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Microbial Enhanced Oil Recovery (MEOR) Technology in Bokor Field, Sarawak

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Abstract

Bokor field was selected as the first field in Malaysia for Microbial Enhanced Oil Recovery (MEOR) technology application which utilizes micro-organisms to facilitate, increase or extend oil production from reservoir through the production of biochemical such as biosurfactant, solvents, gases and weak acids. The field was selected due to its high viscosity crude (4 to 10 cp) and low oil specific gravity of 20^0 API which could resulted in low recovery factor in major reservoirs ranges from 19% to 25% of its original oil in place. This technology also seems to be attractive for the field as it was initially thought to be potential for for reducing the viscosity of the oil and thus improve oil recovery. In addition, reservoir properties for major reservoirs in Bokor field conform to the basic screening criteria of the MEOR application.

This paper mainly discusses the results of the pilot project on MEOR technology application in Bokor field[1]. A feasibility study focusing on candidate selection and comprehensive laboratory analysis was conducted to investigate the feasibility of this technology for improving oil production/recovery. Generally, the feasibility study had indicated that there is a potential oil production improvement with no near wellbore impairment. Biodegradation study on the crude sample indicates complete removal of normal/branched alkanes and partial removal of aromatics due to in-reservoir alteration. Laboratory inoculation on the wellhead crude sample indicated that the microbes were able to slightly reduce the viscosity, break the emulsion and increase the solubility of high molecular weight component without damaging the reservoir. In order to prove the laboratory results and further assess the impact to oil production, a pilot test on three (3) selected wells were carried out. A comprehensive monitoring strategy was developed and the performances were monitored for 5 - 6 months.

Over 5 months period, results from the pilot were found to be encouraging. Significant increase in oil production rate and reduction of water cut were observed demonstrating the effectiveness of MEOR application. The average oil production rate for the period increases by 270 b/d which is equivalent to 47% oil incremental.

Overview of MEOR Technology

Microbial Enhanced Oil Recovery (MEOR) is a technology using micro-organisms to facilitate, increase or extend oil production from reservoir. The concept is more than 40 years old, however, early proposals were poorly conceived and in most cases had no practical value. Recent studies have developed microbial biotechnology to resolve specific production problems in reservoir. MEOR processes involve the use of in-reservoir micro-organisms or specially selected natural bacteria which are capable of metabolising hydrocarbons to produce organic solvents, like alcohols and aldehydes, fatty acids surfactants and other biochemical that are known to be effective at encouraging oil mobility.

The mechanism by which MEOR processes work can be quite complex and may involve multiple biochemical processes. The mechanism can be summarised as follows:

In the reservoir, the MEOR bacteria transport themselves through water and congregate in pore spaces at oil/rock and oil/water interfaces where they metabolise a very small amount of oil to produce organic biochemicals like solvents, surfactants, weak acids and gases[2]. These biochemicals reduce oil viscosity, decrease interfacial surface tension between the oil/rock and oil/water surfaces, and may also restore effective permeability by removing paraffin and scale blockage from pore throats. Finally, new microbial cells are produced and the process continues. The net effect of the entire MEOR process causes previously immobile, unrecoverable oil to become mobile so that it is now available to be swept into producing wellbores, causing an incremental improvement in oil production. As a result of by-products metabolised by microbes, many operational problems associated with paraffin, emulsion, scale and corrosion are also significantly reduced.

Description of Bokor Field

Bokor field is located in the Baram Delta Area about 40 kilometers offshore Lutong (Miri) at a water depth of approximately 220 feet below msl (Figure 1). The porosities range between 15 and 32% and permeabilities from 50 to 4000 mD. Oil gravities range from 19^{O} to 22^{O} API in the shallower reservoirs (1500 - 3000 Ft. ss) to 37^{O} API in the deep reservoirs (6300 Ft. ss). The reservoirs in the Bokor field can be divided into two main groups i.e. the Main Reservoirs (A - F) and the Deep Reservoirs (H - L). This study is focused on A reservoir which is the shallowest reservoir for the field.

The application of MEOR seems to be attractive for Bokor field mainly due to: -

- Low recovery factor in major reservoirs (19 % - 27%)
- Viscous oil (2 cp - 10 cp) produce from shallow reservoir
- Bokor data conform to the basic screening criteria of MEOR application (Table 1)
- In line with Petronas Initiative in promoting IOR/EOR technology application in Malaysia

Table 1 : Screening criteria and Bokor data

	Screening Criteria
Oil Gravity (°API)	**10 to 50**
Temperature (°F)	**<270**
Water Salinity (ppm Cl-)	**<100,000**
Parafin wax (%)	**>=3**
pH	**5 to 8**
Previous biodegration	**Little or none**
Avg. Permeability (md)	**>=20 md**
Porosity (%)	**>=10**
Oil viscosity (cp)	**5 to 50**
H_2S (ppm)	**<10,000**
Pressure Gradient (psi/ ft)	**>0.10**
Water cut (%)	**10 to 50**

As shown in Figure 2, the process of the project has been categorized into three main stages i.e. 1) feasibility study, 2) pilot project implementation and 3) full field scale implementation. This paper only discusses until the completion of the pilot project results implementation.

Feasibility Study

The feasibility studies of MEOR technology application in Bokor field was carried out and completed in April 2000. During the feasibility studies, the focus was on the Main Reservoirs with priority on the shallowest reservoirs i.e. A reservoir. Out of five reservoirs, A resevoir was identified to be potential candidates for MEOR application[3,4,5].

Conclusions from the Lab studies are: -

- Analysis on the **crude properties** of this reservoir indicates low wax, low sulphur, low asphaltene and low pour point.

- **Biodegradation study** indicates complete removal of normal/branched alkanes and partial removal of aromatics due to in-reservoir alteration.

- **Core study**: The product (MEOR) used is non-damaging to Bokor sandstone formation.

- **Rheology study**: There is a slight viscosity reduction in sample inoculated with microbes.

- **Emulsion breakout test**: Samples collected for this study are found to have emulsion problem. These emulsion are very stable at room condition The result indicate that the product is capable of breaking-up the emulsion within 24 hours of inoculation for most samples.

- **Geochemical Test**: After inoculation, there is an increase in the solubility of high molecular weight component as a result of biosurfactant activity.

Based on the above results, it can be concluded that there is potential application of MEOR technology to improve oil recovery in A reservoir. In order to further investigate and evaluate the technology, pilot project was proposed for seleceted candidate wells.

Pilot Project Objective

The pilot test was recommended to extend the laboratory the feasibility study to the field study. In July 2000, the pilot project was successfully carried out on three strings namely, B-1, B-2 and B-3. The locations of the strings on reservoir and production performance status are shown in Figure 3.

A dedicated team was formed for the pilot project implementation. The team comprises members from various disciplines. The specific objectives of the pilot project are : -

- To demonstrate the feasibility of microbial application in the Bokor field.

- To assess the impact on oil production (incremental oil gain and sustainability) during 5 - 6 months monitoring period.

- To justify the potential of future full field scale implementation.
- To gain experience and application knowledge in microbial stimulation through planning, monitoring and evaluating the pilot.

Performance Monitoring/Analysis Strategy for Pilot Project

This section discusses the monitoring strategy that was developed for the project. Performance monitoring/analysis strategy was developed to effectively measure or assess the performance of the project.

The following parameters were being monitored/tested: -

Wellhead Sample/Lab Monitoring/testing

- Compositional analysis
- Dynamic viscosity
- Emulsion Stability (@ reservoir temp.)
- API gravity
- Asphaltene, wax, Sulphur, pour point
- Formation water analysis & Bacteria (SRB) analysis
- Emulsion stability (on-site @ room temp.)

Production Performance Monitoring/Testing

- Production well test (oil, watercut, FGOR, gaslift injection rates)
- Tubing and Casing head pressures.
- Sand production.
- BHP surveys (permeability, skin, productivity index).

Appropriate responsibilities were assigned to team members to ensure smooth monitoring/analysis processes. The 5 – 6 months monitoring plan was also generated and most importantly the Key Performance Indicators for each data were identified to measure the project performance.

Wellhead Sampling

Wellhead samples were collected at specified frequency through out the project monitoring stage. During the sampling exercise, a dedicated personnel was appointed to take the samples as well as to conduct the on-site analyses to ensure consistency of the results. To enable a reliable comparison of the MEOR treatment performances and effectiveness, pre MEOR samples were also included in samples collection as a baseline information.

Two type of samples were taken i) the crude oil and ii) the formation water samples. The samples were taken manually from the wellhead sampling port of each string. The crude samples were labelled and the formation water samples were preserved according to the test requirement. The preserved samples were sent to lab for detailed analyses.

Pilot Project Execution

The project was successfully completed with a total project costs of US $ 0.4 Million and a head of original planned schedule. To minimise the operation cost, the project was carried out as part of the other planned acidizing campaign. Due to limited space on the platform, all equipment such as pumps, tanks and microbes products were placed on a barge. Microbes products were sampled taken and tested prior to mixing operation[6]. The microbes were mixed with water to acquire the required concentration and subsequently injected (bullheaded) into the wells

Upon completion of injection, the wells were shut-in. The shut-in period has been extended from one week to five (5) weeks to coincide with shutdown for maintenance works. The advantages of this opportunity are zero production deferment during treatment and maximize the time for microbes's reaction in the reservoir.

Pilot Project Results

This section discusses the production performance and wellhead sample results over the five (5) months period after the MEOR treatment.

1) Production Performance Results

Production Baseline - Pre-MEOR production trends for the three wells were generated to forecast the well performance without MEOR treatment. This is required in order to assess the well production impact after the treatment. The trends were generated by performing a decline/incline curve analysis over the available historical production data (10–15 years) for oil, watercut or GOR. In order to minimize the effect of gaslift variation on production, the injection rate was closely monitored and controlled to its pre MEOR rates (0.2 - 0.3 MMscf/d).

B-1 Post MEOR Results - The well test results for the the first two weeks indicate that the gross production has increased from 600 b/d (baseline) to 1500 b/d. Historical data confirms the gross production for the string could only reach maximum 600 - 800 b/d eventhough after long shut in period. This indicates that the sudden high gross production could be due to the MEOR treatment. However, two weeks after the treatment, the gross production has dropped and maintained at its baseline. Formation GOR and wellhead pressures were also monitored and no change observed for these performances. Based on the above production test data and daily watercut performance, the monthly average net oil production data was estimated. The production data for net oil and watercut performance was then plotted as shown in Figure 4. Over the past 5 months (post MEOR), the average oil production increased from 152 b/d to 334 b/d. The increase in oil production was mainly due to the drop in watercut performance from 75% (pre MEOR) to average of 45% (watercut performance post MEOR fluctuated between 30% to 82%). The average oil gains of B-1 for 5 months is 182 b/d (equivalent to 120% oil incremental).

B-2 Post MEOR Results – Initially, the gross production for post MEOR was slightly higher. The gross production was declines and approaches the baseline. Formation GOR and wellhead pressures were also monitored and no change observed for these performances. The watercut (Figure 5) declines from 30% to 20% before increases to the baseline. The average oil gain for B-2 for 5 months is 41 b/d (equivalent to 15% oil incremental).

B-3 Post MEOR Results - The gross production for post MEOR was higher than its baseline. Figure 6 shows the net oil and watercut performance. For 5 months post MEOR, no change observed in watercut but due to higher gross production average oil gain of 41 b/d (equivalent to 36% oil incremental) was realized.

Overall Production Performance – As shown in Figure 7, the average total oil gains from the three strings are 274 b/d (equivalent to 47 % oil incremental). This is beyond the expectation of the project which was estimated about 20% oil gains. The higher oil incremental is mainly contributed from the high watercut well, B-1.

Downhole Pressure Buildup Survey Results - Table 2 shows the downhole pressures buildup survey for the strings. No permeability change observed . However, there was a slight improvement in skin and PI for the low permeability wells, B-2 and B-3. This could be one of the causes that contributed the higher gross oil production as mentioned above.

Table 2 : Pre and Post FBUS Results

	Pre Treatment			**Post Treatment**		
Well	Permeability (mD)	Skin	Productivity Index (stb/d/psi)	Permeability (mD)	Skin	Productivity Index (stb/d/psi)
B-1	1926	25	4	1901	27	4.6
B-2	557	29	1.7	525	23	1.9
B-3	664	33	1.8	663	11	2.5

2) Wellhead Sample Analyses Results

Dynamic Viscosity

Dynamic viscosity tests were conducted for crude oil viscosity and 'as received' wellhead samples to measure the viscosity profile(viscosity vs temparature) of the samples before and after microbes injection (after 6 hours, 3 days, 2 weeks and 1 months of microbes treatment).

Analyses on crude oil viscosity for B-1 (Figure 8), B-2 and B-3 shows insignificant changes after MEOR treatment. This is consistence with the findings during feasibility studies whereby whole oil gas chromatography traces suggest that Bokor oil has been biodegraded to the extend that the normal and branched alkanes have been totally removed due to in-reservoir alteration leaving cyclic alkanes and aromatics.

Test on "as received' wellhead sample for B-1 (Figure 9) at the reservoir temperature of 48°C are in a small range of 21 to 22 cP and 18 to 22.5 cP, respectively. As the temperature lower, the viscosity differences are significant. This can be explained in a way that, at higher temperature, the emulsion tends to break up resulted in a viscosity close to the oil viscosity. As the temperature lower, the emulsion starts to form and therefore larger viscosity differences can be observed, depending on the nature and severity of the emulsified samples.

Hydrocarbon Compositional Analysis

The objevtive of the analysis is to detect any changes in the properties of the crude oils. The bulk properties of the oils that were used to monitor the effect of MEOR process on the Bokor oils are API gravity, bulk composition, pour point temperatures, and wax, sulphur and asphaltene contents.

The API gravities show that the Bokor oils are considered to be heavy with values ranging from 17 to 20 °API. The low API gravities of the oils as supported by whole oil gas chromatography, is due to the complete absence of normal and branched alkanes removed during in-reservoir biodegradation by indigenous microbes and/or water washing taking place in the reservoir after accumulation.

The API gravity of the samples show that there is not much variation in the API values in samples collected after 6 hours, 3 days, 2 weeks and 2 months compared to the pre-treatment samples. This indicates that there is hardly any change in the bulk properties of the oils with soaking time. The results, as expected, are consistent with those reported in the feasibility studies. This finding is supported by other bulk property data such as wax (1.0 to 2.8 wt %), asphaltene (0.03 to 0.13 wt%) and sulphur (0.12 to 0.15 wt%) contents which do not show any significant change in the values with soaking time. The very little or no variation in the bulk property values may be explained by the fact that the Bokor oils accumulated in these shallow A reservoirs have been biodegraded.

Bulk composition of the oils shows that the content of the aromatics (45 to 60 %) is relatively very high in all the samples at the expense of the saturates (34 to 49 %). This classifies the Bokor oils as napthenic-aromatic oils. The shift in the property of the oils from paraffinic to napthenic-aromatic resulted from the removal of paraffins during in-reservoir biodegradation. The high aromatic fraction in the oils relative to the saturates could be one of the reasons for the high tendency of the Bokor oils to form emulsion. This is because the aromatic compounds are more polar and therefore relatively more soluble in water compared to the less polar saturated hydrocarbon compounds.

Whole oil gas chromatographic (GC) traces of all the Bokor oils indeed indicate that the normal and branched alkanes have been totally removed due to in-reservoir alteration or biodegradation. In order to see more clearly the changes in the geochemical properties of the oils with soaking time (pre-treatment, 6 hours, 3 days, 2 weeks and 2 months), histograms were plotted to reflect the distribution of the hydrocarbons contained in the oil. Results show that there is a slight difference between oils treated with demulsifier and those without.

The analysis of oil treated with demulsifier show that there is an increase in the lower molecular weight components at the expense of the higher molecular components with soaking time (Figures 10). This shows that there is a breakdown of higher molecular weight compounds to lower ones, which could result in a slight increase in the quality of the oils. This slight increase in oil quality may not be detected or noted in the bulk property data as the bulk property analyses are less sensitive to changes as compared to whole oil GC or GCMS which are very sensitive.

In the case of oils not treated with demulsifier, the histograms of the hydrocarbon distribution show that there is an increase in the higher molecular weight components relative to the lower ones in samples of up to two weeks soaking time. One possible explanation for this is the increase in the solubility of the higher molecular weight components as a result of biosurfactant activity of the microbes in dissolving the insoluble hydrocarbons found in higher abundance in biodegraded oils. These results, however, are just the opposite of the samples treated with demulsifier. The actual reason for this observation is still unknown but needs further laboratory investigation to understand the behaviour of emulsions and the chemistry of demulsifier. However, for sample with two months soaking time, there seems to be a decrease in the high molecular weight components compared to the two weeks sample. This suggests possible breakdown of high molecular weight components as seen in samples treated with demulsifier.

Emulsion stability

It is anticipated that the treatment will reduce the stability of the crude oil emulsion. The stability of the emulsion is very important to be studied because it will provide information on net oil content (water cut), time to reach stable emulsion, percentage of stable emulsion, effect of temperature and effectiveness of MEOR treatment.

Based on the analysis done for all samples on site, it is observed that the degree of emulsion stability has reduced significantly. Prior to the treatment, the emulsion separation tested using gravity settling without demulsifier method, showed a very low rate. After the treatment, the emulsion become less stable. For example, the rate of separation based on the 1, 4 and 24 hr settling, all the three wells showed a similar trend or curves. Immediately after the open up of the well, the rate of emulsion separation increase to more than 90%. However these effect only observed temporarily, after 2 weeks opened up, the rate decreased and continuously reverted to it initial stages. Figure 11 shows the summary of emulsion separation rate for each strings based on 1 hr, 4 hr. and 24 hr. settling time. Only high water cut well show some degree of reduction on the water cut level, whereas for the other two wells no significant improvement on the water cut level. However the analysis is only based on a grab sample at that particular time and not really representing the actual performance of the water cut.

Under controlled condition in laboratory, the samples were allowed to settle for 7 days at both room and reservoir temperature (48°C). The volume of emulsion, oil and water was monitored.

The observation (Figure 12) for all samples at reservoir temperature (48°C), indicates emulsified crude breakout completely into oil and water less than a week of laboratory time. This will slightly help the fluid to flow faster because the viscosity of the oil and water will be lower compare to viscosity of emulsion.

The trend of emulsion vs. time obtained for all three wells clearly described the effectiveness of the microbial products in reducing emulsion stability. The effectiveness of the microbes in breaking the emulsion decreases as the production time increases when most of oil near the wellbore is being produced.

Formation Water sample analysis

The composition of the formation water before and after the treatments has no significant change[7]. Based on the lab analysis the composition analysis of the three wells showed a typical value for a production wells in Baram Delta Area. The sulfide level of the formation water is significantly low and no significant change after the treatments (Figure 13).

Bacteria analysis

From the test conducted on-site[8,9,10,11], the SRB activity in the three wells is very minimal, in other words the SRB is not detected by the SRB rapid Check kits (below detection level). Based on the experienced in other nearby fields, the SRB Rapid Check method, cannot detect all the SRB present in the water. However, theoretically high sulfide level in the formation water will also an indicative of SRB activity in the wells, and by analyzing at the trend of the sulfide and sulfate levels in the formation water analysis, the level of sulfide detected was significantly low compare to the some higher value in other field in Baram Delta Area. It was observed that there is a slightly increased of sulfide level in the formation water immediately after the well opened up. The effect could be due to accumulation of Hydrogen Sulfide during the close in. However, the level is reduced to it baseline after continuos production. Hence it does confirm that, no significant SRB activity in the three wells before or after the treatments. However for a future test, an alternative method such as prepared SRB media (SRB conventional test) can be considered to analyze the present of SRB in the systems.

Possible Mechanisms of Oil Gains

Three possible mechanisms to explain the changes of the well performances have been made :-

1. **Skin reduction and Improvement in PI** – Based on the pressure buildup tests, it is proven that the microbes can clean up the damaged formation. For this case there could be a solubilization of heavy components that plugged the near wellbore formation.
2. **Demulsification & Destablization of emulsion** – It was physically observed that emulsion problem has been reduced. Though this is not the ultimate objective of the technology application, it helps to improve the oil production. It can be explained by coalescence of oil droplet which bacteria cells act as wetting bridges between oil droplets in the continous phase (Figure 14).
3. **Watercut reduction** – The reduction was significantly observed for the high watercut well(B-1). This could be explained by the possible change in fluid relative permeability due to wettability change and reduce in interfacial tension between oil and water (Figure 15).

Conclusions

Based on the above, it can be concluded that the pilot project was a successful project and has achieved all its objectives. The results can be summarized as follows :-

Production Performance Results

1. Production increase observed is either due to high gross production (improvement in PI), reduction in emulsion stability or reduction in watercut.
2. The total average net oil gain after 5 months post MEOR is 270 bbl/d (47% oil incremental).

Wellhead Sample Results

1. At reservoir temparature, no significant viscosity change observed for both wellhead and crude oil samples. This is due to the fact that Bokor crude has been biodegraded.
2. Viscosity change observed for both wellhead and crude oil samples at surface temp.
3. Hydrocarbon compositional analysis indicates that there is an increase in the solubilisation of heavy components and breakdown of high molecular weight into low molecular weight components.
4. Emulsion stability reduces, thus improves the production/lifting performance of the well.
5. No adverse effect observed in formation water & bacteria (SRB) analysis

Project Economics

1. The total actual project costs are US$ 0.4 Million. Potential reduction in operational costs is possible to further improve the economics.
2. NPV (@15% discounted rate) after 5 months is US$ 0.003 Million (oil price :US$16/bbl).
3. The projected NPV (15% discounted rate) for 9 months is US$ 0.14 Million (oil price :US$16/bbl).

Recommendations

1) To continue monitor the performances of the three(3) wells.
2) It is highly recommended to repeat this project for other well candidates producing from the same reservoir to further ascertain the findings. Higher priority should be given to the wells which have the following elements :-
    a) formation damage
    b) emulsion problem
    c) high watercut
3) To share experiences and results of the project with others.
4) The study on MEOR application on well with emulsion problem should be conducted to have in depth understanding of the mechanisms.
5) To create database to document data, knowledge and experiences for future reference.

Acknowledgements

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Figure 1 : Location map of Bokor field

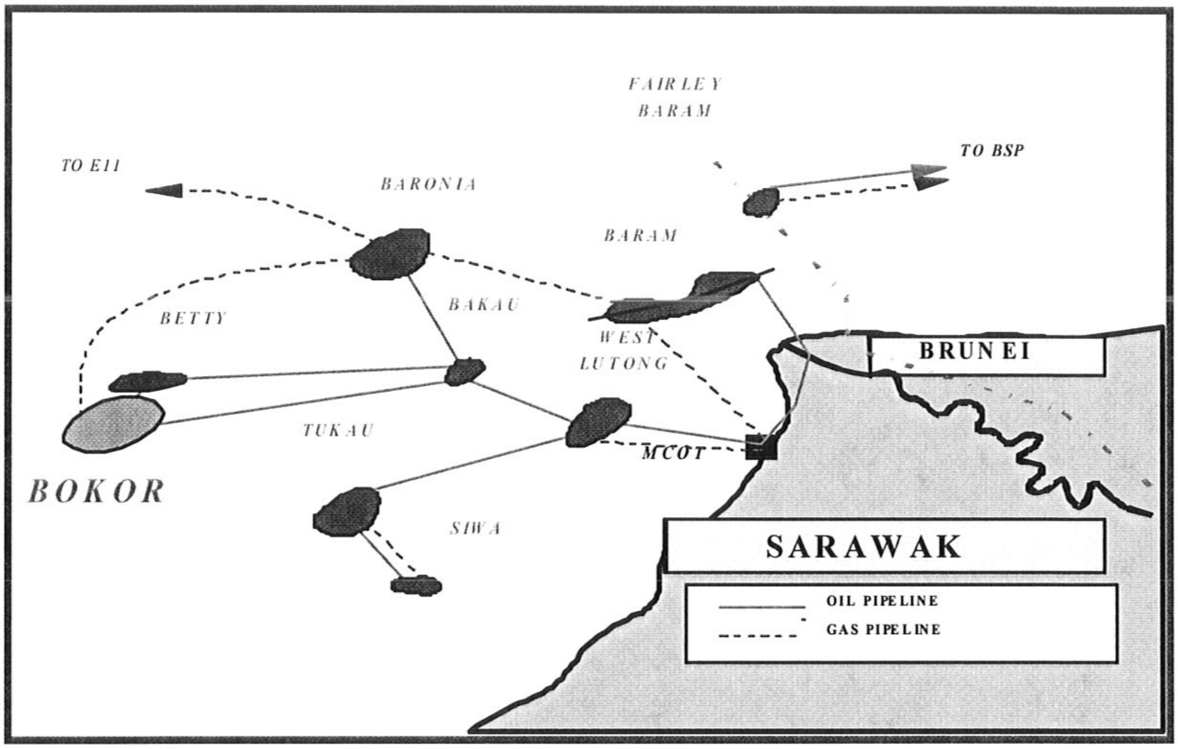


Figure 2 : Flowchart of the systematic approach for MEOR project in Bokor field

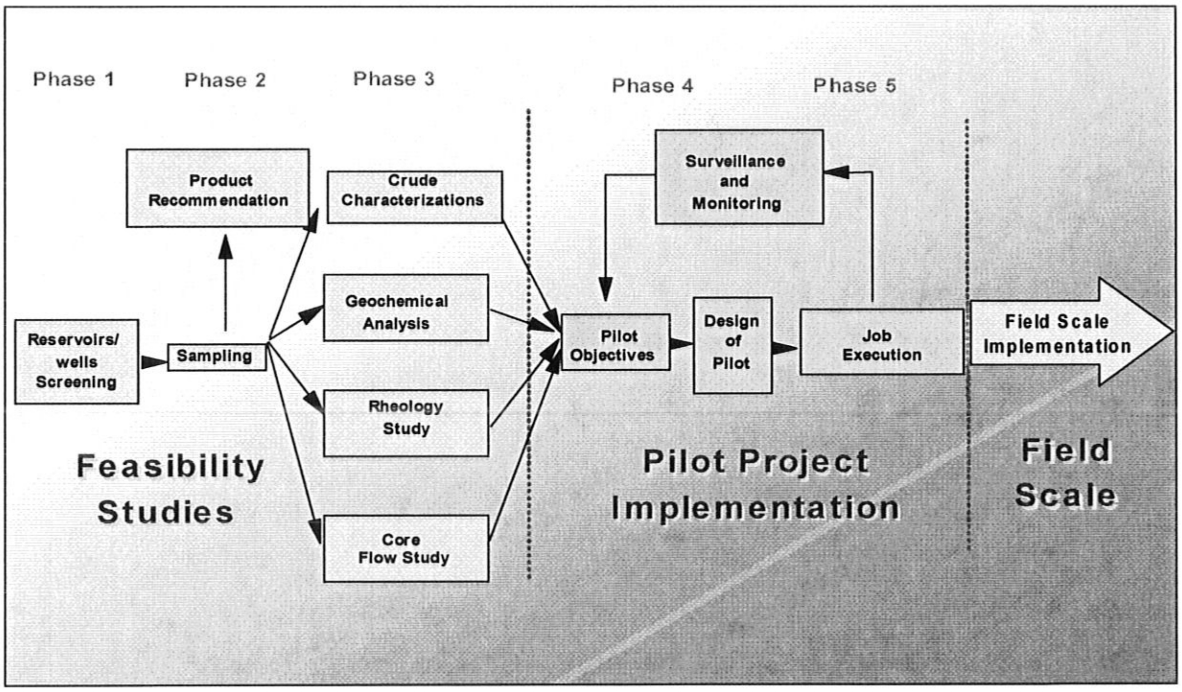
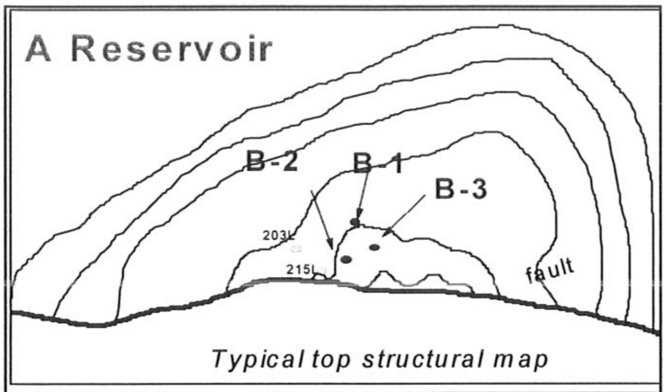


Figure 3 : Location of the well and production performance status



well	oil rate (stb/d)	watercut (%)	GOR (scf/stb)	liftgas (scf/stb)	Reserves (MMstb)
B-1	160	75	180	0.3	0.2
B-2	290	30	150	0.3	0.3
B-3	150	50	150	0.3	0.4
Total	600			0.9	0.9

Figure 4 : B-1 Net oil/watercut Post-MEOR Performance

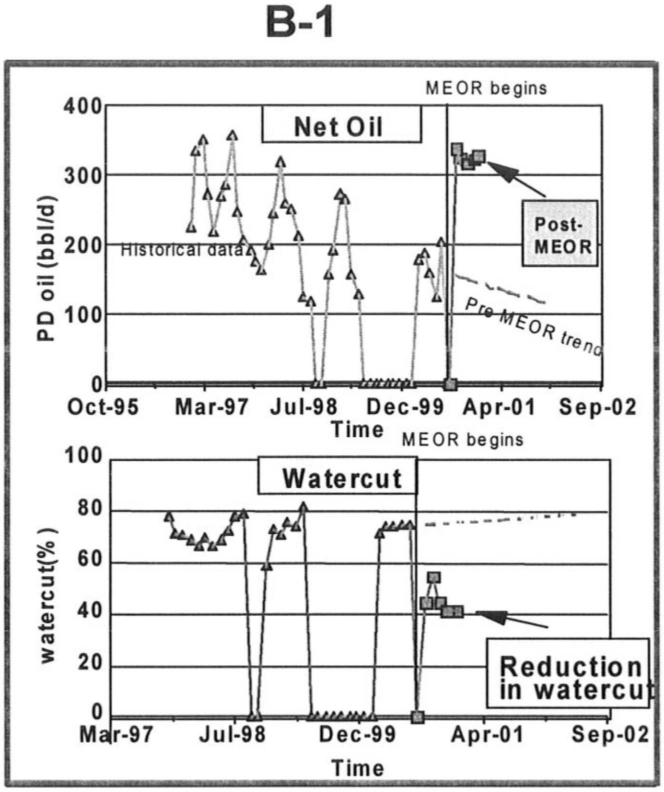


Figure 5 : B-2 Net oil/watercut Post-MEOR Performance

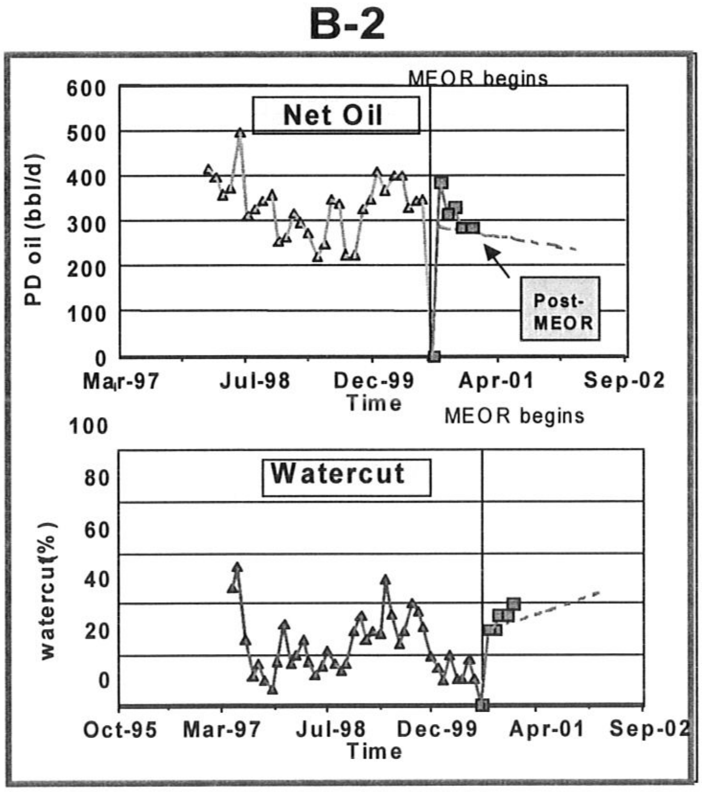


Figure 6 : B-3 Net oil/watercut Post-MEOR Performance

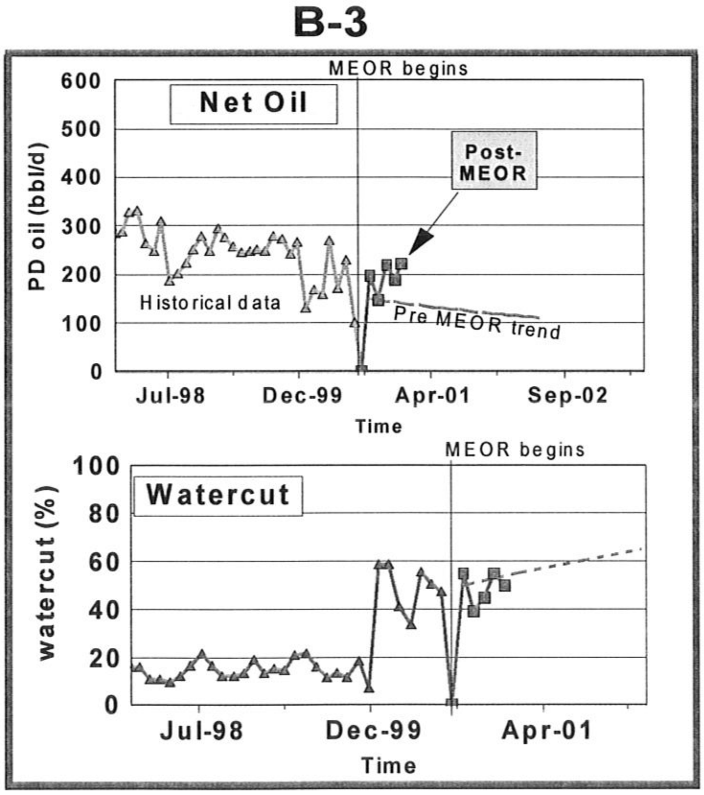
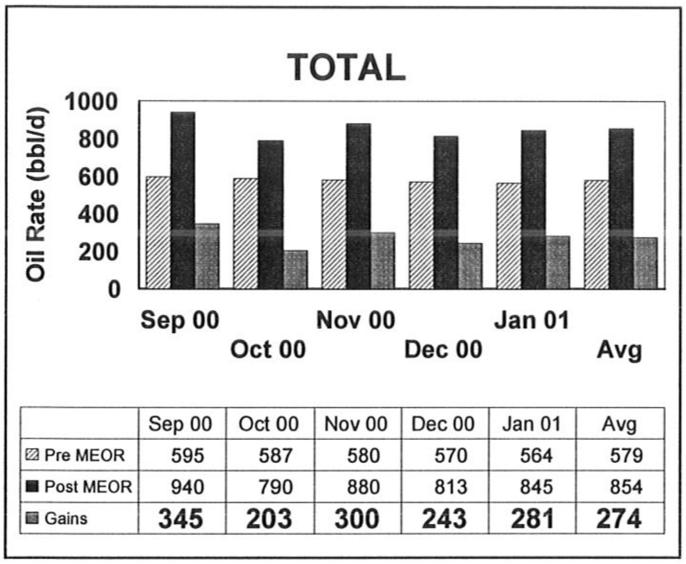
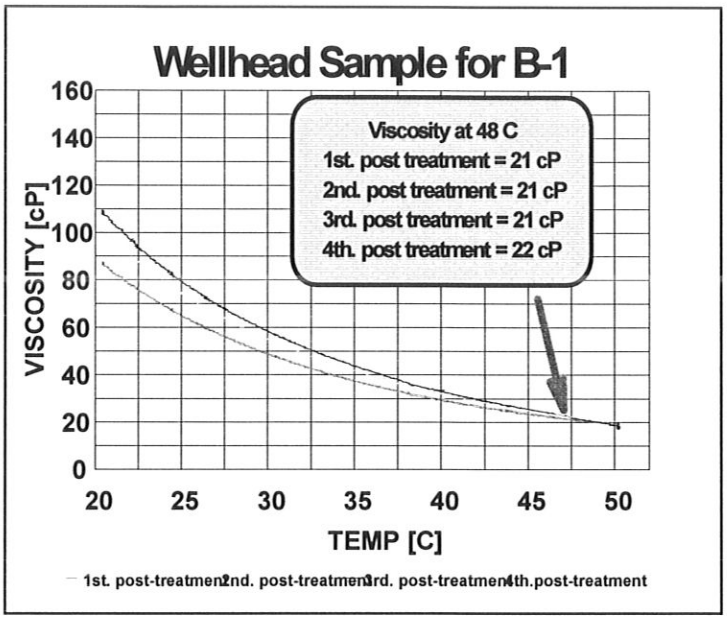


Figure 7 : Total Monthly Average Net Oil Production Performance



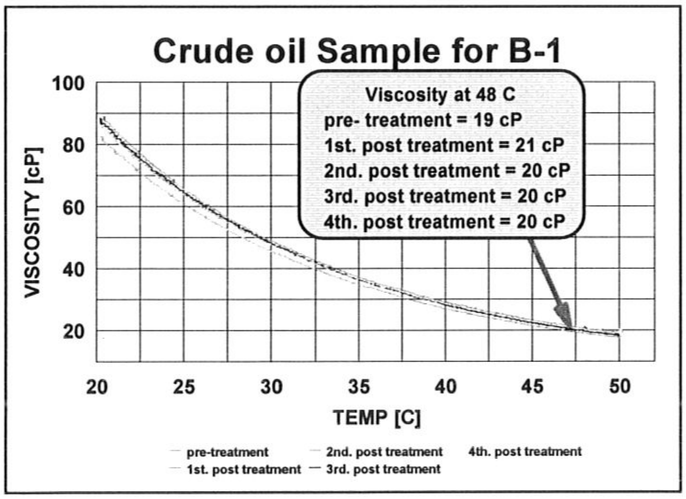
	Sep 00	Oct 00	Nov 00	Dec 00	Jan 01	Avg
▨ Pre MEOR	595	587	580	570	564	579
■ Post MEOR	940	790	880	813	845	854
▦ Gains	**345**	**203**	**300**	**243**	**281**	**274**

Figure 8 : Post MEOR "Wellhead Sample" viscosity analysis



Viscosity at 48 C
1st. post treatment = 21 cP
2nd. post treatment = 21 cP
3rd. post treatment = 21 cP
4th. post treatment = 22 cP

Figure 9 : Post MEOR "Crude oil Sample" viscosity analysis results (vs temparature)



Viscosity at 48 C
pre- treatment = 19 cP
1st. post treatment = 21 cP
2nd. post treatment = 20 cP
3rd. post treatment = 20 cP
4th. post treatment = 20 cP

Figure 10 : Hydrocrabon Compositional analysis results (Pre and Post treatment MEOR results comparison)

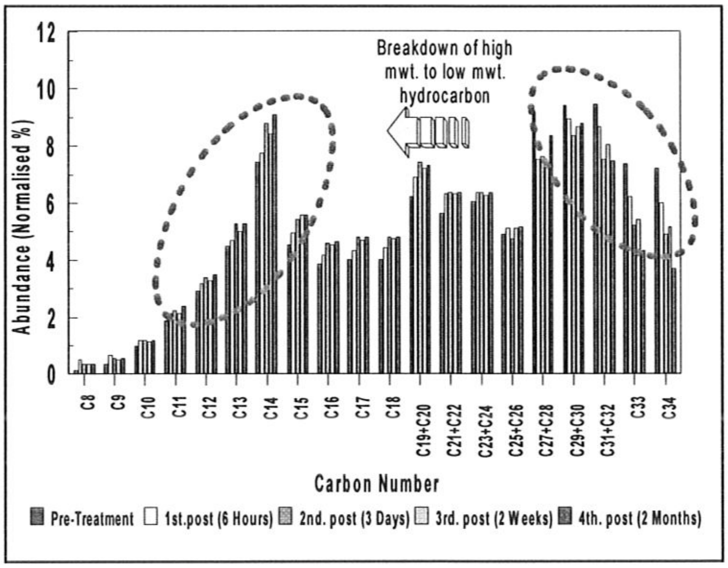


Figure 11 : Emulsion stability results – Onsite measurement

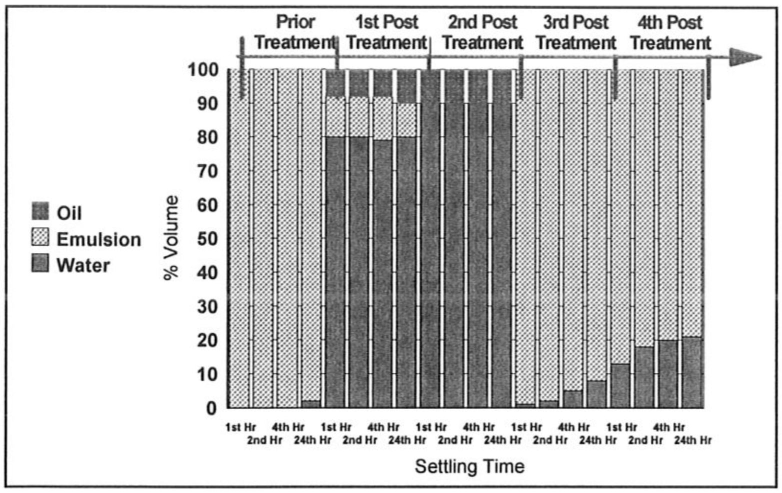


Figure 13 : Formation water analysis results

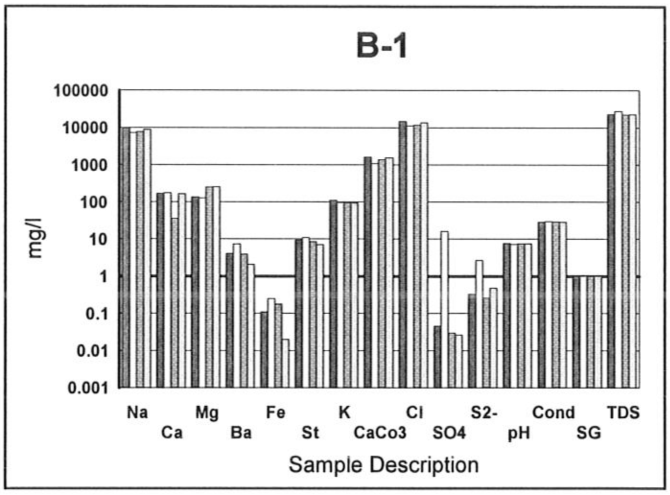


Figure 12 : Emulsion Stability analysis-B-1

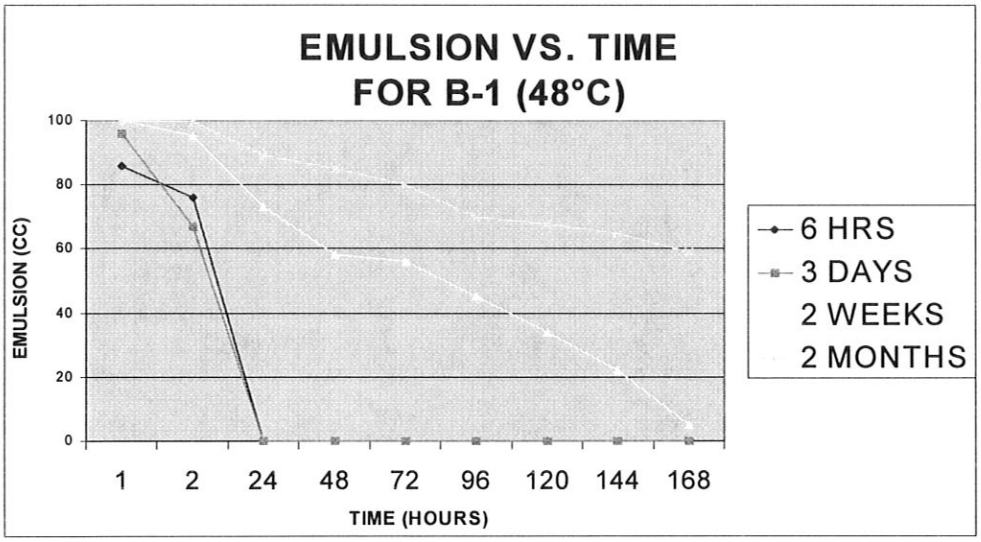


Figure 14 : Mechanism of Emulsion stability reduction

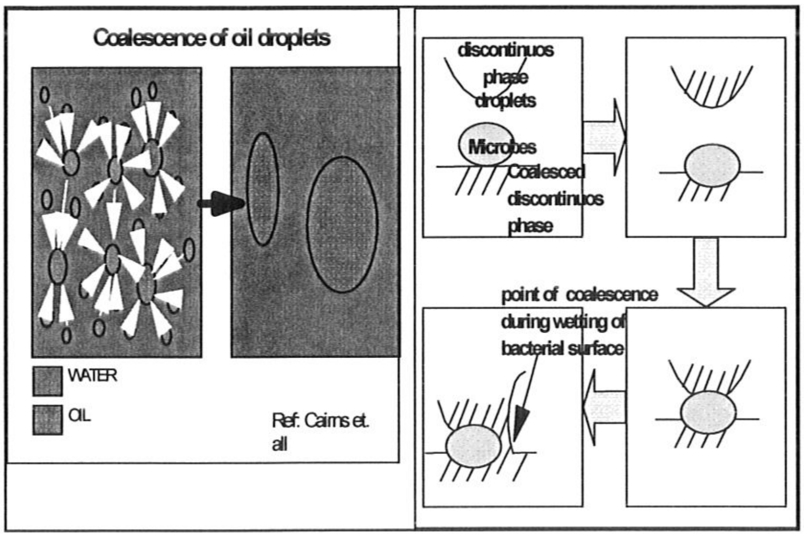


Figure 15 : Possible mechanism of watercut reduction