea water, and oil.

The results showed that sea water and nutrient solution has the lowest rate of corrosion while the effluent from the model has higher corrosion rate than the third solution of sea water, nutrient and bacteria. The most corrosive solution was the sea water. These results indicate that the presence of *Pseudomonas Aeruginos*a and its bio products do not represent a high corrosive media for the equipment used in the MEOR project. Resulting photographs by binocular microscope show that the occurrence of corrosion under the bacterial growth is a function of the bacterial type. It was found that some of species of bacteria cause minimum corrosion. This study contributes to the successful application of MEOR process.

Introduction

As a result of environmental system and process characteristics, microbiologically influenced corrosion became a prominent problem in the oil field. Sulfate reduction bacteria (SRB) and acid producing bacteria (APB) are present in the produced fluids and greatly enhanced by the addition of polymer during the injection production process.

SRB corrosion involves a number of chemical entities such as hydrogen sulfide and bisulfide anions (resulting from the dissimilatory reduction of sulfate anions by bacteria) and metastable sulphur compounds like thiosulfate and polythionates.[1] These chemical species are well known in the corrosion literature by their deleterious effects on ferrous metals.[2]

When exposed to sulphur species in bio-environments, iron and steel first develop a poorly protective film of mackinawite (an iron sulfide rich in iron) that changes later, to a more stable iron sulfides through different chemical and electrochemical paths.[3] In all cases, iron sulfides are characterized by their marked cathodic effects on the hydrogen reduction reaction which leads indirectly to an increase in the corrosion rate. An important feature of the anaerobic corrosion of carbon steel by SRB, not always taken into account in the literature, is that in practical situations metal surfaces are covered by deposits of different chemical and biological nature (oxides, sulfides, hydroxides and biofilms). In many cases, the bio-corrosion process is closely related to the passivity breakdown by metabolic products of aggressive characteristics, added to the media by bacteria metabolism.

Considerable work had been done to define the effects of CO_2 and H_2S on corrosion rates of pipeline, casing, and tubing steels, particularly at higher pressure and temperatures typical of down hole environments and in gases in which CO_2 is the only acid gas present. Corrosion of pipes, pumps, turbine blades coolers, super heaters, fuel cells and exhaust systems causes enormous industrial expenses due to production downtime, accidental injuries and replacement cost. According to Zenneti[4, 5], the rate of cost of the United States exceeds 10 billion Dollar per year. The market for corrosion inhibitors in the United States is expected to increase to 7.1 billion Dollar per year.[6]

Project Background

Microbial enhanced oil recovery (MEOR) is well-known as a developing and promising method used to improve the oil recovery through microbial activities. The basic theory behind this is very simple. Specifically selected suitable bacteria and nutrients are introduced into the producing formation, near the wellbore, and are flooded inside the reservoir. The microbes are encouraged to produce bio-metabolites and extend colonization outward into the producing formation. Bio-production of solvents, polymers, acids and surfactants is produced in-situ. These fluids remove the remaining oil and increase the oil production. During this process the bacteria and its metabolisms is passing through the injection facilities, tubing, casing, and production facilities. The metabolism of these bacteria may affect these facilities and cause a corrosion which will affect the economics of the process.

Pseudomonas Aeruginosa is bacterial species that was isolated from crude oil produced from Kareem Rudeis Formation within Belayim Marine Field (This is an Egyptian oil field located in the Gulf of Suez). The authors previously proved that this type of bacteria has the capabilities of producing bio gases, bio-surfactants and acids. It decreases the viscosity of the oil and the surface tension of the aqueous and oleic solutions.[7] This bacteria succeeded to increase the oil recovery factor from a pilot model and simulate the reservoir conditions, by around 20% when using a nutrient with molasses base.[8]

As the corrosion rate is playing a great effect on the economic evaluation of the MEOR projects, so studying the effect of the metabolism of these bacteria on corrosion, is necessary. The present work is an attempt to investigate the effect of some species of bacteria, isolated from crude oil, on corrosion.

Characteristics of the Fluid and the Bacterial Solutions

A pilot model was used to perform the flooding runs. It was designed with suitable dimensions to simulate the reservoir conditions. The pilot was connected with vacuum pump, manometer, water path and compressor.

Table 1 presents the composition of the formation water and sea water which were used in the displacement tests. An Egyptian crude oil sample that was selected specifically and tested to be sure that it is free from any indigenous bacteria. The characterization of this oil sample is shown in Table 2.

The bacteria *Pseudomonas Aeruginosa*, which was isolated from crude oil, produced from Egyptian oil field.[7] This bacterium has the following characterization: round, granular, entire, flat, colorless, translucent, an aerobic, gram-negative, short rods, no spore was performed and not resistant to acid. In a previous work, it was found that the best nutrient type for this bacteria, which gives the maximum recovery, was composed of Molasses (2 gm/lit), NaCl (5 gm/lit) and KNO_3 (10 gm/lit).[8]

One type of incubation media, was selected to incubate the bacteria, it is known as the "modified media"[7] which was selected specially for the bacteria *Pseudomonas Aeruginosa* to get a higher growth rate. The composition of this modified media type is given in Table 3.

Another three different bacterial solutions (Bacilli, Cocci A, and Cocci B) were prepared. The properties of the bacterial solution are shown in Table 4.

Table 1 : Chemical composition of the two brine solutions

Components	Sea water	Formation water
NaCl [ppm]	28,500	50,000
$CaCl_2$ [ppm]	1,500	42,000
$MgCl_2$ [ppm]	3,000	8,000
$CaSO_4$ [ppm]	7,000	0
Total salinity [ppm]	40,000	100,000

Table 2 : Physical properties of the crude oil used

Properties	Value
Initial reservoir pressure, psi	3000
Reservoir temperature, ^oF	180
Bubble point pressure, psi	1350
GOR, SCF/STB	260
Oil Gravity, API	20
Pour point, ^OC	-3
Density	0.92
Asphalt content, %	12

Table 3 : The composition of the modified media[7]

Media No.	Composition	Weight [gm/lit.]
Modified media	Protease peptone	20
	Glycerol	10
	K_2HPO_4	10
	$MgCl_2.6H_2O$	1.4

Table 4 : Properties of the bacterial solutions

Bacteria Characteristics	pH	Surface Tension, dyne/cm2	Viscosity, cp
Bacilli	7.04	31.8	1.35
Cocci A	8	56	1.25
Cocci B	6.68	34.4	1.31

Corrosion Rates

Two standard carbon steel coupons with number of A65 and O529 having the same material of the casing and tubing which are used in the oil and gas wells, were used to study the different rates of corrosion that may result from the use of different salinities and bacterial solution during the MEOR projects.

Simulating the different phases exposed to the tubing and casing inside the well, first the reservoir is under water injection then injecting a solution composed of sea water, nutrient and bacteria after that injecting the seawater and nutrient. During the phase of production, the well will expose to the effluent solution which includes bacteria and its metabolism, nutrient, formation water, sea water, and oil. Therefore, three different corrosive solutions were prepared to simulate the first three fluids path inside the wells. The first one is the sea water, the second is sea water with nutrient and the third one is sea water with nutrient and bacteria. The fourth solution was the effluent fluids that come out from the displacements which was a mixture of the sea water, formation water, nutrient, oil, bacteria *Pseudomonas Aeruginosa* and its metabolisms.

The first solution was used to study the rate of corrosion on the material of the storage tank of water injection. The second solution was used to study the effect of the prepared injection solution of the nutrient on the material of the storage tank, and the third one was to study the effect of the presence of bacteria used in this project, before its pumping into the well, on the material of the production tube and casing, while the fourth solution was used to study the effect of the effluent solution, which comes out during the production, on the production tube, flow lines and surface facilities.

The coupon number (O529) was exposed to the second and the third solutions while the coupon number (A65) was exposed to the first and fourth solutions respectively. Each coupon was soaked in every solution for a time period of 45 days inside the incubator at temperature of 30°C.

The weight loss corrosion method was used as it is suitable for all oilfield operations including oil, water and gas handling system. Corrosion coupon testing consists of the exposure of a small specimen of metal (the coupon) to the environment of interest for a period of time to determine the reaction of the metal to the environment. Corrosion coupons are used to evaluate the corrosion of various systems, to monitor the effectiveness of mitigation programs, and to evaluate the suitability of different metals for specific systems and environments. The following are the detailed steps for the different experimental procedures of this method.

The coupons were cleaned before and after the exposure to the corrosive solutions. Then, the average corrosion rate was calculated using the following formulas: [9]

$$CR = \frac{W * 365 * 144}{(A) * (T) * 453.6} \quad (1)$$

Where,

CR = corrosion rate, mils per year
A = initial exposed area of coupon, square inches
T = exposure time, days
W = mass loss, grams

Exposed time must be considered when interpreting corrosion coupon data. Short-term exposure (15 to 45 days) will provide quick answers but may give higher corrosion rates than long-term exposures. Aggravating conditions, such as bacteria fouling, may take time to develop on the coupon. Short exposure time may be advantageous when evaluating inhibitor effectiveness. Long exposures (60 to 90 days) are often required to detect and define pitting attack. Because exposure time affects test results, exposure periods should be as consistent as practical. A tolerance of + 7% allows a variation of ±2 days on a 30-day exposure. This is satisfactory for most applications. Here in this study the exposed time used is 45 days because of the presence of bacteria. Table 5 gives a quantified definition of the corrosion rate if it is low, moderate, high or severe.

Table 6 shows the degree of weight loss of each coupon due to the corrosion effect of each of the four solutions and, it gives also the corrosion rate of each solution as calculated by using equation 1. Meanwhile, i give the level of corrosion of each solution.

Table 5: Quantative categorization of coupon corrosion rates for oil production systems[10]

	Average Corrosion Rate	
	US Customary (mpy*)	**Metric (SI) (µm/a**)**
Low	<1.0	<25
Moderate	1.0-4.9	25-126
High	5.0-10	127-254
Severe	>10	>254

*mpy = mils per year

**µm/a=micrometer/annum

Table 6 : Corrosion rate calculations and its degree of severity

Solution No.	**Solution composition**	**Coupon No.**	**Area [in^2]**	**Time [d]**	**Weight loss [g]**	**Corrosion rate mpy**	**Level of corrosion**
1	Sea water	A65	4.32	45	1.14	0.67	Low
2	Sea water + nutrient that has a composition of molasses (2gm/lit), NaCl (5gm/lit) and KNO_3 (10gm/lit).	O529	4.35	45	0.21	0.12	Low
3	Sea water + nutrient + bacteria	O529	4.35	45	0.56	0.33	Low
4	The effluent solution of displacement run with composition of Sea water + nutrient + Formation water + bacteria + Metabolisms (surfactant, acid) + oil	A65	4.32	45	1.02	0.6	Low

Binocular Microscope

Some steel specimens were cut from casing steel. These samples were then immersed in three different bacterial solutions (Bacilli, Cocci A, and Cocci B) for a period of four weeks. The specimens are then examined using a binocular microscope.

Analysis of the Results

It is important to note that all of the four solutions give a result of low corrosion rate which means that using of the bacteria *Pseudomonas Aeruginosa* in the MEOR process is safe from the point of view of corrosion effect on the surface equipments, production tubes and casing.

Inspection of the obtained results reveals the following:

1. The first solution, sea water, gives the highest corrosion rate with respect to the other solutions due to its higher salinity which enhances the localized corrosion forms, promoting separation between anodic and cathodes areas, and the galvanic coupling effects, especially in the presence of oxygen and chlorides.
2. When adding the nutrient to the sea water (second solution), the corrosion rate is reduced too much because of the presence of molasses having CN groups (cyanide group) which are considered as active site to be adsorbed on the coupon surface, and hence it forms a protective film layer which decreases the corrosion rate.
3. The addition of the bacteria (third solution) to this media increases the corrosion rate, this may be attributed to the consumption of the CN groups (cyanide group) by the bacteria and also the production of acidic gases by bacteria that may increases the acidity of the solution which affect the metal of the coupon and hence increase the corrosion rate.
4. In the last media (fourth solution) the corrosion rate is increasing due to the presence of the formation water with its high salinity.

The results showed that the best solution from the corrosion imbibitions is the second solution then the third one and comes last the fourth and first solutions.

Resulting photographs by binocular microscope show that the occurrence of corrosion under the bacterial growth is a function of the bacterial type. Fig. 1 indicates that corrosion had not occurred in the absence of bacteria or bacterial products. The corrosion occurred under the bacterial growth of Cocci A and B as shown in Figs. 2 and 3. These figures show how much change in the surface appearance and reveal that general surface corrosion has occurred in the presence of bacterial-glucose solutions of Cocci A and Cocci B respectively.

It was found that some of species of bacteria (Bacilli) cause minimum corrosion. A careful inspection revealed that light pitting in various parts of the surface occurred when using Bacilli bacterial glucose solutions as shown in Figure 4.

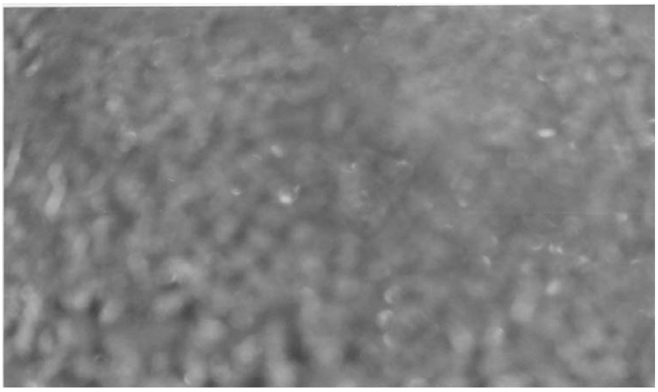

Figure 1: Photo micrograph of steel surface appearance in the absence of bacterial solution.

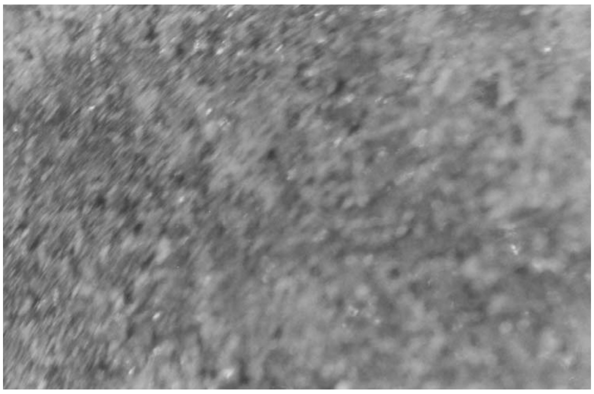

Figure 2: Photo micrograph of steel surface appearance in the presence of bacterial-glucose solution (Clocci A).

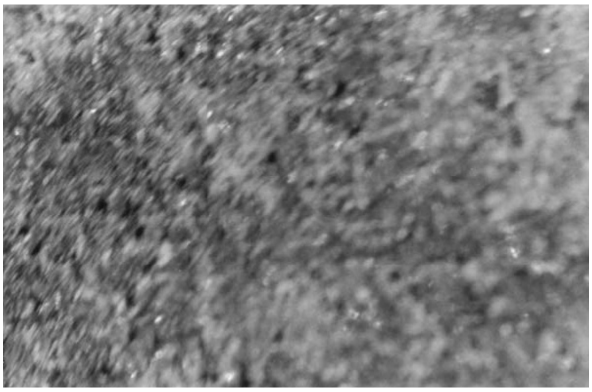

Figure 3: Photo micrograph of steel surface appearance in the presence of bacterial-glucose solution (Clocci B).

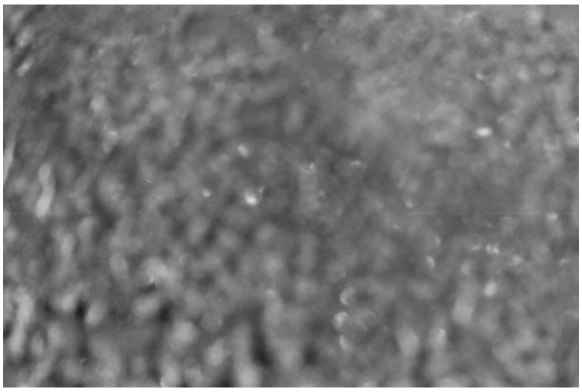

Figure 4: Photo micrograph of steel surface appearance in the presence of bacterial-glucose solution (Bacilli).

Conclusions

Based on the work performed during this study it is clear that:

- The solution of the sea water and nutrient has the lowest rate of corrosion while the effluent from the model has higher corrosion rate than the third solution of sea water, nutrient and bacteria. The most corrosive solution was the sea water.
- Each of the four solutions used in this study has a low level of corrosion rate which means that the presence of the bacteria *Pseudomonas Aeruginos*a and its bio products does not represent a high corrosive media for the equipment used in the MEOR project. This means that the *Pseudomonas Aeruginos*a is safe to be used in the field from the corrosion point of view.
- Bio-corrosion under present study conditions was found to be a function of bacterial type. Bacilli species of the bacterial solutions used cause minimum corrosion.

Abbreviation

APB	Acid Producing Bacteria
GOR	Gas Oil Ratio
MEOR	Microbial Enhanced Oil Recovery
mpy	Mils per Year
SRB	Sulfate Reduction Bacteria
μm/a	Micrometer/Annum

Symbols

A	Initial Exposed Area of Coupon, square inches
A65	Number of Standard Carbon Steel Coupon
$CaCl_2$	Calcium Chloride
CN Groups	Cyanide Group

CO_2	Carbon Dioxide
CR	Corrosion Rate, mils per year
H_2S	Hydrogen Sulfide
$MgCl_2$	Magnesium Chloride
NaCl	Sodium Chloride
O529	Number of Standard Carbon Steel Coupon
T	Exposure Time, days
W	Mass Loss, grams

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