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Field Implementation of DuPont's Microbial Enhanced Oil Recovery Technology

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Abstract

For the last 7 years DuPont with different partners has done research into the application of Microbial Enhanced Oil Recovery technology (MEOR). In laboratory tests, we have observed in excess of 15% increased recovery factor. This exceeded our expectations. In a field test, described in this paper, we have observed a ~15-20% increase in production rate.

After extensive fundamental research (5) we have learned many critical aspects of microbial EOR. We have demonstrated two mechanisms that exceeded, in the lab, the targeted increase in the recovery factor.

1. Improved sweep efficiency by plugging of high permeable zones thereby forcing water to produce oil from previously unswept parts of the reservoir.
2. Reduced oil / rock surface tension resulting in a change in the wettabilty of the rock and lower residual oil saturation.

This paper describes the field data used to demonstrate the effectiveness of the improved sweep efficiency by using a microbe to plug high permeable zones in a target reservoir – called bioplugging.

Our approach has been to inoculate the reservoir with a microbe that under the optimal nutrient conditions will express the needed function – in this case bioplugging for improved sweep efficiency. The microbe and the nutrients are tailored to the conditions of each reservoir thus giving MEOR the greatest chance for success. We have tested the efficacy of the microbial treatment with a series of slim tube tests and interwell tests.

Our experience with field implementation has taught us important lessons on how to inoculate and feed microbes in an oil reservoir at a scale needed to support the commercial implementation. Issues that had to be address include assuring the effectiveness of the treatment using realistic lab tests, assuring that the treatments do not bypass the reservoir, assuring that the reservoir is not blinded by the inoculation, and understanding the effects of biocides and corrosion inhibitors that are commonly used in the oil field. Production data for the pilot test has shown a change in the decline curve indicating a significant increase in oil production rate and a corresponding decrease in water cut. Oil production has increased in the field by 15 to 20% with a corresponding reduction in water cut. Our ongoing research has provided many insights into the appropriate application of microbial EOR. The unique aspects of each production area, the nature of the oil, the water, the formation matrix, and the background microbial population and their complex interactions must all be assessed when considering the potential application of microbial EOR. The amount of work described for assessing potential MEOR mechanisms is extensive. However, this process has been streamlined and we have been able to assess new target reservoirs for potential MEOR treatments quickly.

We believe that Microbial Enhanced Oil Recovery has the potential to improve the recovery of oil with very low capitol investment and a much smaller environmental footprint compared to other EOR techniques.

Introduction

Much work has been done to understand the application of MEOR in an oil reservoir setting (1). Treatments include both huff and puff and interwell water flooding applications (2). Our focus has been the application of MEOR as an interwell treatment. In this application, the reservoir is inoculated with a selected strain and fed with an optimized set of nutrients in a manner that accomplishes the desired effect deep in the reservoir. A potential target reservoir must meet a set of criteria. The criteria we have developed are listed in Table 1. The fields must be under water flood (Table 1). Water flooding is the means to transport the microbes and nutrients into the reservoir. To support microbial growth, an efficient electron acceptor is necessary (Figure 1). In the anaerobic environment of a reservoir, oxygen is not considered a viable option due to corrosion issues and limited carrying capacity in the injected water. Addition of sulfate could encourage oil well souring by sulfate reducing organisms. Therefore, we have restricted ourselves to a limited set of electron acceptors, concentrating mostly on nitrate. The pore throat diameter of the rock (Table 1) must be high enough to allow passage of microbes (3). The next three criteria in Table 1, temperature, salinity and pH, are the keys to determining the type and diversity of life seen in the reservoir. In most cases it is the combination of the temperature and salinity that are the determining factors since pH is often buffered to a neutral value due to natural minerals in the clays or cements of the rock. Very high oil viscosity, (Table 1), makes it difficult to evaluate fluids from a reservoir in sandpack or microbiological experiments. Down hole pressure is also a consideration. At extreme pressures only pressure tolerant microbes (piezophiles) will operate efficiently.

Table 1 – Criteria for MEOR applications.

Production mode	Secondary – fields under water flood
Metabolic Pathway	Anaerobic with restricted electron acceptor
Permeability	>50 to 100 milliDarcy
Reservoir Temperature	< 60 – 70ºC (<140 – 160ºF)
Salinity (injected and produced waters)	~<8% Total dissolved solids (TDS)
pH	5 – 9 (6 – 8 ideal)
Oil viscosity	<500 cp (preferred)
Down hole pressure	<3000 psi (preferred)

This paper presents data that shows improved oil recovery for a field pilot using bioplugging of water channels that result in improved sweep efficiency. This is a continuation of the field trial described in SPE146483 (Reference 4 -- presented at the 2011 SPE ATCE). When doing this field pilot several aspects were addressed:

- Making certain that the targeted mechanism (improved sweep efficiency by bioplugging) is suitable for this field.
- Assessing the effects of oil field chemicals including biocides and corrosion inhibitors on the effectiveness of the treatments.
- The fact that the pilot was done on individual wells and not on the entire battery or unit level. Only three (out of ten) injectors were treated in the field that was serviced by the central fluid processing unit at the battery.
- Gathering reliable data to monitor the progress of the well test

These aspects are discussed in detail below for this MEOR well test.

Targeted Mechanism

The oil reservoir being tested meets the criterion outlined in Table 1. Implementing MEOR is described in more detail in earlier papers (4, 5). Due to the high salt content of the injection and produced waters, it was important to select an organism that can tolerate a higher salt content. Using screening tests described in a previous paper (5), an organism and nutrients were selected to work under high salt conditions. As part of the planning process for the well test, realistic lab tests were run to assure the effectiveness of the treatments using authentic well fluids (live injection waters, dead oil). In this case, hydraulically constrained slim tubes similar to those previously described (4) were prepared and the proposed inoculation and nutrient feeding protocol was scaled to run on these slim tubes. In addition, the slim tube tests described below provided a controlled test bed to measure important properties of the microbiology that can impact the operation of a MEOR treatment. As illustrated in Figure 1, the expression of a desired EOR function requires microbes (top of the triangle) a carbon source (lower left of the triangle) and an electron acceptor (lower right of triangle). The unique combination of microbes and nutrients used in this well test causes the generation of extracellular polymeric substances that form a biofilm which reduces the permeability of preferred water channels in the reservoir. This is often referred to as bioplugging. Restriction of these flow channels should lead to redirection of water into less swept or unswept zones thereby improving the sweep efficiency of the water flood. There are three characteristics of the target reservoir treated in the pilot test that led us to believe that bioplugging would lead to improved sweep efficiency.

1. Mobility ratio. The oil in this reservoir has an API gravity of 23 and a viscosity of 56 cp. Consequently the mobility ratio is unfavorable and will result in water fingering in the formation even for a homogenous reservoir.
2. Permeability variation. The formation grades from shale to very fine grained sand. Permeability varies considerably with depth. Figure 2 shows the permeability plotted as a function of depth through the pay zone. This profile is based on core analysis for one of the producer wells used in this field test. High permeable streaks are apparent in this profile. This same data was used in a log normal plot of the permeability, Figure 3. From this plot, the estimated Dykstra-Parsons permeability variation factor, Equation 1, can be calculated. It is about 0.77 indicating that the pay zone is fairly heterogeneous. This high value for the permeability variation would indicate the potential for poor vertical sweep efficiency even if the oil-water mobility ratio was favorable.
3. Directionality of the permeability. There is some directionality to the permeability in the target field. The flooding pattern is an inverted nine spot pattern. Due to this directionality of the reservoir, the production wells along a diagonal line from the injections have higher water cuts than other producers in the pattern. These same producer wells along the diagonal have watered out sooner than others.

Equation 1: Dykstra-Parsons permeability variation factor

$$V = (k_{@50\%} - k_{@85\%}) / k_{@50\%}$$

Where
k@50% is the permeability at 50% of the samples
k@85% is the permeability at 85% of the samples

These three characteristic, the unfavorable mobility ratio, the permeability variation and the directionality in the reservoir make the application of the bioplugging mechanism a viable way to improve sweep efficiency.

Effects of field chemicals

The production of oil and gas from oil reservoirs requires maintaining equipment and pipelines underground or on the surface. This equipment and pipelines come in contact with potentially corrosive fluids in oil-field applications including injection brines used in water flooding operations. Corrosion can be a significant problem in the petroleum industry because of the cost and downtime associated with replacement of corroded pipelines, well tubing and associated equipment.

Sulfate reducing bacteria (SRB), which produce hydrogen sulfide (H_2S), are amongst the major contributors to corrosion of ferrous metal surfaces and oil recovery equipment (9). These microorganisms can cause souring, corrosion and plugging. To combat corrosion, chemical inhibitors including biocides are used to decrease the corrosion rate of a metal. These chemicals are often toxic to microorganisms. Corrosion inhibitors or biocides in the injection water can be particularly problematic. Their affects can persist well beyond the equipment that the chemicals are meant to protect. Detecting the presence and the effects of corrosion inhibitor chemicals or biocides is an important consideration for the application of any MEOR technology. DuPont has evaluated and understood the impacts of these chemicals on our MEOR technology and we have overcome this hurdle successfully. In the MEOR pilot described in this paper, corrosion inhibitors and biocides were being used. However, our tests determined that these chemicals would not impact the performance of the MEOR technology.

Field test on only part of a unit.

The MEOR pilot was done to three injectors that communicated to 17 producers in an inverted 9 spot pattern. This represents only about a third of the production from the central fluid process unit or battery that services this part of the field. Consequently, any impact from operational changes to the field not treated with the MEOR technology must be factored into the evaluation of its success or failure. In the best case, there would be no changes to the wells in the part of the field unaffected by the pilot. A number of mechanical difficulties (e.g., loss of injector support or production well outages due to tubing failures or freeze up in the winter) can impact the operation of specific wells both inside and outside the pilot but in the same unit. These difficulties must be taken into account in the test evaluation. In this case, we designed the test to get additional data to support any change in production data. As described below, these data included the injection pressures of the treated injectors and the water cuts from the producers in the pilot. Clearly, a better way to pilot is to run the test on all the wells serviced by the fluid processing unit.

Field Data

One of the most important challenges when implementing MEOR in the field is the ability to gather meaningful field data. Improved sweep efficiency by selective bioplugging of watered out channels is the goal of this interwell field test. Increased injection well back pressure (at a constant injection rate) is a necessary (but not sufficient) leading indicator that the required bioplugging has occurred. Measuring the injection pressure at a constant injection flow in a consistent manner in the field is the challenge. We continued to use a method to measure injection pressure developed for this pilot and described in an earlier article (4). Figure 4 shows the injection pressure data for the three injectors in the pilot using the method described in reference 4. There is clearly an increase in the back pressure for two of the wells. The third well only showed a pressure response after being reworked due to mechanical difficulties. The increase in injection pressure happened within a few months and was sustained for the duration of the MEOR test. This clearly demonstrates that we have been able to develop significant and sustainable bioplugging in this reservoir as this MEOR test was designed to do.

Figure 5 shows oil production at the unit level. Most of this production was not affected by the MEOR treatment. Only about a third of the injection water generated by this unit was going to the 3 treated injectors. Despite this, within four months of the start of the MEOR test, there is an increase in production above the decline curve. This increased production becomes significant if a new production trend is established. As shown in Figure 5, the production from this unit is following a new trend curve that is shifted higher and has a shallower slope than the pre-MEOR decline curve.

Water cuts from the 17 affected producers were monitored to confirm that the increased production was a result of the MEOR treatment. The water cuts for the affected producer wells were measured through the test and composite water cut for these groups of wells was calculated. Fifteen of the seventeen producer wells showed a significant decline in water cuts. The change in the composite water cut and corresponding increase in oil production for the affected wells is shown in Figure 6. Negative deviations in water cut indicated reduced water cuts resulting in more oil being produced (the rates on the pump jacks were held constant). The increased oil produced calculated from the water cut data is consistent with the increased production shown in Figure 5.

Conclusions

Our ongoing research and work on a pilot test have provided many insights into the appropriate field application of microbial EOR. The unique aspects of each production area, the nature of the oil, the water, the formation matrix, and the background microbial population and their complex interactions must all be assessed when considering the potential application of microbial EOR. In this paper we discussed these:

- Reservoir characteristics and conditions must match the intended EOR mechanism and growth environment for the microbes. In this pilot the reservoir characteristics indicated a need to improve sweep efficiency – which was the target of the MEOR test.
- Toxic affects of oil well chemicals used in the field must be considered. In this pilot, those affects were negligible. But in other reservoirs we have found them to be significant impediments to a successful MEOR treatment.
- If a pilot is done on only part of an operating unit, additional supporting data is needed to confirm the treatment's success.
- The MEOR pilot described in this paper appears to have increased production by an additional 15 to 20%. Confirmation by testing an entire unit is being planned.

We believe that Microbial Enhanced Oil Recovery has the potential to improve the recovery of oil with the potential for very low capitol investment and a much smaller environmental footprint compared to other EOR techniques.

References

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Figures

Figure 1 -- “Fire” triangle for microbial metabolic activity.

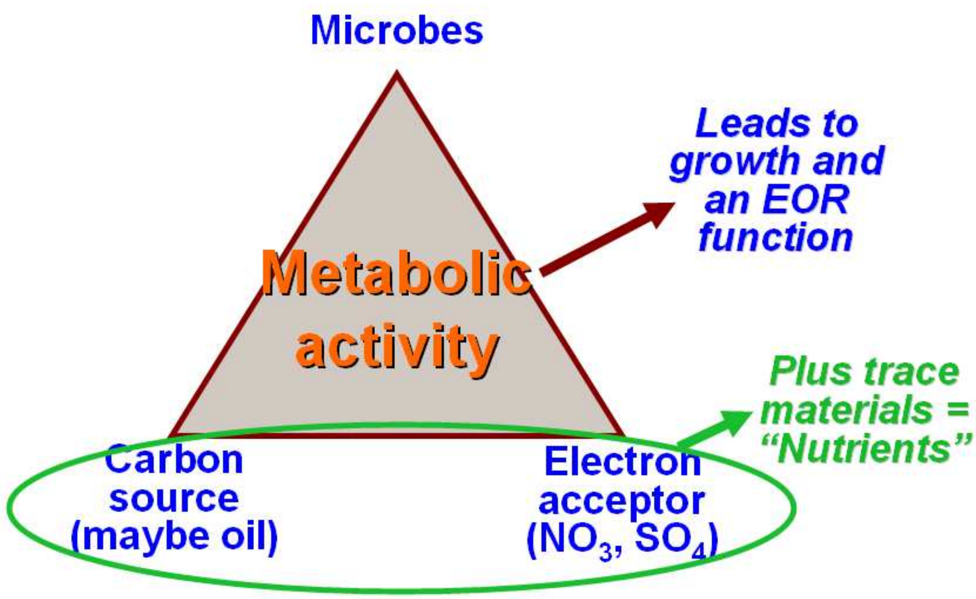

Figure 2 – Permeability as a function of depth of the target reservoir.

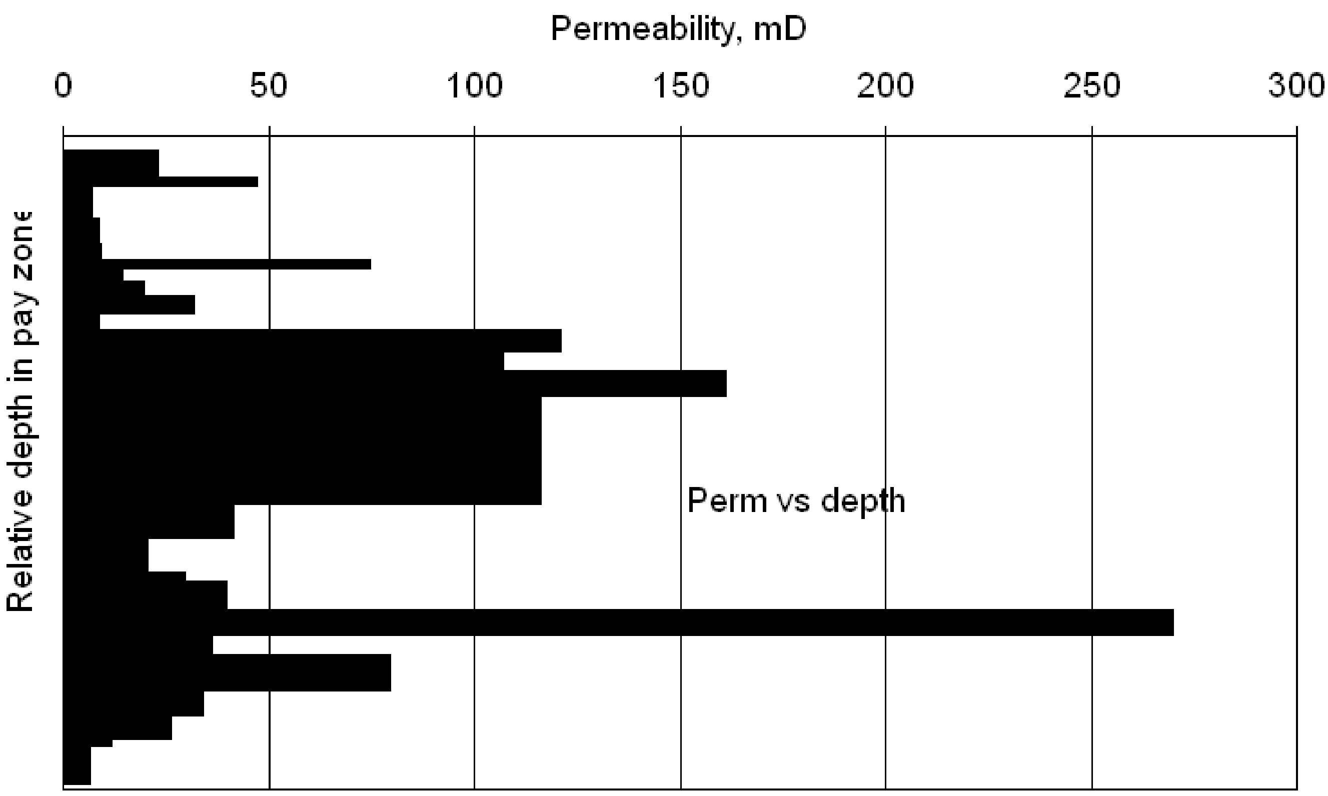

Figure 3 — Log normal permeability distribution from the data in Figure 2. The Dykstra-Parsons permeability variation factor is estimated to be 0.77 [0 means uniform and 1 means extremely heterogeneous].

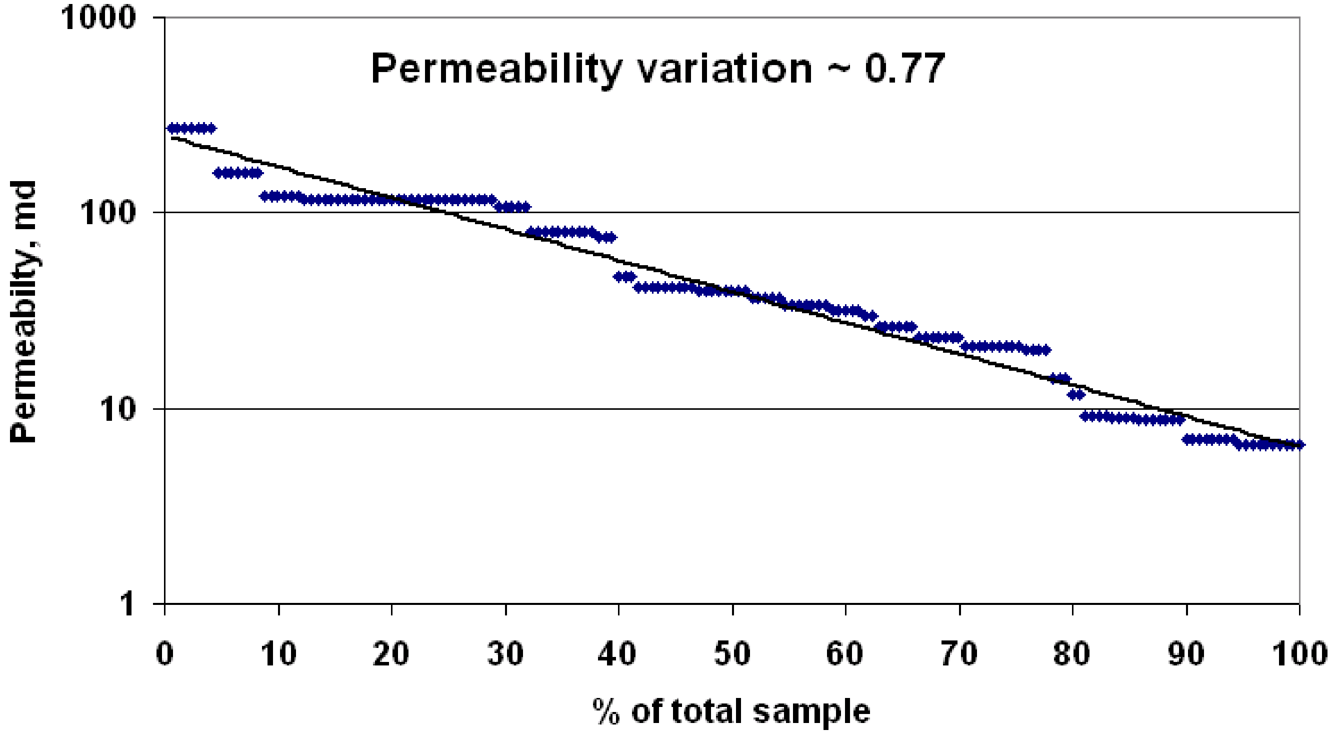

Figure 4 – Injection pressure for the three treated wells. .

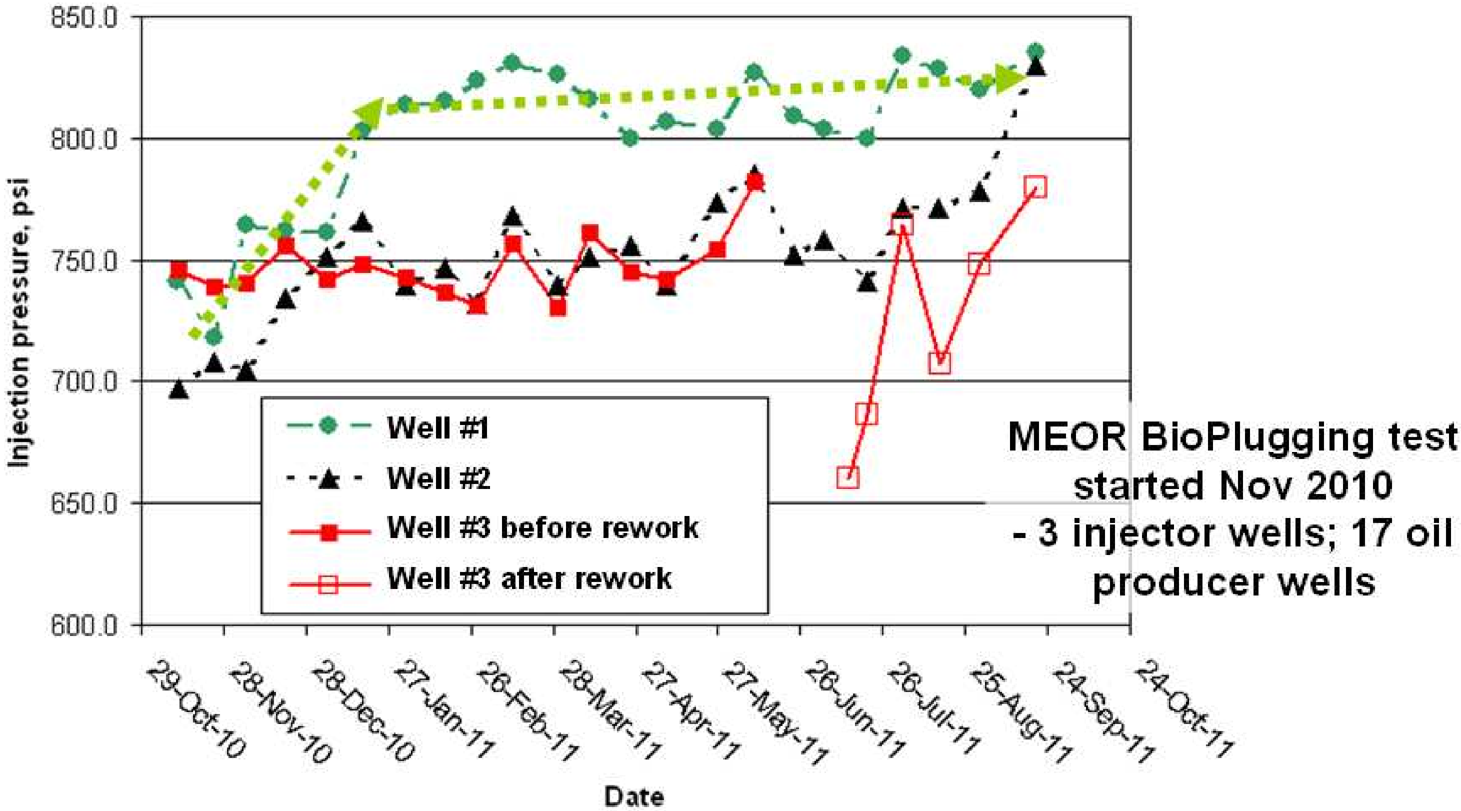

Figure 5 – Oil production at the battery level. Only 3 out of 10 injectors serviced by this battery were treated (~30% of the injection water). .

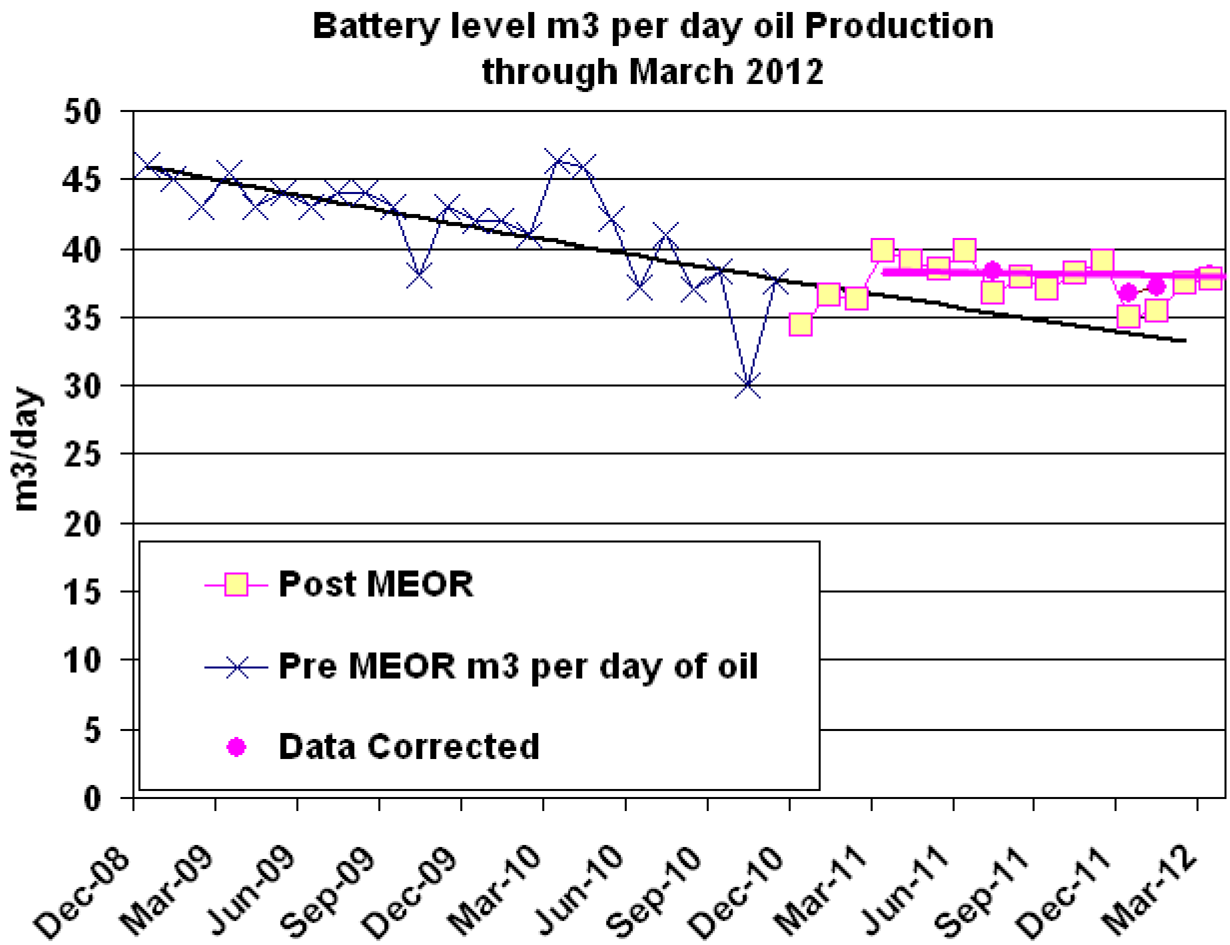

Figure 6 – Change in water cut and relative increase of the oil production for the producer wells in the test.