An Experimental Optimization Technique to Select and Determine the Best Nutrient Type and Composition, for the Bacteria Suitable for MEOR – Determination of its effect on the Relative Permeability Curves
M.Samir*, Sh. Selim**, S. A. El-Tayeb***, Abdel Waly***, and M. H. Sayyouh ***

Abstract
The technology which is currently being developed for improvement the properties of reservoir fluid and rocks is the Microbial Enhanced Oil Recovery (MEOR) techniques in which microbes are activated, either in-situ or ex-situ, to produce bioproducts or microbial mass which may alter the properties of the reservoir fluids and rocks and hence it enhances the oil recovery from the reservoir.
Relative permeability data are essential for all calculations of fluid flow in oil reservoirs. These data are used in making engineering estimates of productivity, injectivity, and the ultimate recovery from reservoirs, for evaluation and planning of production operations, diagnose formation damage expected under various operational conditions and for understanding the mechanism of chemical enhanced oil recovery processes.
The activity of bacteria may be increased by using an optimization technique to select the best suitable type of media and nutrient which can be used to activate the bacteria.
In a previous work for the authors, it was succeeded to isolate and identify three types of bacteria, obtained from three different oil samples that were taken from three different Egyptian oil fields. After that, an extensive effort was directed to select the best type of bacteria, from these three isolated types, which will be suitable for MEOR and it was found that, the best type is the Pseudomonas aeruginosa. The best media suitable for this selected type was also determined.
This paper will highlight the work done to determine the best type of nutrient and optimize the percentage of its components and to determine the effect of the Pseudomonas aeruginosa bacteria on the relative permeability curves of two identical cores plugs collected from the Gulf of Suez area. Petrography tests (thin section, SEM), pore through radius and two displacement tests had been done to evaluate these effects.
The results indicated that the best nutrient type have a molasses base with concentration of 2 gm/lit in addition to the NaCl [5gm/lit] and KNO3 [10gm/lit]. The using of the Pseudomonas aeruginosa leads to an increase in the relative permeability of oil, a decrease in the relative permeability of water, and an increase in the wettability of rock to water. An increase in the ultimate oil recovery by about 12% of the original oil in place was also obtained during the displacement runs that made to measure the relative permeability curves of the core plug due to using Pseudomonas aeruginosa bacteria.

* Petrobel (Belayim Petroleum Company)
** Ein-Shams University
*** Cairo University
Introduction

A major problem that must be resolved in enhanced oil recovery techniques is how to mobilize the residual oil after waterflooding\(^1,2\). Physiochemical oil displacement mechanisms have high microscopic sweep efficiencies under laboratory conditions, but, when these processes are applied to actual reservoirs, the volumetric sweep efficiency dominates the ultimate success of the process.

Among of the most important factors that affecting the degree of sweep efficiency, and thus the performance of a waterflood or EOR process, are 1) permeability variation, 2) interfacial tension between fluids and 3) wettability.

Research groups in many countries have conducted studies of enhanced oil recovery by means of various media such as gas, steam, water, chemicals and bioproducts. The approach in general, is to improve the physico-chemical characteristics of reservoir fluids and rocks\(^3\).

Microbes undergo metabolism process in their lives, producing metabolites in the form of enzymes which are useful for the microbes themselves, and bioproducts which are useful for their environment. Enzymes are used as catalyst, for degradation of nutrient and food materials. Bioproducts such as surfactant, bio-acid, biogas, biopolymer, bio solvent, etc. are useful for the MEOR process. The type of the bioproducts depends on the type and composition of the nutrients consumed by the microbes from their environment. Nutrients of food materials required by the microbes consist basically of seven types, namely water, energy source, carbon source, electron acceptor, essential minerals, nitrogen source, and growth factor\(^4\).

Out of the positive effects of microbial activities in oil field environment is their ability to result in enhancing oil recovery. This is due to the fact that the microbes, in their activities and metabolism, produce bioproducts in the form of chemicals. Biosurfactant can reduce the interfacial tension between oil and the formation water, while biopolymer controls the mobility of the water that used in water flooding. Biofilm and biomass may plug the pores of reservoir rocks and then change the direction and pattern of fluid flow in the rock. Biogas production increase reservoir pressure and assists in forcing oil out of the rocks. Bio acid, on the other hand, assists in dissolving rock particles and open pore mouths, thus increase rock porosity and permeability and allowing more fluid to flow.

In Cairo University a research group (authors of this paper) working in a research project concerning the study of the possibility of applying the MEOR on the Egyptian oil fields. The first part in this project was to isolate and identify some types of bacteria present in Egyptian oil fields\(^5\), the second part is to determine the best type of these bacteria isolated to be used in MEOR and determine the best media and nutrient type for the selected bacteria\(^6\).

These studies showed that the best type of bacteria, from the three isolated types, was the *Pseudomonas aeruginosa*. The best media for the selected type was a media that called a "modified media" which has a composition as given in table 1 and a nutrient that has a carbon base.

The relative permeability curves can change due to any change in the rock and fluid properties such as porosity, absolute permeability, pore size distribution, saturation status, wettability, saturation history, over burden pressure, temperature, interfacial tension, initial wetting phase, viscosity, boundary effect and the presence of indigenous bacteria\(^7-27\).

The aims of the present study are: 1) to determine the best type of nutrients that make the used bacteria gives its maximum activity, 2) to optimize the quantity of the substances which constitute this best nutrient which will be used in the flooding test,
and 3) to study the effect of the bacteria *Pseudomonas aeruginosa* and its metabolism on the rock and fluid properties, which will, has a direct impact on the relative permeability curves.

**Experimental work**

**Material**

**Bacteria**
The bacteria of type *Pseudomonas aeruginosa*, which was isolated (in a pervious study of the authors) from an Egyptian crude oil, is used to perform the different relative permeability runs that were carried out in the present study\(^5\). This bacterium has the following characteristics: round, granular, entire, flat, colorless, translucent, an aerobic, gram-negative, short rods, no spore was performed and not resist to acid \(^5\).

**Media**

One media that is called a "modified media"\(^6\) was chosen to incubate the used bacteria. This media was selected specially for the bacteria *Pseudomonas aeruginosa*, as it was proved that it makes the bacteria give a higher growth rate. The composition of this modified media is given in table 1\(^28\).

**Nutrients**

Five different carbon source nutrients will be used to select, among them, the best one. These five nutrients are: Lactose, Sucrose, Gloselarol, Dextrose and Molasses in addition to two types of salts NaCl and KNO\(_3\) (this is because it is proved in a previous study by the authors\(^5\) that the nitrite salt is the best type of salt that can be used for *Pseudomonas aeruginosa* bacteria).

**Brine water**

Two brine solutions were used in the present work, the first is the formation water (with salinity of 100,000 ppm) and the second one is the sea water (with salinity of 40,000 ppm). Both of them was obtained from an oil field, that is differ from the field which the used bacteria are isolated from its crude, this field is located in the Gulf of Suez area, Egypt. The compositions of these two brine solutions are given in table 2.

**Oil**

The crude oil that is used in the present study, to saturate the model, was obtained from the same field from which the brine solution was collected. This crude was tested, with the two brine solutions, to be sure that they are free from any indigenous bacteria and the crude oil was found to have the characteristics as shown in table 3.

**Core plug**

Two identical cores plug, of 1.5-inch diameter and 2-inch length have a lithology of sandstone, were used in order to perform the runs of relative permeability. These two cores were cut from the formation of the same field from which the oil and formation water samples were taken to be used in the present study.

**Apparatus**

**Fluid properties apparatus**

Some apparatus, as for measuring the fluid properties such as pH meter, conductive meter, Interfacial tensiometer and Brookfield digital rheometer to measure the viscosity was used.

**Relative permeability apparatus**

A “Core-Lab” displacement type water-oil relative permeability apparatus was used to perform the water oil relative permeability tests \(^29\). A schematic diagram of this apparatus is shown in Fig. 1. This apparatus was designed to permit the simultaneous measurement of volumes and rates of flow of water and oil produced from a core.
sample subjected to an external water drive under a constant differential pressure. The accumulative volumes of water and oil produced are collected in the receiving tubes. The resultant data, together with time and differential flooding pressure measurements, are used to calculate relative permeability of both oil and water.

**Experimental procedure**

Due to the fact that the criteria for judgment the performance of the bacteria under study, with different media and nutrients, at different salinities and temperatures, is that: the best performance of the bacteria could be obtained under the following conditions: 1) the viscosity of the oleic phase should be at its minimum level, 2) the surface tension, and the conductivity of the aqueous phase should be also be at their minimum level and the pH value of the aqueous phase is close to 7 which is the most suitable value. As these criteria will be used to different nutrients, to select the best one for the bacteria under study. So, in the following a general description for the experimental procedures that will be used for the determination of the different properties of the aqueous and the oleic phase.

**General procedure for the determination of the physical properties of the aqueous and oleic solutions:**

1. Clean and sterilize the graduated test tubes using the following sequence:
   - Wash each tube with detergent and tap water followed by distilled water then put it inside the oven at a temperature higher than 100 °C for 15 min for drying.
   - Cover each test tube with the cotton plug and put it inside the oven at temperature of 160 °C for 60 min for sterilization.
2. Prepare the solution of each nutrient, of the five nutrients that will be used in the present study, in a separate flask then put all the flasks inside the Autoclave for 20 min to sterilize the nutrients.
3. Put the oil sample in a separate flask, then put it inside the Autoclave for 20 min to sterilize the oil sample.
4. Prepare the media which will be used and put it inside the Autoclave for 20 min for the sterilization.
5. Transfer 3 cm³, in front of a flame, (under sterilized condition) from the used bacteria solution to the new solution, which will be used after a time period, (one or two days) to standardize the age of bacteria.
6. In front of the flame (under sterilized condition) open a sterilized empty tube and put inside it, 25 cm³ of sterilized oil, 22 cm³ of the selected sterilized nutrient and 3 cm³ from the bacteria solution and repeat this step for all the nutrients types that will be used in this research.
7. Seal off the test tubes very well, using a sterilized plug and shake it to get a good contact between the aqueous nutrient solution and the crude oil in order to be sure that the bacteria is distributed all over each tube, then close the tubes with a cotton plugs.
8. The tubes should leave for incubation during a time interval of one week at constant temperature of 30 °C.
9. The aqueous and the oleic phase volumes, in each tube, were recorded and the separation of the aqueous phase from the oleic phase using pipit was done, then measure separately the fluid properties of each phase such as: viscosity, surface tension, pH and conductivity.
Optimize the nutrient type and quantity

Selecting the best nutrient type

Five types of carbons source nutrients were selected to feed the bacteria as: Lactose, Sucrose, Gloserol, Dextrose and Molasses and in order to choose the best one, the following steps should be used:

1- Prepare one liter from the modified media with a final pH value equal to 7 using the composition that is given in table 1.
2- Add 3 cm$^3$ from bacteria solution to the modified media prepared and lift the flask for 24 hours for incubation under 30 °C.
3- Prepare one liter for a solution having KNO$_3$ [10gm/lit] and NaCl [5gm/lit].
4- Take the quantity of the solution which is prepared in step 3 and divided it equally into 5 flasks and adding the different carbon source as: Lactose, Sucrose, Gloserol, Dextrose and Molasses (one type for each flask) with concentration of 2 gm/lit.
5- Prepare 5 test tubes, put inside each tube 22 cm$^3$ of certain nutrient sample (one for each tube), 3 cm$^3$ from the modified media and 25 cm$^3$ of oil.
6- Lift the 5 tubes for one week for incubation at 30 °C.
7- The aqueous and oleic phase volumes, in the tubes, were recorded and the separation of the aqueous phase from the oleic phase using pipit was done, then measuring separately the fluid properties of each phase such as viscosity, surface tension, pH and conductivity.

Determine the optimum concentration of the best nutrient type

In order to determine the optimum concentration of the best nutrient, that was determined according to the results of the preceding experimental work mentioned above, the following experimental procedures must be follows:

1- Prepare one liter from the modified media with a final pH value equal to 7.
2- Add 3 cm$^3$ from bacteria solution to the modified media prepared and lift the flask for 24 hours for incubation under 30 °C.
3- Prepare one liter for a solution having KNO$_3$ [10gm/lit] and NaCl [5gm/lit].
4- Take the one liter of the solution which prepared in step 3 and divided it equally into 5 flasks and adding different quantities of the best nutrient, that was determines according to the results of the previous section, its obtain a final different concentration in each flask for example 0.5, 1, 2, 4 and 6 gm/lit (one concentration for every flask) as now have five samples of the best nutrient.
5- Prepare 5 test tubes, put inside each tube 22 cm$^3$ of one of the five nutrient samples (one for each tube), 3 cm$^3$ from the modified media and 25 cm$^3$ of oil.
6- Lift the 5 tubes for one week for incubation at 30 °C.
7- The aqueous and oleic phase volumes, in the tubes, were recorded and the separation of the aqueous phase from the oleic phase using pipit was done, then measuring separately the fluid properties of each phase such as viscosity, surface tension, pH and conductivity.

Determine the optimum concentration of the KNO$_3$ salt

In order to determine the optimum nitrate salt concentration, use the following:

1- Prepare one liter from the modified media with a final pH value equal to 7.
2- Add 3 cm$^3$ from bacteria solution to the modified media prepared and lift the flask for 24 hours for incubation under 30 °C.
3- Prepare one liter from the solution that having the optimum concentration of best nutrient as results from the previous sections.

4- Take the one liter which prepared in step 3 and divided it equally into 5 flasks and adding a different quantities of the salt KNO₃ to obtain a final concentration of 2, 4, 6, 8 and 10 gm/lit. of this salt in the five tubes. So now you five different nutrient samples with five different concentration of the nutrient salt.

5- Prepare 5 test tubes, put inside each tube 22 cm³ of one of the five nutrient samples (one for each tube), 3 cm³ from the modified media and 25 cm³ of oil.

6- Lift the 5 tubes for one week for incubation at 30 °C.

7- The aqueous and oleic phase volumes, in the tubes, were recorded and the separation of the aqueous phase from the oleic phase using pipit was done, then measuring separately the fluid properties of each phase such as viscosity, surface tension, pH and conductivity.

**Procedures for relative permeability measurements**

The use of the two identical cores plug in the two runs, with and without bacteria, will help to avoid the effect of the following factor that can change the shape of relative permeability curve as: porosity, permeability, pore size distribution and pore radius, saturation history, over burden pressure, initial water saturation, viscosity and boundary effect in the shape of the relative permeability curves. A normal sterilization procedure for the fluids (oil, sea water and formation water) and rock will be performed before each run to avoid the effect of the indigene’s bacteria or any other contaminated bacteria while the preparation of the plug.

**Determination of the mineralogical properties of the used core**

In order to determine the type and composition of mineral inside the used plug the following tests were performed: Petrographically test, the thin section, under plane polarized and crossed polarized light test, and the SEM photomicrograph test.

**Determination of the physical properties of the used core**

The helium gas expansion porosimeter apparatus is used to determine the porosity of the used core while the nitrogen permeability apparatus is used to determine its absolute permeability. The positive displacement mercury pump, with a close chamber apparatus, is used to determine the pore throat size distribution of the used core.

**Calculation of Ko at Swi and Kw at Sor (end points relative permeability)**

After flushing all the water inside the core by oil, then the core will be at its initial water saturation so measuring the Ko at Swi is suitable at that moment by applying Darcy's equation:

\[
K_o = \frac{14700 \times \mu_o \times L \times V}{\Delta P \times A \times T}
\]

Where
- \(K_o\) = Permeability of oil at Swi (md)
- \(\mu_o\) = viscosity of oil in (cp)
- \(L\) = Length of the plug (cm)
- \(V\) = Pore volume (cc)
- \(\Delta P\) = Differential pressure (psi)
- \(A\) = Cross sectional area (cm²)
- \(T\) = Time (sec)
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Also, after flushing all the oil from the plug the core will be at the residual oil saturation $S_{or}$, so by applying the same equation above, the $K_w$ at $S_{or}$ can be calculated.

**Procedure for determine the relative permeability curves**
To study the effect of bacteria and avoid the different factors which may affect the shape of the relative permeability curve follow the following steps:

1- Use the same plug for the two runs. The first run (without bacteria) and the second run (with bacteria).
2- The cleaning procedure for each run will be the same and must be done before each run.
3- Use the same temperature, over burden pressure and injection pressure while the two tests.

Measuring the basic properties (porosity, permeability) for each core before the run to be sure it is still the same, for the two core plugs.

**Steps for the first run without bacteria**
1- The core sample, to be tested, was cleaned with toluene in a Soxhlet extractor to remove oil, and with methanol to remove salt. Then, the core sample was dried in an oven.
2- After cleaning the core sample, it was evacuated and saturated with the formation water that has a salinity of 100,000 ppm.
3- Then, the brine water was displaced by oil until no recovery water (i.e., the core sample is at its irreducible water saturation).
4- The core fluids were then displaced by sea water (40,000 ppm). The accumulative volumes of produced oil and water were collected in the receiving tubes. The resultant data, together with time and differential flooding pressure were recorded to calculate the values of the relative permeabilities to oil and water.

**Steps for the second run without bacteria**
The second run were carried out (with bacteria) to determine the effect of presence of bacteria by repeating all procedure above, except that, in step number 4, the oil was displaced by a mixture of the sea water with bacteria, the best nutrient, at its optimum concentration, the KNO$_3$ salts with its optimum concentration and the NaCl salt. After that let the bacteria incubated inside the core for one week to allow the metabolize of the bacteria reach to its maximum efficiency.

**Results and discussions**

**Optimize the nutrient quantities**

**The best nutrient type**
Table 4 illustrate the results of measuring of the physical properties the aqueous and the oleic phase for the 5 different carbon source nutrient that used in the present study (Lactose, Sucrose, Gloseral, Dextrose and Molasses). It is clear from this table that the best carbon source is Molasses, as it gives for the oleic phase the lowest value of the viscosity 61.05 and for the aqueous phase the minimum surface tension (32 dyne/cm), also the lowest value of the conductivity (8 mv) and most suitable value for the pH (7.1).

**The optimum concentration of the best nutrient**
Table 5 illustrate the results of the physical properties measured for the aqueous and oleic phase for the 5 different Molasses concentration (0.5, 1, 2, 4 and 6 gm/lit). It is clear from table 5 that, the optimum concentration is found to be 2 gm/lit. when
increasing the concentration of Molasses above this value, a decrease in the activity of the used bacteria is observed. This may be due to the increase in the osmotic pressure of the solution over that of the bacteria cell. This may lead the cell to plasmolyze, which may reduce the bacterial activity.

**Optimum concentration of KNO$_3$ salt**

Table 6 illustrate the results of the physical properties measured for the aqueous and oleic phase at the 5 different KNO$_3$ concentration (2, 4, 6, 8 and 10 gm/lit). It is clear from this table that the 10 gm/lit is the optimum value to be used. It can be note from this table that, when increasing the concentration of KNO$_3$ salt above its optimum value, the rate of change of the different properties is very small and can be neglected. This means that the lowest amount of KNO3 salt that is needed to feed the bacteria with the required amount of oxygen is 6 gm/lit. and above this value the total amount of oxygen is not consumed by the bacteria.

**Mineralogical properties of the core plugs**

Fig. 2 shows the results of the petrographically test, the interpretation of this figure shows that, the sample is composed of Dolomitic sub lithic arenite. The detrital grains are mainly Quartz arenite, with subordinates’ quantities of lithic fragments (granite) and feldspars. The main authigenic mineral is the ferroan dolomite, with very minor quantities of Pyrite and Kaolinite.

The end of the core plug was used to prepare thin section and sample for SEM (Scanning Electron Microscope). The thin section was studied under plane polarized and crossed polarized light. Figures 3a and 3b represent photomicrograph of the thin section.

The SEM photomicrograph shows common rhombic dolomite crystals as shown in Fig. 4a, well crystallized pore filling Kaolinite booklets are also shown in Fig. 4b.

From these results of petrographic interpretation, the percent of shale is very small so the physical properties of the core plug such as, porosity, pore volume, bulk volume and so on, will not be affected due to its use in determination of the relative permeability runs. Table 7 shows the results of the basic core properties that were measured before each run. It is clear from these results that the parameter is almost the same for the two core plugs.

**Values of the end points of the relative permeability curves**

Table 8 shows the results of the calculations of the end points obtained from relative permeability curves.

The Ko at Swi in the two runs are the same while Kw at Sor in the second run (with bacteria) is much higher because the residual oil in the second run is less than its value in the first run.

The oil recovery in the second run is higher than its value in the first run by 12%. This is may be due to the change in the interfacial tension between the oil and sea water which was in the first run around 58 dyne/cm, while in the second run, after incubating the bacteria with the sea water for one week, was 18 dyne/cm.

**Pore throat size using mercury injection**

Fig. 5 represents the distribution function of pore throat radius. The pore throat radius distribution is unimodal, the modal width is varied between 4 and 50 microns with the mode at 12 microns. Fig. 6 shows the cumulative distribution of pore throat size and the amount of pore volume that is controlled by each pore throat size. The curve of modal distribution could be separated into two segments at pore throat radius 4 microns. The sizes between 4 and 50 microns are controlled about 82% of the pore volume of the sample that is contributing to the fluid flow inside the core sample.
Determine the Best Nutrient Type and Composition, Suitable for MEOR (9)

While the size below 4 microns controlling 18% of the pore volume that is not contributing to the fluid flow. This part of pore volume is supposed to represent the irreducible water saturation. The flooding results of the sample showed that the irreducible water saturation is about 20% which match with that conclusion. On the other hand, the contribution part of the pore volume is unimodal, this means that, there is a homogeneity in the pore geometry of the studied sample. Consequently, the flooding performance is expected to be high with a late break through of water.

Relative permeability curve
Fig. 7 shows the relative permeability curves in both cases of using bacteria and without bacteria. This figure illustrates the difference of the relative permeability between the two runs, which indicate the following:

1- There is a late in the breakthrough, due to homogeneity pore geometry of the studied samples.
2- The residual oil saturation value is decreased by about 12% in the second run.
3- At any given water saturation, the Kro in the second run (with bacteria) is always higher than its value in the first run (without bacteria), this may be due to the lower interfacial tension.
4- The cross over point in the second run (with bacteria) was moved to 61% instead of 57% water saturation in the first run (without bacteria), which indicates tendency of rock towards water wet.

Oil-water relative permeability ratio
Fig. 8 illustrates the oil-water relative permeability ratio (Kro/Krw) for the two runs. The interpretation of the two curves indicate that the threshold saturation is 56%. Below that saturation, the oil-water relative permeability ratio is nearly the same in the two runs. But after the threshold saturation the oil-water relative permeability is much higher in the second run (with bacteria) which indicate an increase in the oil relative permeability due to the effect of the lowering of the interfacial tension because of the biosurfactant produced by the bacteria.

Oil recovery
Fig. 9 shows the curve of cumulative water injection in the core, when measured as a number of pore volumes, as a function of oil recovery during the displacement of the oil by water in the two runs. The two curves indicate that:

1- Before the point of intersection of the two curves (about 42% oil recovery at a given water injected), the oil recovery from the core sample flooded without bacteria was slightly higher than the oil recovery from core sample flood with bacteria. This indicates that, so it is not recommended to inject the bacteria before ending the phase of water flooding (injection).
2- After the intersection point, the value of the oil recovery from the core sample flooded with bacteria is much higher than the sample flooded without bacteria.
3- The percent of the ultimate oil recovery in the first run (without bacteria) is mainly constant (42 %), after the injection of six pore volume up to nine pore volume of water which indicates that any increase in the volume of the water injection will not increase the oil recovery while in the second run, with bacteria, the oil recovery still increase (54 %) after 14 pore volume water injection. This means that the bacteria still active during the history of the flooded period.
Conclusions
Based on the experimental results obtained in this work, the following conclusions can be obtained:

1- The best type of carbon source nutrient suitable for the used type of bacteria is the nutrient that has Molasses.

2- The optimum composition for the selected nutrient is: Molasses [2gm/lit], NaCl [5gm/lit] and KNO₃ [10 gm/lit].

3- The change in the shape of the relative permeability curves is mainly due to the change in the interfacial tension and small effect of the wettability.

4- The presence of bacteria in the displacement run that was performed to determine the relative permeability curves of the used core, cause the following:
   a) An increase in the relative permeability to oil.
   b) A decrease in the relative permeability of water.
   c) An increase in the wettability of rock by water.
   d) An increase in the ultimate recovery of oil by about 12%.

5- It is better to start the injection of bacteria after the end of the water injection phase.

Recommendation
Study the effect of different reservoir conditions (temperature, salinity) on the performance of the used bacteria and the amount of oil recovery from an experimental model which simulate the reservoir conditions.

References


Determine the Best Nutrient Type and Composition, Suitable for MEOR


29- Operation manual Core Lab" The fundamentals of core analysis" 7501 STEMMONS Freeway, Box 47547. Dallas, Texas 75247.214/613-8270.
TABLE 1- THE COMPOSITION OF THE MODIFIED MEDIA (28)

<table>
<thead>
<tr>
<th>Media No.</th>
<th>Composition</th>
<th>Weight [gm/lit.]</th>
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<tbody>
<tr>
<td>Modified media</td>
<td>Proteose peptone</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Glycerol</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>K$_2$HPO$_4$</td>
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<tr>
<td></td>
<td>MgCl$_2$.6H$_2$O</td>
<td>1.4</td>
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TABLE 2– CHEMICAL COMPOSITION OF THE SEA WATER AND THE FORMATION WATER FOR THE FIELD UNDER STUDY.

<table>
<thead>
<tr>
<th>Components</th>
<th>Sea water</th>
<th>Formation water</th>
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<tr>
<td>NaCl [ppm]</td>
<td>28,500</td>
<td>50,000</td>
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<tr>
<td>CaCl$_2$ [ppm]</td>
<td>1,500</td>
<td>42,000</td>
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<tr>
<td>MgCl$_2$ [ppm]</td>
<td>3,000</td>
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<tr>
<td>CaSO$_4$ [ppm]</td>
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<td>Total salinity [ppm]</td>
<td>40,000</td>
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TABLE 3- PHYSICAL PROPERTIES OF THE USED CRUDE OIL.

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<tr>
<th>Properties</th>
<th>Value</th>
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<td>Initial reservoir pressure, psi</td>
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<tr>
<td>Reservoir temperature, ºF</td>
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<td>Bubble point pressure, psi</td>
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<td>GOR, SCF/STB</td>
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<td>Oil Gravity, API</td>
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<td>Pour point, ºC</td>
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<tr>
<td>Density</td>
<td>0.92</td>
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<tr>
<td>Asphalting content, %</td>
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TABLE 4- SENSITIVITY ANALYSIS ON THE TYPE OF CARBON SOURCE IN THE NUTRIENTS

<table>
<thead>
<tr>
<th>Type of Carbon source</th>
<th>Oleic phase Viscosity cp</th>
<th>Aqueous phase pH</th>
<th>Aqueous phase Conductivity ms</th>
<th>Aqueous phase Surface tension Dyne/cm</th>
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</thead>
<tbody>
<tr>
<td>Lactose</td>
<td>67.13</td>
<td>5.35</td>
<td>8.5</td>
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<tr>
<td>Sucrose</td>
<td>68.14</td>
<td>5.83</td>
<td>23</td>
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<td>Gloverol</td>
<td>71.06</td>
<td>6.9</td>
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<td>Dextrose</td>
<td>68.67</td>
<td>6.16</td>
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</tr>
<tr>
<td>Molasses</td>
<td>61.05</td>
<td>7.1</td>
<td>8</td>
<td>32</td>
</tr>
</tbody>
</table>
TABLE 5- SENSITIVITY ANALYSIS ON THE CONCENTRATION OF MOLASSES

<table>
<thead>
<tr>
<th>Concentration of Molasses (gm/lit.)</th>
<th>Oleic phase Viscosity (cp)</th>
<th>Aqueous phase pH</th>
<th>Aqueous phase Conductivity (mv)</th>
<th>Aqueous phase Surface tension (Dyne/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>67.48</td>
<td>6.08</td>
<td>15.08</td>
<td>47</td>
</tr>
<tr>
<td>1</td>
<td>65.24</td>
<td>5.85</td>
<td>11.15</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>61.05</td>
<td>7.1</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>64.63</td>
<td>6.16</td>
<td>13.01</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>66.5</td>
<td>5.82</td>
<td>17.63</td>
<td>48</td>
</tr>
</tbody>
</table>

TABLE 6- SENSITIVITY ANALYSIS ON THE CONCENTRATION OF KNO₃

<table>
<thead>
<tr>
<th>Concentration of KNO₃ (gm/lit.)</th>
<th>Oleic phase Viscosity (cp)</th>
<th>Aqueous phase pH</th>
<th>Aqueous phase Conductivity (mv)</th>
<th>Aqueous phase Surface tension (Dyne/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>64.53</td>
<td>6.2</td>
<td>10.75</td>
<td>38</td>
</tr>
<tr>
<td>4</td>
<td>63.46</td>
<td>6.02</td>
<td>12.56</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>61.5</td>
<td>7</td>
<td>8.61</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>61.15</td>
<td>6.9</td>
<td>8.52</td>
<td>32</td>
</tr>
<tr>
<td>10</td>
<td>61.05</td>
<td>7.1</td>
<td>8</td>
<td>32</td>
</tr>
</tbody>
</table>

TABLE 7- BASIC CORE PROPERTIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Before Run 1 (without bacteria)</th>
<th>Before Run 2 (with bacteria)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air permeability</td>
<td>1159</td>
<td>1171</td>
</tr>
<tr>
<td>Porosity</td>
<td>24.2</td>
<td>24.6</td>
</tr>
<tr>
<td>Pore volume</td>
<td>11.22</td>
<td>11.32</td>
</tr>
<tr>
<td>Bulk volume</td>
<td>46.3</td>
<td>46</td>
</tr>
<tr>
<td>Grain density</td>
<td>2.65</td>
<td>2.66</td>
</tr>
</tbody>
</table>

TABLE 8- RESULTS OF THE END POINTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Run 1 (without bacteria)</th>
<th>Run 2 (with bacteria)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swi [%]</td>
<td>0.198</td>
<td>0.202</td>
</tr>
<tr>
<td>Ko at Swi [md]</td>
<td>100</td>
<td>100.5</td>
</tr>
<tr>
<td>Sor [%]</td>
<td>0.36</td>
<td>0.24</td>
</tr>
<tr>
<td>Kw at Sor [md]</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>
Fig. 1- A schematic diagram for the relative permeability apparatus that used to perform the relative permeability tests.

Fig. 2- Petrographic interpretation
Determine the Best Nutrient Type and Composition, Suitable for MEOR

Fig. 3a - PPL thin section

Fig. 3b - XPL thin section
Fig. 4a- SEM section (Dolomite)

1- Dolomite

Fig. 4b- SEM section (Kaolinite)

2- Kaolinite
Determine the Best Nutrient Type and Composition, Suitable for MEOR

Fig. 5- Distribution of Pore throat radius

Fig. 6- Distribution of pore throat radius cumulative
Fig. 7- Comparison between the Water-oil relative permeability curve of the first run (without bacteria) and the second run (with bacteria) at 30 °C.

Fig. 8- Oil-water relative permeability ratio curve for the two runs at 30 °C.
Fig. 9- The oil recovery % of pore volume Vs cumulative water injection, number of pore volume for the two runs at 30 °C.