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Considerations for Field Implementation of Microbial Enhanced Oil Recovery

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Abstract

For the last 6 years DuPont with different partners has done extensive fundamental research into the application of Microbial Enhanced Oil Recovery technology (MEOR).

We have demonstrated two mechanisms that have shown in the lab, more than a 10% increase in the recovery factor.

1. Increased 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 lower residual oil saturation.

This paper describes the key laboratory tests and preliminary field data used to evaluate these two mechanisms.

Our approach has been to inoculate the reservoir with a microbe that under the optimal nutrient conditions will expressed the needed function -- bioplugging or reduced oil saturation. The microbe and the nutrients are tailored to the conditions of each reservoir thus giving MEOR the greatest chance for success. This paper presents challenges that were raised as a result of extensive lab work that are relevant to the implementation of MEOR on a field level.

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 in about 6 months.

We believe that Microbially Enhanced Oil Recovery has the potential to improve the recovery of oil with the potential for very low capital 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 n 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. 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 key criteria 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. Down hole pressure is also a consideration. At extreme pressures only pressure tolerate microbes (piezophiles) will operate efficiently.

Table 1 – Criteria for MEOR applications.

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

It is important to have a holistic understanding of the entire system that may impact the efficacy of the treatment. This paper presents challenges that were raised as a result of extensive lab work that are relevant to the implementation of MEOR on a field level. Challenges include

- Effectiveness of treatment using slim tube tests
- Assuring that the treatments (nutrients and inoculum) do not bypass or short circuit the reservoir
- Assuring that the well is not blinded by the inoculation
- Minimizing sulfide production during the well test
- Assuring containment of the microbes within the well environment
- Gathering reliable data to monitor the progress of the well test

Each of these challenges is discussed below for a current ongoing MEOR well test.

Effectiveness of the treatment in a slim tube test

The oil reservoir being tested meets the criterion outlined in Table 1, except that the salinity is slightly higher than 6% total dissolved solids listed there. The reservoir has a high vertical perm variation and a poor oil-water mobility ratio. Consequently, improved flow conformance by permeability modification is the focus of this well test. Implementing this MEOR mechanism is described in more detail in an earlier paper (4). 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 (4), an organism and nutrients were selected to improve sweep efficiency by forming bio plugs under high salt conditions. As part of the planning process for the well test, slim tube 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. The proposed inoculation and nutrient feeding protocols were scaled to run on these slim tubes. Figure 1 shows the effectiveness of the treatment using the selected plug bug as compared to a nutrients only treatment. The pressure drop in this slim tube was measured for several months through out the preparation and treatment of these slim tubes. The base permeability (about 1 Darcy) of the slim tubes was measured during that time. This is higher than the permeability reported for the target reservoir. Thus, successful bioplugging of these slim tubes with a reasonable amount of nutrients suggests the possibility of successful application of this method in the oil reservoir. Multiple slim tubes were treated in parallel in the same set up. Two slim tubes are shown in Figure 1. The pressure drop for both slim tubes was stable before inoculating on day 15 of the test. The red bars indicate the timing and duration of the batch fed nutrients for both slim tubes starting after the shut in period. As shown in Figure 1, the pressure drop for the slim tube inoculated with the selected bio plugging microbe showed about a 4x increase in the pressure drop as a result of bioplugging through day 48. At this point, the pressure drop had become too high to continue and this slim tube was shut down, removed from the apparatus and examined. The other slim tube (“inoculated” only with live injection water) continued to be fed with nutrients. It continued to show no evidence of bioplugging for another month at which point this slim tube was shut down as well. This slim tube lab test provided evidence that the inoculation and nutrient feeding protocol had a good chance to form bio plugs in this oil reservoir.

Detecting short circuits in the reservoir

The oil reservoir being tested has experienced some water breakthrough events or short circuits according to the operator. If such an event were to occur for the one of the injector – producer pairs being used on an interwell test; it would potentially result in the inoculum and nutrients bypassing the reservoir. Consequently, a bio mass bloom may result in the water separation equipment in the produced fluid processing area. This concern prompted us to perform a dye test on the injector wells to be used in this interwell test (2). This dye test, if repeated after the MEOR treatment, would also provide another diagnostic tool to be used to understand changes in the reservoir that may have occurred as a result of the MEOR treatment. Since there were multiple injectors that had some common producers, the dye test was staged in such a way that Fluorescein dye was used in combination with various salts. In this way, the presence of the dye would indicate water breakthrough and further analysis (ion chromatography) would indicate which injector was responsible for the breakthrough. If such a breakthrough event was detected, a shut in period would be added to the inoculation protocol for the injector that was responsible for the breakthrough. This would eliminate the production of nutrients in the production fluids by providing time needed by the microbes to consume the nutrients. If a gross breakthrough was detected (transit times a matter of hours) then it was likely we would not inoculate that injector. The dye test was started more than a month before the scheduled well inoculation. The sampling protocol for the produced fluids was designed to have a higher sampling rate immediately after dye injection and a lower sampling rate as time progressed. This would assure that a bypass event would be "caught" since a faster bypass event will result in a dye pulse that is high in concentration but short in duration. The sampling protocol was stretched out to nearly a month in hopes that we would be able to measure the short part of the residence time distribution of the fluids in the reservoir. Despite our best efforts, no dye was ever observed in any samples. No dye was observed even when a sensitive quantitative measurement technique was used that could "see" the dye when not evident by eye. This was good news and assured us that there would be no issues with nutrients being produced that would foul water / oil separation equipment. However, we were unable to observe the residence time distribution in the reservoir. Although we had no issues with short circuits in this reservoir, consideration should be given to detecting them and modifying procedures when operating in fields that are known to have had short circuits.

Well blinding during inoculation

The limit on reservoir permeability shown in Table 1 relates to the size of the pore throats relative to the size of the microbe. The range shown is very conservative since there is not a one to one correspondence between pore throat size and permeability. Pore throat length and torturosity also impact permeability. The challenge is to have enough room to pass the microbes through the pore throats. This challenge is a bit more complicated when trying to pump a high concentration of microbes through porous media. Transient pressure increases have been observed when inoculating authentic cores with a high concentration of microbes (5). In this case, the cores met the minimum permeability requirements and would allow the microbes to transit through the pore throats. However, high concentrations of microbes can bridge the pore throats – temporarily blinding the rock face. In addition, microbes can form agglomerates under certain conditions and de-agglomerating them is important to assure that single cells are present at the rock face. Inoculation procedures for the injector wells were modified to minimize the formation of agglomerates (6, 7) and to detect blinding of the well early in the inoculation protocol. If blinding was detected then procedures were in place to re-inoculate at a lower cell concentration. The injector wells were pre-inoculated with a small amount of the inoculum at the desired cell concentration (about 10^8 cells/cc). A pumper truck was used to pump a small amount of inoculum into the well at a fixed flow rate. This was followed by clean injection water from the pumper truck. Accurate flow and pressure instrumentation on the pumper truck and at the well allowed for the continuous monitoring of the injection pressure as the slug of inoculum traveled down the well and into the face of the formation. The transit time to the face of the formation was estimated from the tubing volume and flow rate. No increase in the injection pressure was observed for any of the treated wells when the inoculum entered the face of the formation. Consequently, the full volume of the undiluted inoculum was subsequently pumped into the wells. Again, no pressure increase was observed when the much larger volume of the full inoculum was pumped into any of the injector wells. Although we were able to use the full undiluted inoculum in these well tests, it is important to consider measures to assure that blinding of the well face will not occur when inoculating wells in a different formation or even other untreated wells in the same formation. Procedures to assure proper de-agglomeration of the cell mass and procedures to detect blinding should be in place as they were for this well test.

Eliminating sulfide production

The slim tube tests described above also provide a controlled test bed to measure other important properties of the microbiology that can impact the operation of a MEOR treatment. As illustrated in Figure 2, 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 presence of sulfate in the injection water along with an accessible carbon source plus sulfate reducing bacteria can lead to undesirable sulfide production and oil well

souring. Sulfate is in sea water and is often found in most brines used for injection water. Recent work on the microbiology of petroleum systems (8, 9) shows a high incidence for the presence of sulfate reducing bacteria in oil well systems. Consequently, in most cases any excess source of carbon provided as part of a MEOR well treatment can lead to unwanted sulfide production in the field. Our approach has been to use nitrate as the electron acceptor. The key is to have the nitrate in excess compared to the source of the carbon. In this case, the source of carbon will be exhausted by the nitrate reducing bacteria before sulfate reducing bacterial can use it. Further, an excess of nitrate is known to suppress oil well souring (10). The utilization of the carbon relative to the nitrate will depend on detailed metabolic activity of the microbe population. This microbe population will be a combination of both the inoculated microbe and the background microbes present in the well system. Consequently, the carbon utilization must be measured under conditions representing the microbial community in the inoculated reservoir in order to assure that nitrate is in excess.

Data from the slim tube test described above provided data to determine carbon utilization for the oil reservoir targeted for our MEOR treatments. During each batch feeding of the slim tube, some nutrients are not consumed. These can be observed by ion chromatography in the produced waters of the slim tube. Samples must be taken quickly and carefully in order to minimize further metabolic activity in them. Figure 3 shows the concentration profile versus residence time for unreacted nitrate in the produced waters from the slim tube. The curve drawn through the data is the fit of the data to a simple dispersion model of the slim tube. Remarkably, the dispersion length found from the model fit is very consistent with many slim tubes (and sand packs) we have constructed and tested over the years. In this specific set of samples, illustrated in Figure 3, there was no carbon source detected. It had been completely consumed in the slim tube. This demonstrates that the nitrate was in excess relative to the concentration of the carbon in this nutrient mix. This type of measurement was repeated for many batch feedings. In the first few batch feedings immediately after inoculation, both the carbon source as well as the nitrate is observed in the produced waters from the slim tubes. The microbes have not established a large enough presence in order to “grab” all the nutrients as the batch of nutrients pass through the slim tube (under constant flow conditions). This is consistent with the fact that not much pressure drop has developed from bio-plugging (Figure 1). Analysis of later batch feedings (once the bioplugging has developed) shows only nitrate or nitrite but no carbon source – as in the case shown in Figure 3. The concentration of carbon source and nitrate + nitrite measured in the produced water of the slim tube for many batch feedings is shown in Figure 4. The concentration of the carbon source is shown on the Y axis. The nitrate plus nitrite is shown on the X axis. The first product of nitrate reduction is nitrite. Nitrite still has a great potential to accept electrons and suppress sulfate reduction activity. At most nitrite is about 10% of the nitrate in these data. Near the origin in Figure 4, the data shows no carbon source – the data lies along the X axis. This clearly demonstrates that the nitrate is in excess for the nutrient mix developed for this organism and in this back ground of organisms present in the injection water. At greater than 500 ppm nitrate + nitrite, there is an upward trend in the data. The carbon source and nitrate + nitrite are present in the produced water. There appears to be a linear relationship between the residual carbon and nitrate + nitrite. The slope of this line is the consumption or utilization of carbon relative to nitrate. Using this carbon utilization, the formulation of the nutrient can be optimized to assure that excess nitrate will be present once all the carbon is consumed. This optimized nutrient feed was subsequently used in the interwell test described above. We expected to eventually see the nitrate in the produced waters from the field. Figure 5 is the nitrate/ nitrite analysis of the produced waters from the producer wells in the field being treated. Nitrate appears to breakthrough at 4 months after the start of the test (well was inoculated and periodic batch nutrient feedings were started). Only a slight amount of nitrate is observed – but enough to assure us that the carbon source being supplied to this MEOR test is not being used by sulfate reducing bacteria. The timing of the appearance of the nitrate is significant. The 4 months should correspond to the fastest transit time in the reservoir for the wells being tested. This is consistent with the dye tracer test discussed above. After 6 months, nitrite is detected (Figure 5). The delayed appearance of the nitrite may reflect the evolving microbiology of the reservoir.

Containment of the microbes

One of the selection criteria for the microbe is not to be pathogenic (BioSafety Level or BSL 1). Despite this, it is important to understand where the inoculated microbe ultimate ends up and at what concentration. The best outcome is for the inoculated microbe to remain in the reservoir and never be at a significant concentration in the produced water. To help provide an indication of the fate of the inoculated microbes in the reservoir, the effluent concentration of the inoculated microbe was monitored in a slim tube experiment that was nearly identical to the one described above. After inoculating the slim tube with live injection water, an effluent sample was taken and cell counts were measured, Table 2. A day later the slim tube was inoculated with our bioplugging organism. The cell counts of the inoculum are also shown in Table 2. The bio-plugging microbe was about 100 times higher in concentration than the native microbes in the live injection water. Following inoculation this slim tube was shut in for 5 days. The control slim tube was inoculated with only live injection water and was also shut in for 5 days.

At the end of this shut in period, sterile injection brine was pumped onto both slim tubes and nutrients were periodically fed to the slim tubes. The same total amounts of nutrients were batch fed in this manner to both slim tubes.

Throughout this test, the slim tube's absolute pressure and the pressure drop across each of the slim tubes were automatically measured and logged for the two slim tubes. After 10 days, there was a discernable increase in pressure drop in the inoculated slim tube that became more pronounced with time. At the end of 30 days, the pressure drop had increased by a factor of 4. At this point, an effluent sample from both the control and the slim tube inoculated with the bioplugging microbe was taken and a population study was done. This study was done by streaking the effluent samples onto LB plates, allowing the colonies to grow and then randomly picking and typing the colonies. The results are shown in Table 3. The slim tube inoculated with bioplugging microbe show that about 5.7 % of the colonies were bioplugging microbe. In contrast the control slim tube showed no colonies with this identity at the sampling level to which this experiment was done. This indicates that the bioplugging microbe will be a very small percentage of the free swimming or planktonic population and that the inoculated microbe will be contained in the reservoir. This may be indicating the effectiveness of the bioplugging microbe at sticking to the sand inside the slim tubes – as expected.

TABLE 2: Cell counts of the Inoculum used on the slim tube.

Analysis	Concentration (colony forming unit [CFU] per cc.
Cell counts pre-inoculation with live injection brine	8.1E+04 CFU/cc
Cell counts of the inoculum	4E+06 CFU/cc
Cell counts in effluent after 5 day shut in	2.2E+06 CFU/cc

Table 3: Estimated % population of the planktonic cells

	Live injection water plus selected bioplugging microbe		Live injection water only
	% of microbe population		
alpha- Thalassospira	56.3		24.1
arcobacter	1.1		21.7
Marinobacter	Not detected		18.1
Halomonas	19.5		28.9
Idiomarina	10.3		6.0
Vibrio	Not detected		1.2
Bioplugging organism	5.7		0
Stenoytophomonas	2.3		Not detected
Citrobacter	2.3		Not detected
Ochrobactrum	1.1		Not detected
Georgenia ferrireducens	1.1		Not detected

In similar fashion, we have been monitoring for the presence of the bioplugging microbe in the interwell field test. Samples of the produced water were collected and analyzed. These were collected from wells that are communicating with the injector wells and in the comingled produced water from that part of the field serviced by the centralized fluid processing unit. After the DNA has been harvested from the produced water samples, a process call real time Polymerase Chain Reaction (or rt-PCR or qPCR – reference 11) is used to amplify and detect DNA that is specific to the bioplugging organism. This process is very sensitive and highly selective to the bioplugging microbe. In all the samples taken since the start of this interwell test, there has been no significant signal associated with the bio plugging organism detected in any samples. This is consistent with the slim tube data shown above and our belief that the bio-plugging microbe is sticking to the reservoir rock.

Meaningful production data – measuring leading indicators of the effectiveness of the well treatment

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 the 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. The well head pressure is often measured using glycerol filled mechanical gauges that freeze up during cold weather. Although injection water flows are relatively constant when averaged for a month, the instantaneous flows can vary substantially. From the beginning we had decided that the injectivity data collected when the batch of nutrients are pumped into the injector wells would provide us with consistent injectivity or backpressure data for the treated wells. This data was a bit more complicated than we had anticipated. Pressures were observed to change as the batch of nutrients were injected into the well. Figure 6 shows a typical set of pressure data measured during a batch treatment. The injecting pressure (measured at the top of the well) drops with time but then becomes constant after about 50 minutes. The explanation of this behavior is simple. Its interpretation became the basis for getting a better measurement of the injectivity of the well. The nutrient solution is slightly denser than the normal injection brine. As this nutrient solution fills the well, the static head it contributes increases. The injection flow is constant; however, the pressure drop into the reservoir is constant. The increase static head at a constant flow translates to a lower top side injection pressure. Once the well is filled with the nutrients, the pressure becomes constant. This is happening after 50 minutes. This drop in the top side injection pressure was consistently seen every time we pumped nutrients into the well. The data is shown in Figure 7. All the batch treatments show the same decline in the injection pressure with time. More importantly for each batch treatment the curve appears to shift upwards on the plot – indicating that there is an over all increase in the back pressure in the well. A line was fitted to each of the curves shown in Figure 7. From these fits, the zero time intercept was determine and plotted with time from the start of the test. This is shown in Figure 8. There is clearly an increase in the back pressure that has developed in the well for the period of time shown. The increase in back pressure came sooner than we had

anticipated. This clearly demonstrates that we have been able to develop significant and sustainable bioplugging in this reservoir.

Conclusions

Our ongoing research has 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. Specific challenges that should be address when doing a field test of MEOR include:

- Effectiveness of treatment using slim tube lab tests
- Assuring that the treatments (nutrients and inoculum) do not bypass or short circuit the reservoir
- Assuring that the wells are not blinded by the inoculation
- Minimizing sulfide production during the well test
- Assuring containment of the microbes within the well environment
- Gathering reliable data to monitor the progress of the well test

As described in this paper, we have already seen substantial changes occur on a reservoir scale (increasing back pressure) for the short time this well test has been in operation. We continue to monitor water cuts and oil production and hope to report our progress in this well test in a later paper.

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

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Figures

Figure 1 – Slim tube bio plugging test showing the contrast between using a microbe and nutrients selected for bio plugging compared to nutrients only. Authentic fluids (live injection water and dead oil) used.

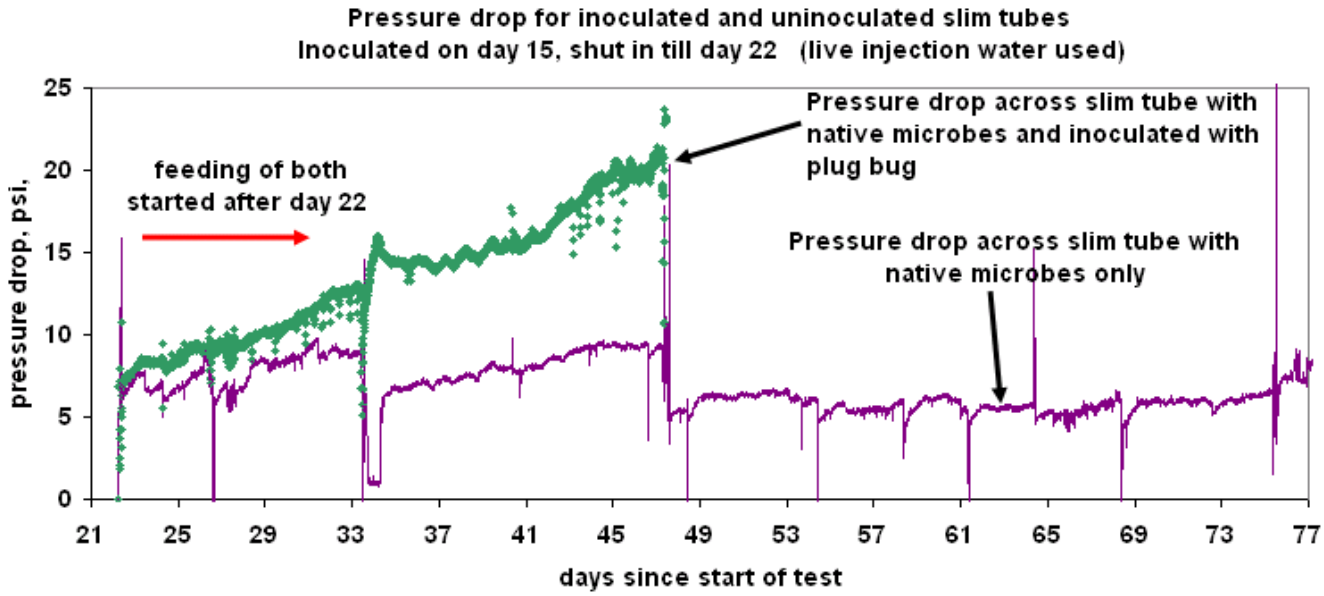

Figure 2 – "Fire" triangle for microbial metabolic activity.

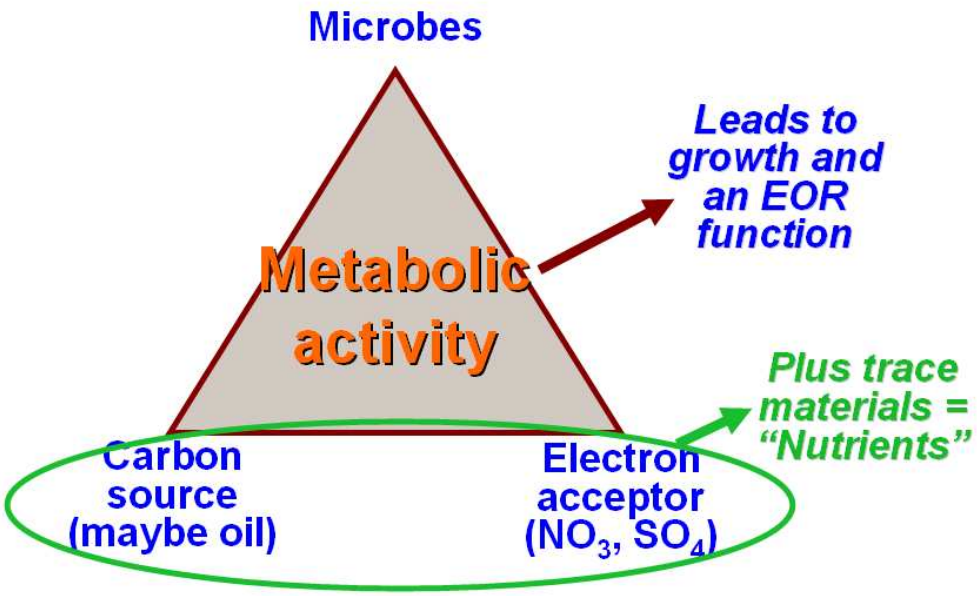

Figure 3 – Excess nitrate concentration observed in the effluent of the slim tube experiment. .

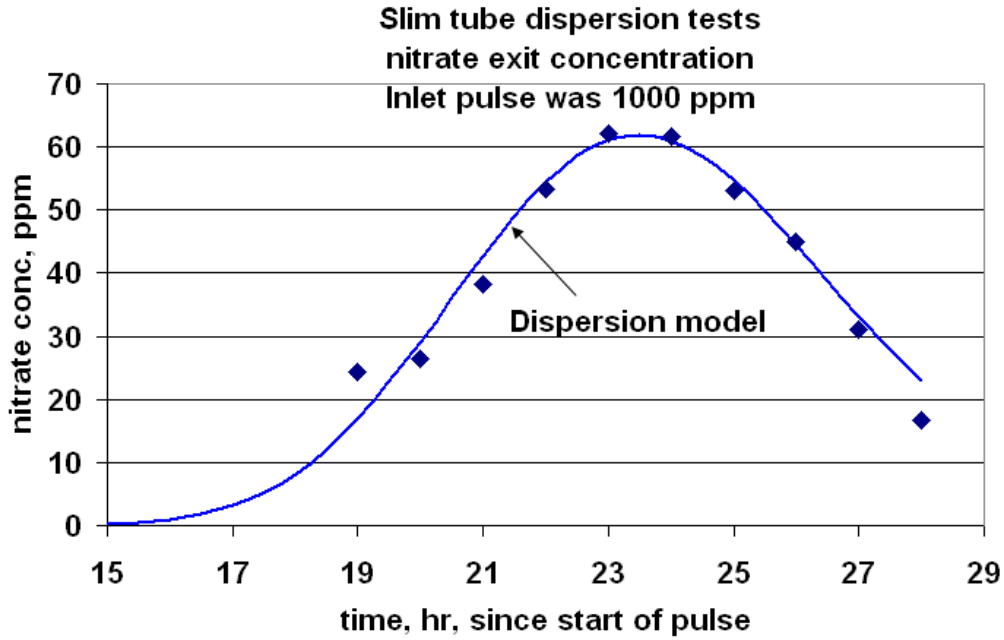

Figure 4 – Excess carbon concentration versus nitrate + nitrite concentration in the effluent of the slim tube experiment. .

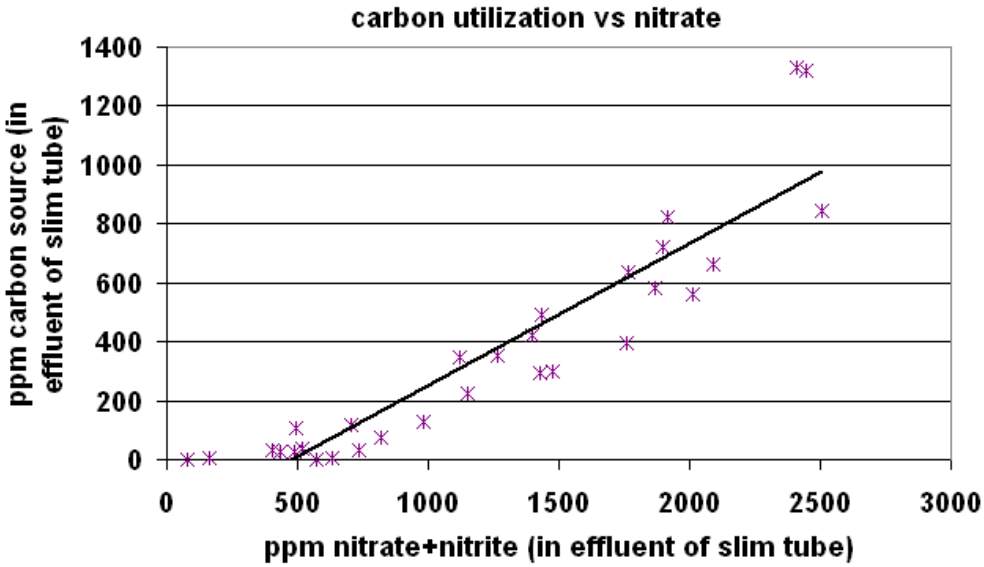

Figure 5 – Trace concentrations of nitrate and nitrite in the produced waters of the well test. .

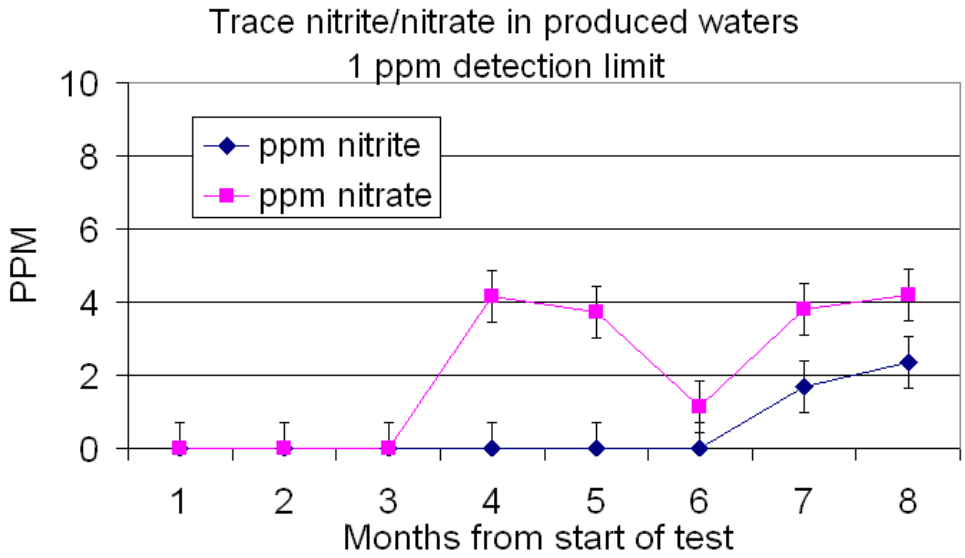

Figure 6 – Injection pressure as the nutrient solution is fed to the injector well. .

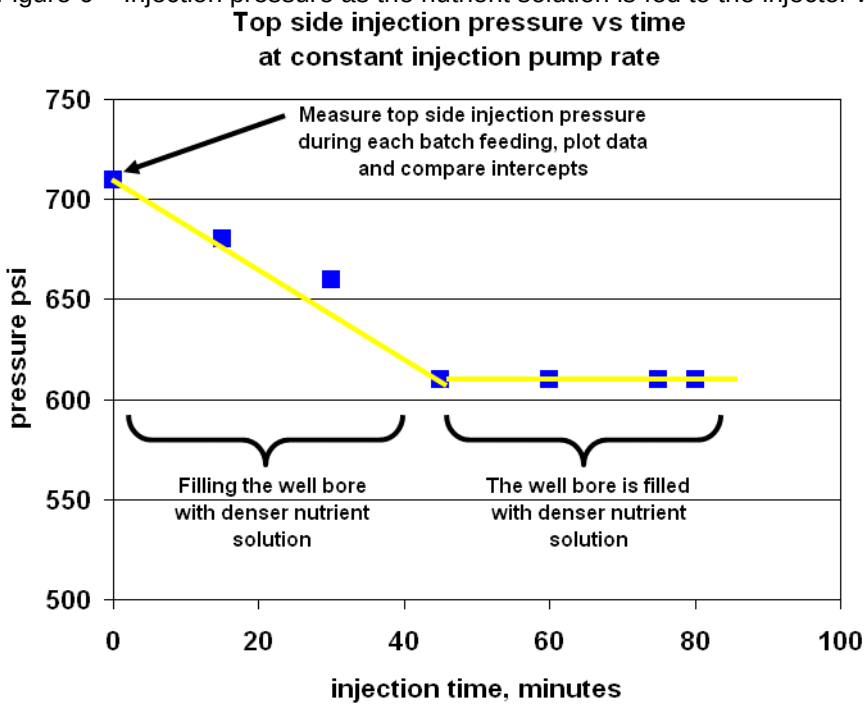

Figure 7 – Injection pressure when pumping the nutrient solution for many batch treatments. .

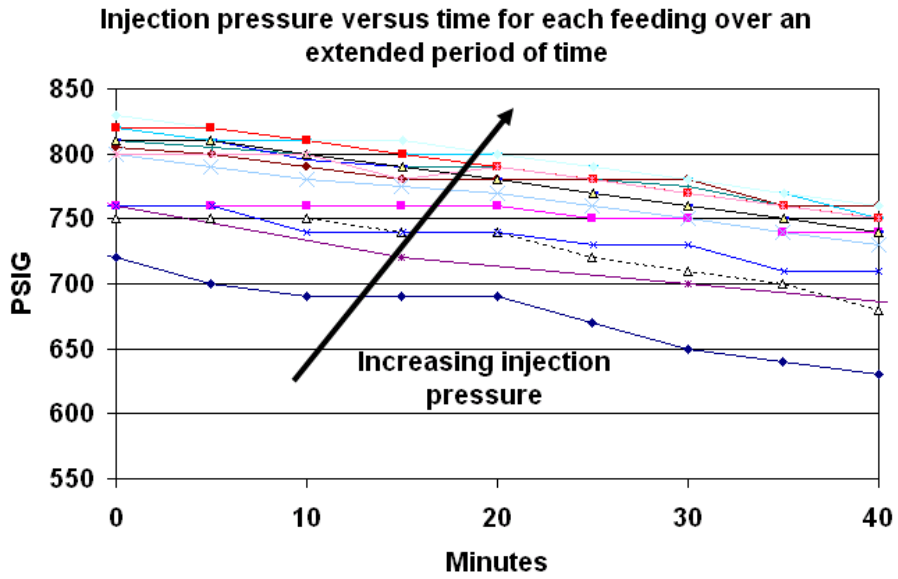

Figure 8 – Time zero intercepts of the linear fits of the curves shown in Figure 7. .