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Microbial Enhanced Oil Recovery: Diverse Successful Applications of Biotechnology in the Oil Field

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Abstract

The field history and performance of microbial culture products for the oil field is examined. For over 15 years, microbial culture products have been used for paraffin control, production enhancement, well bore treatments as well as for scale and corrosion problems. The wide-ranging capacity of microbes to effect positive changes in oil and water properties is described. The broad spectrum of oil types and formations that have been treated successfully is reported along with treatment protocols. Mechanistic considerations for modes of action are analyzed. Traditionally, these considerations involve the continuous production of biosurfactants, solvents and other oil mobilizing agents.

Continuous advancement of microbial technology has led to more recent development of new applications that use unique metabolic capabilities of microorganisms to address specific well problems. Examples of applying these products to problems in oil field production systems are shown. The outlook for development of new technologies and the future application of these products to the oil field is discussed.

Introduction

Microbial culture products occupy an increasingly important and growing segments in oil field production operations. They are a truly environmentally benign treatment technology that can be used to replace and augment many conventional technologies, including many oil field chemicals. The extraordinary diversity of microorganisms with the concomitant likelihood for many more such products in the future suggests that their role in oil field operations will continue to expand and will supplant many conventional technologies in the next 100 years. It is therefore important to review the prior and current uses of this technology.

Historical Applications of Microbial Culture Products

Paraffin Control. Microbial culture products (MCPs) were first used in 1986 in the Austin Chalk formation in Texas to control paraffin deposition. The theory behind these products was that microorganisms can be isolated and combined in novel mixtures which will produce biochemicals that will mimic the action of classic oil field chemicals such as pour point depressants, crystal modifiers and wax dispersants. The advantage of using such biological products is the fact that the microorganisms will 1) produce these biochemicals continuously and 2) attach to surfaces where paraffin deposition is occurring and act directly at the site of deposition.

The first successful application of these products began a pattern of expansion that continued throughout the 80s and 90s. Paraffin deposition results in a variety of problems for oil field operators, ranging from plugging of tubulars to occult formation deposition that reduces formation permeability. A continual increase in the number of products available to the industry allowed the expansion of the microbial technology for paraffin control into a variety of different oil types and formations.

Conventional technologies to control paraffin deposition are thermal and chemical treatments. Both of these technologies have limitations that restrict their long-term effectiveness. In particular, hot oil or water treatments may lead to increased formation damage by forcing deposited high molecular weight paraffins into the formation where they can contribute to pore throat plugging and lead to production loss.

Development of MCPs represents a successful alternative technology to remove paraffin deposits without causing lasting formation damage. Long term use of MCPs showed no damage to the oil field production system and their use increased throughout the mid continent region in the early 1990s. Examples of the successful application of this technology in the oil field have been previously documented in SPE papers.[1,2,3]

An example of the type of changes produced in paraffinic oils that were associated with control of wax deposition is shown in Figures 1 and 2. In the first Figure, the viscosity of the oil has been reduced by microbial treatment. This reduction in viscosity is probably due to the production of small solvent molecules by the microbial population. These solvent molecules include alcohols, ketones and aldehydes and are functionally similar to oil field chemicals used as wax dispersants and pour point depressants. This "thinning" action can also be seen in Figure 2 where the metabolic capacity of the microorganisms to degrade high molecular weight paraffin molecules results in a change in the hydrocarbon profile of the oil as detected by gas chromatography. With a reduction in the average molecular weight in the hydrocarbon component, increases in API gravity and reductions in viscosity are frequently seen. This reduction in viscosity may lead to increased relative permeability and increased oil production, which will be discussed in later sections.

Scale and Corrosion Control. Observations that some of the biochemicals produced by microorganisms had properties similar to scale and corrosion control chemicals lead to the development of new MCP product lines to address these oil field problems. The deposition of mineral scales in oil wells is a well-understood phenomenon. It is often related to the commingling of waters of different chemical types that produce a blend of ions that exceeds the solubility limit for compounds such as calcium carbonate, calcium sulfate or barium sulfate (to name the most commonly encountered oil field scales). Scale deposition can also be related to temperature and pressure changes occurring in the production string as the fluid column is brought to the surface.

Conventional chemical technologies utilize compounds that control scale through either chelation or dispersant mechanisms. Microbial biochemicals such as organic acids are naturally occurring chelating agents that bind cations and thus restrict their capacity to form mineral deposits. Likewise, microbial biosurfactants such as rhamnose and trehalose glycolipids serve a similar function. Other microbial compounds may act as filming agents, coating surfaces and preventing nucleation sites for scale growth from forming.

The ability of MCPs to prevent scale growth *in vitro* is shown in Figures 3 and 4. These photomicrographs show how the growth of typical oilfield scale crystals in brine can be controlled by treatment with MCPs. The mechanisms by which MCPs control scaling are chelation, crystal modification, and dispersion of scale nuclei. Filming activity of biosurfactants also prevents attachment of scale crystals to surfaces.

Such filming agents may also act as passivating agents for controlling corrosion of metal surfaces. By coating surfaces, the interaction between corrosive compounds such as carbonic acids and sulfides is mitigated and corrosive processes reduced. Another effect associated with microbial culture product use is a decrease in the number and activity of sulfate reducing bacteria. Presumably due to competition for the usually limiting nutrients found in oil field production systems, decreases of two to three logs in sulfate reducing bacteria numbers are common.

Waterflood Treatments. MCPs have found successful applications in waterfloods as well. In waterflood operations where injection of the drive fluid is restricted by scale and/or organic deposits, MCPs have been used to open up injector wells and improve injectivity. Deposits of mineral scale can form at any location in an injection system from surface equipment to downhole in the formation, and preformed scale from the surface may be carried downhole by the fluid flow. Skin and formation damage can also occur in injection wells by organic deposits such as paraffin or asphaltene precipitates, or stable emulsions formed from residual oil and grease carried over during re-injection of produced water.

Buildup of scale and/or organic deposits in the near wellbore region blocks pore channels, which decreases permeability and can severely restrict fluid flow into the formation. These occlusions are a leading cause of reduced waterflood efficiency. MCP scale and corrosion control products can be used to inhibit and remove these occlusions from injection wells. Treatment of injection systems with MCPs has been shown to increase volumes of water injected as well as reduce injection pressures and energy costs. Application of MCPs for these types of treatments has been the subject of previous reports.[4,5]

In the reservoir, MCPs produce several enhanced oil recovery compounds that decrease capillary forces and increase oil mobility. Microbial metabolites such as surfactants, solvents, low-molecular-weight organic acids, and gases are well-known oil mobilizing agents. These products work by the same mechanism as traditional EOR chemicals to reduce interfacial tension, decrease oil viscosity, and improve the microscopic sweep efficiency of the waterflood. Application of MCPs in waterflooded reservoirs to improve sweep efficiency and increase recoverable reserves has been widely used.[5,6]

Well Stimulation for Increased Oil Production

By far the largest application of microbial culture products, both in terms of volume of products used and number of wells treated, is well stimulation to increase the oil production rate. Mechanisms by which MCPs stimulate increased oil production range from removing skin and/or formation damage and opening pore channels, to improving oil flow properties.

As oil flows through the reservoir toward the wellbore, high-molecular-weight fractions such as waxes, paraffins, and asphaltenes precipitate out of the oil, forming deposits on the rock matrix and occlusions in the pore channels. This deposition can become much more severe if the producing temperature is near or below the cloud point, or if decreased pressure near the wellbore allows dissolved gases to bubble out of the oil. Buildup of organic deposits can decrease permeability, change relative permeability, and restrict or block fluid flow through pore channels. In addition to organic deposition, skin and formation damage can also be caused by precipitation of mineral scales, or by formation of stable emulsion in the near-wellbore region.

Stimulation of wells with MCPs involves injection of specific microorganisms into the damaged zone, where they can colonize the region and produce bioproducts *in situ*. The production of the aforementioned solvent molecules can directly solubilize hydrocarbon deposits present in pore throats, increasing the effective porosity and permeability of the formation. Biosurfactants can also solubilize such deposits, in addition to mobilizing scale particles and other occlusions from the fluid channels. When the well is reopened after stimulation, damage from the near-wellbore region is mobilized in the fluid flow and removed from the well.

A significant advantage of MCPs when compared to traditional technologies, is that colonies remain in the formation for some period of time after production is resumed, and continue to metabolize specific compounds and produce bioproducts, which affect oil properties. Strain-specific metabolic activity targets long-chain paraffins and shortens the paraffin chain, causing a distinct shift in the hydrocarbon distribution. Direct metabolic action of the microorganisms on the oil can reduce oil viscosity and increase relative permeability. Biosurfactants can also produce changes in wettability, increasing relative permeability. A variety of positive mechanisms are thus available in using MCPs to increase oil flow from the formation and increase production.

The typical protocol for such treatments to increase production involves a bullhead injection of product-water mixture into the formation at matrix rates. Injections are generally planned for delivery 3 to 6 feet into the formation. This maximizes the likelihood of removing hydrocarbon deposition, emulsion blockages or other types of near-wellbore formation damage. A typical treatment protocol is given in Table 1.

Stimulation of production wells with MCPs commonly results in a 20–50% increase in oil production rates. Production curves illustrating the types of increases obtained are given in Figure 5 and 6. The wells shown in these figures were producing a medium gravity (~36 °API) paraffinic oil from a sandstone formation. Wells exhibited signs of skin and formation damage, and production rates were declining due to paraffin deposition in the near-wellbore region. Stimulation injections were designed to treat a 5-6 ft. zone around the wellbore for paraffin damage and increased oil production. Oil production increased by an average of 39% (field average) after stimulation with MCPs and production rates remained elevated for more than one year.

Frac Damage Repair

Another area where MCPs have been used successfully is to remediate polymer damage caused during well fracturing. Hydraulic fracturing is a widely used stimulation method to increase production from oil and gas wells. It is routinely used in new completions to increase drainage rates and maximize field development. Also, favorable economics in today's markets have caused many producers to fracture stimulate developed or mature fields in order to get the most out of existing wells and maintain production rates. However the full potential of fracture stimulation is often not realized because gelling agents used in the frac fluids cause formation damage.

Polymer solutions or gels are normally used in frac fluids to increase viscosity. A common problem that frequently plagues the use of frac polymers and gels is incomplete or inadequate breakage of gel. Residual gelling agents cause damage to the formation by decreasing permeability and blocking flow from producing zones. This can lead to lower than expected production increases from fracturing jobs or in extreme cases, complete loss of production.

Microbial culture products have been developed which will degrade guar and other gel polymers. Unlike chemical breakers, MCPs do not react non-specifically with minerals or other chemicals, and they are not consumed by the reaction. Instead, MCPs act as true catalysts to break down the polymer. They catalyze specific metabolic reactions such as breaking the polymer backbone and/or removing or modifying functional side groups. This specific metabolic activity decreases the molecular weight of the polymer and reduces fluid viscosity.

An example of polymer degradation and subsequent viscosity reduction in a frac fluid is shown in Figure 7. The frac fluid was a guar-based gel crosslinked with borate. Note that after the MCPs initially attack the gel and significantly reduce viscosity, they continue to degrade the polymer long after a reactive chemical breaker would have been expended. This biocatalytic activity is inherent of MCPs and insures that their activity will continue until the polymer is degraded. Continued degradation and removal of both broken and unbroken gel material through the long-term activity on MCPs allows improved formation flow, and leads to increased production in the well.

Examples of two wells which sustained severe damage after fracture stimulation with guar-based fluids are shown in Figures 8 and 9. The well in Figure 8 was producing approximately 150 Mcf/d of gas from a carbonate formation before fracture stimulation with a guar-based fluid. Swabbing was performed after fracturing, but the well would not flow back the frac fluid and gas production was completely blocked. Treatment with MCPs designed to degrade the guar polymer resulted in flowback of frac fluid and commenced gas production. The well continued to release fluid with residual frac polymer for several months after production resumed.

An oil well shown in Figure 9 flowed for approximately two months after fracture stimulation before residual polymer in the produced fluids reached a plug point and the well plugged off completely. MCPs were injected into the well to degrade the residual polymer and reopen the flow channels to fluid flow. When flow was resumed the oil production rate quickly exceeded the maximum rate the well had produced at before treatment with MCPs, indicating that even before reaching the point of plugging off, production was severely restricted by residual polymer damage. After treating the residual polymer damage, oil production stabilized at the elevated rate.

Summary

The historical use of microbial culture products clearly illustrates their effectiveness in a wide range of oil field applications. The fact that their use has grown as an economic alternative to conventional technologies over the past 15 years demonstrates their long-term viability for the industry. What is their future?

It is useful to consider the potential of microbial technology with respect to the vast array of biochemical capabilities found in microorganisms. Microbes inhabit virtually all terrestrial and marine habitats, including environments of chemical and thermal extremes. The cumulative genetic information present in this huge and diverse collection of microorganisms indicates an enormous biochemical potential for new products and technologies.

Microbial biotechnology for the oil field is only in its infancy. It is clear that the number of applications will only continue to increase. Widely reported successes in the application of microbial culture products have caused their use to gain widespread acceptance. We can expect the next 100 years to see a gradual replacement of conventional technologies with new and improved microbial culture products. This will lead to a more environmentally benign image for the petroleum industry and increased assurance that the industry will be able to meet future needs for safe, clean energy.

Conclusions

1. MCPs have been proven to be safe and effective solutions for treating many common problems in oil production.
2. Historically, applications of MCPs were designed around their production of biochemicals which worked the same as traditional EOR and well treatment chemicals.
3. Recent advances in biotechnology have led to development of new applications of MCPs using enzyme-specific metabolism to treat well problems.
4. Biotechnology holds the potential to provide many more new and innovative solutions to the oil industry in the future.

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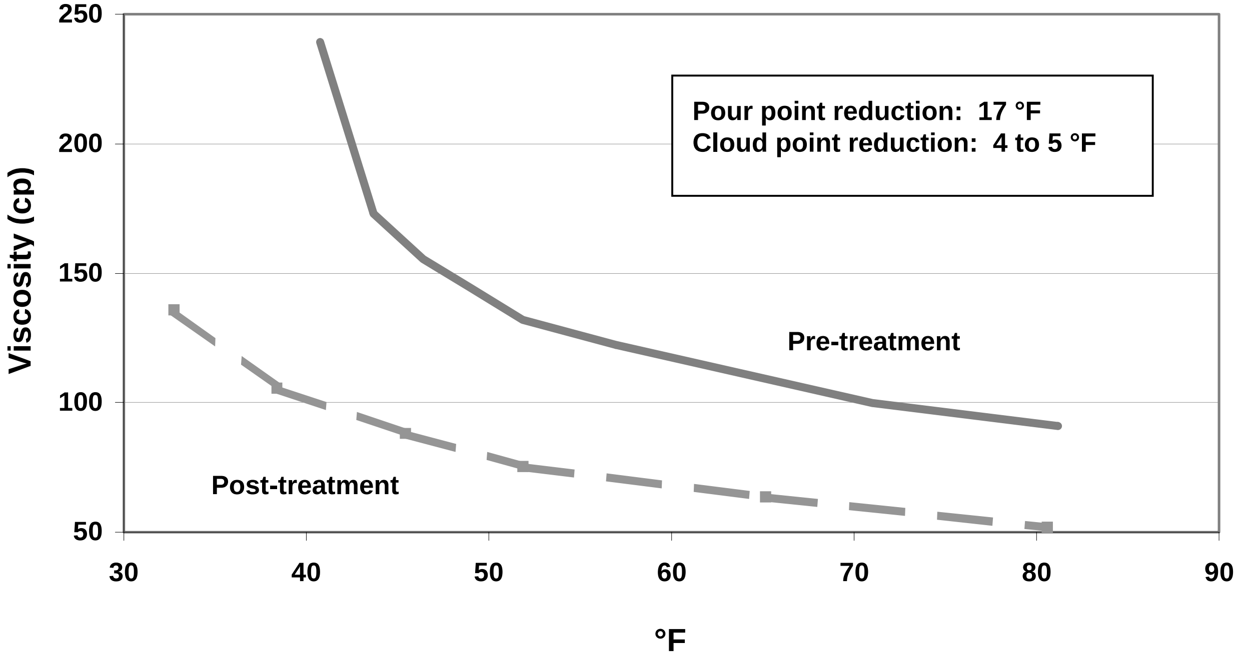


Figure 1. Effect of treatment with Microbial Culture Products on crude oil viscosity.

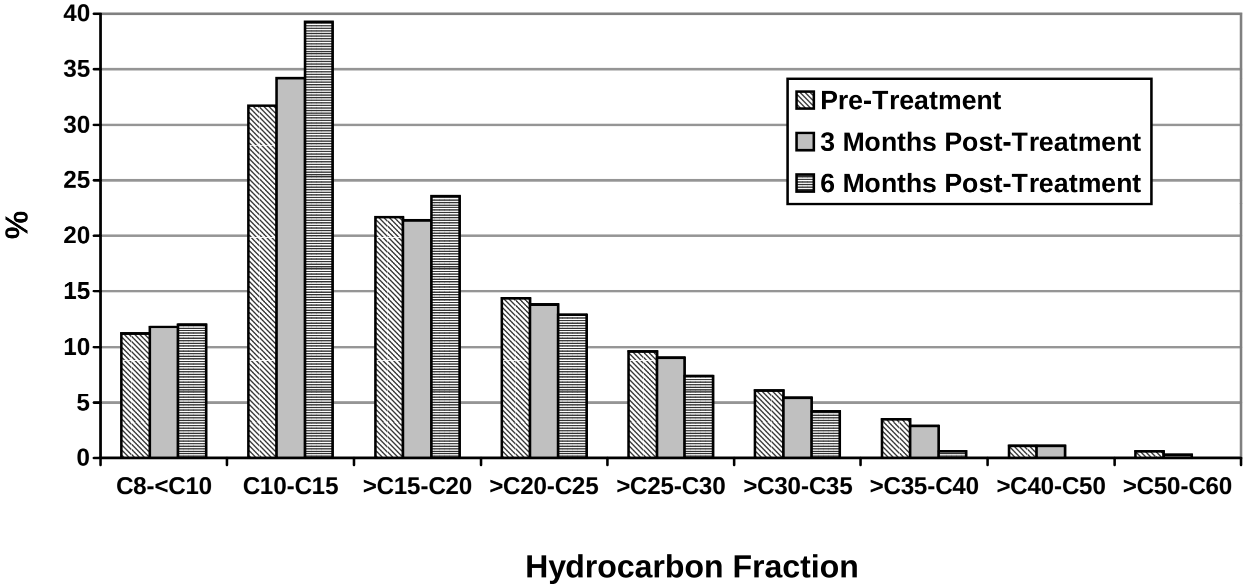
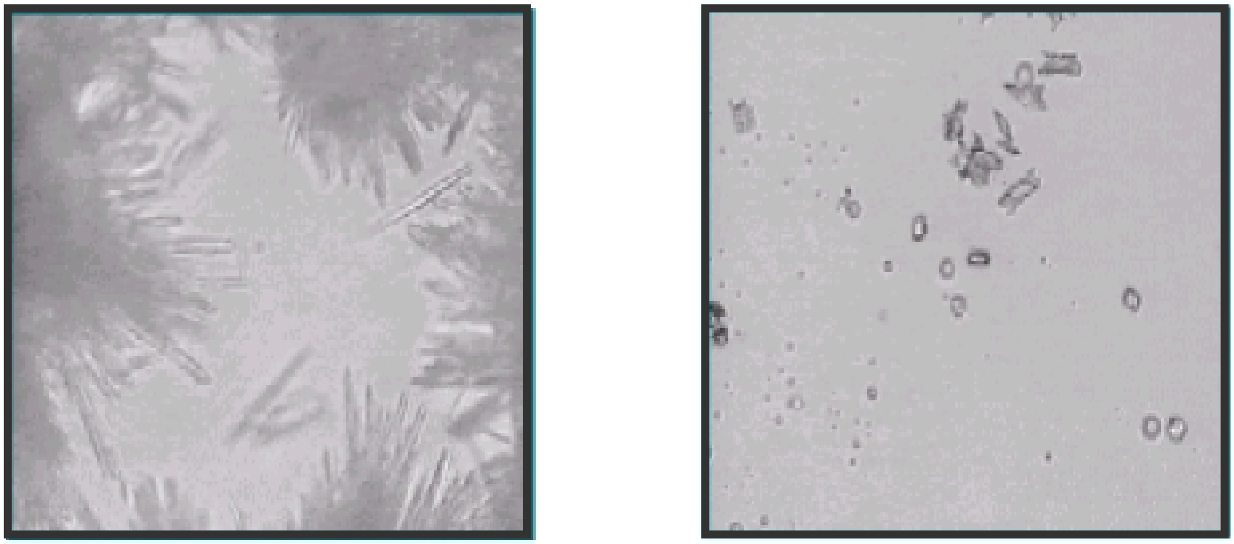
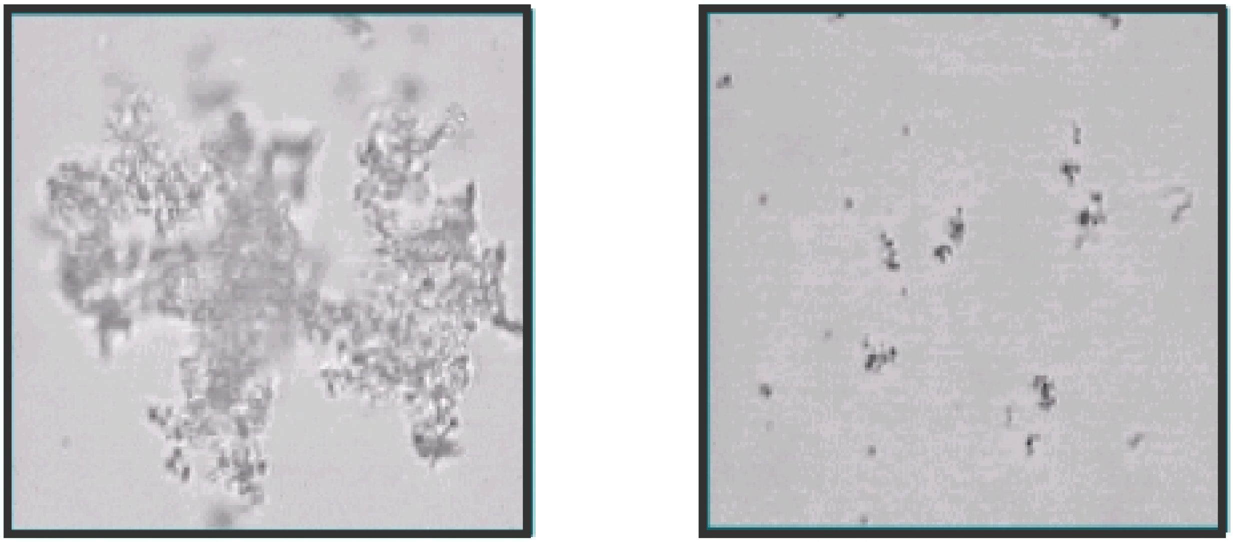


Figure 2. Effect of treatment with Microbial Culture Products on hydrocarbon distribution in wellhead samples of crude oil.



Untreated **Treated with MCPs**

Figure 3. Effect of microbial culture products on formation of calcium sulfate scale in brine. Note large scale crystals in untreated solution.



Untreated **Treated with MCPs**

Figure 4. Effect of microbial culture products on formation of barium sulfate scale in brine. Note large scale crystals in untreated solution.

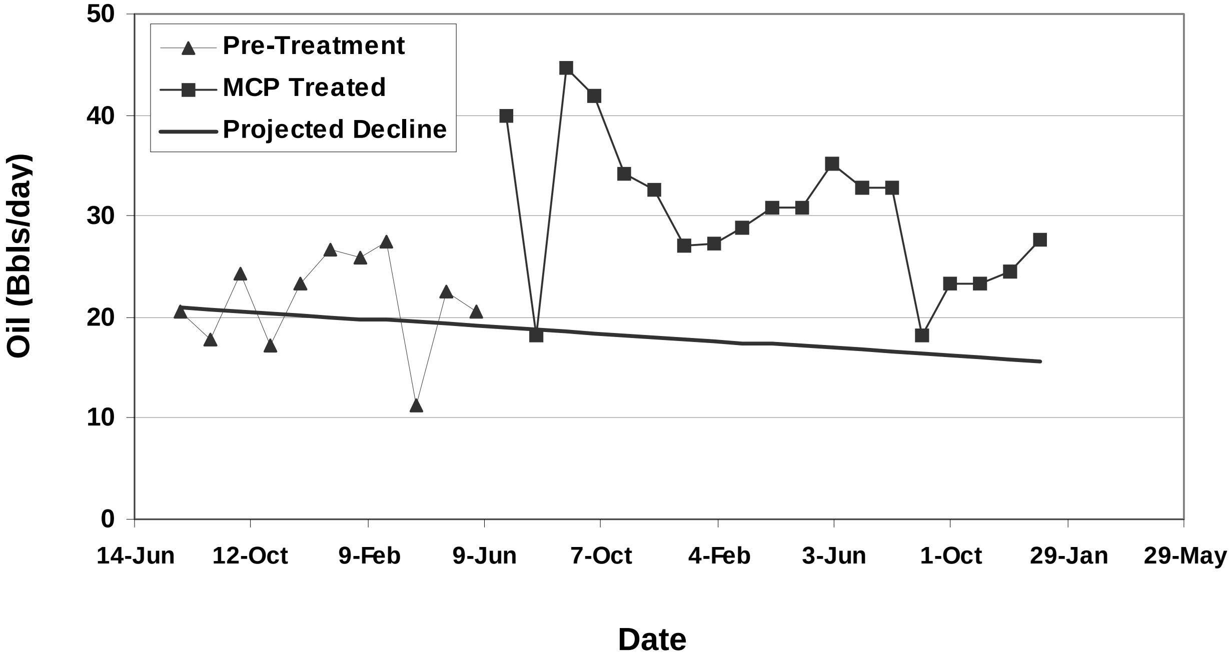


Figure 5. Oil production history for well group #1.

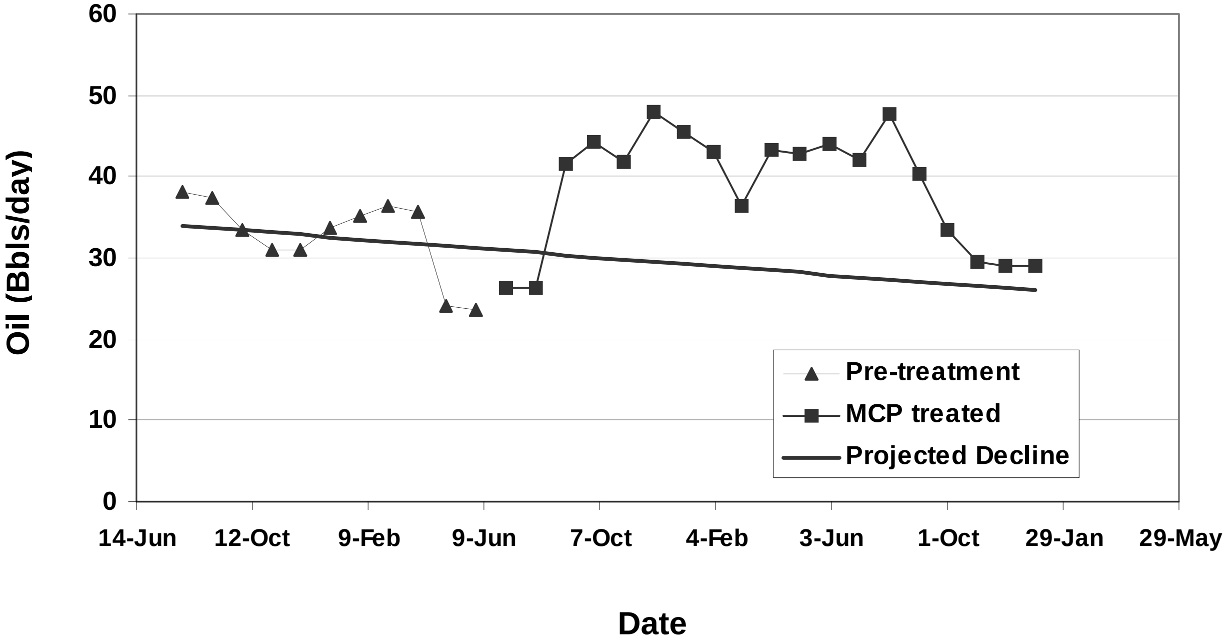


Figure 6. Oil production history for well group #2.

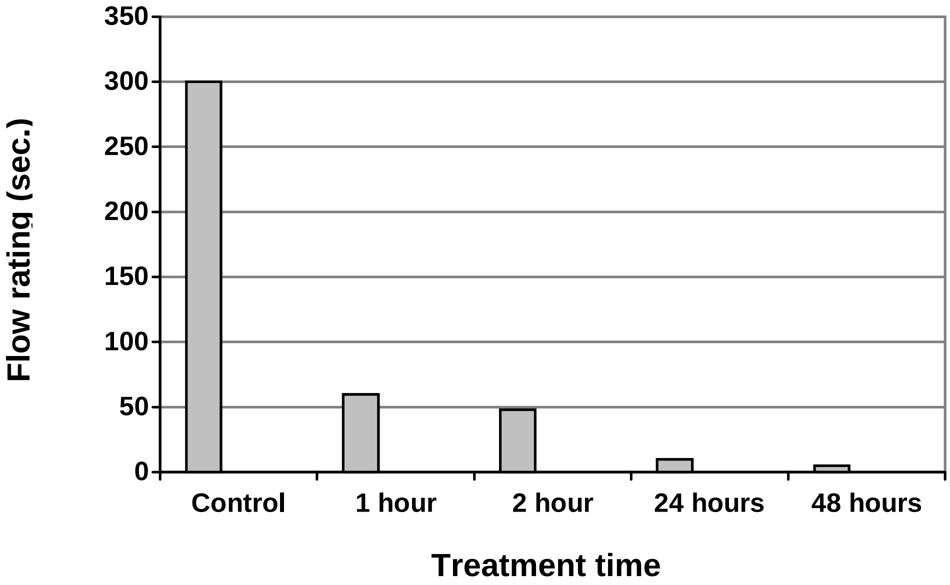


Figure 7. Viscosity reduction of frac fluid (guar crosslinked with borate) with Microbial Culture Products.

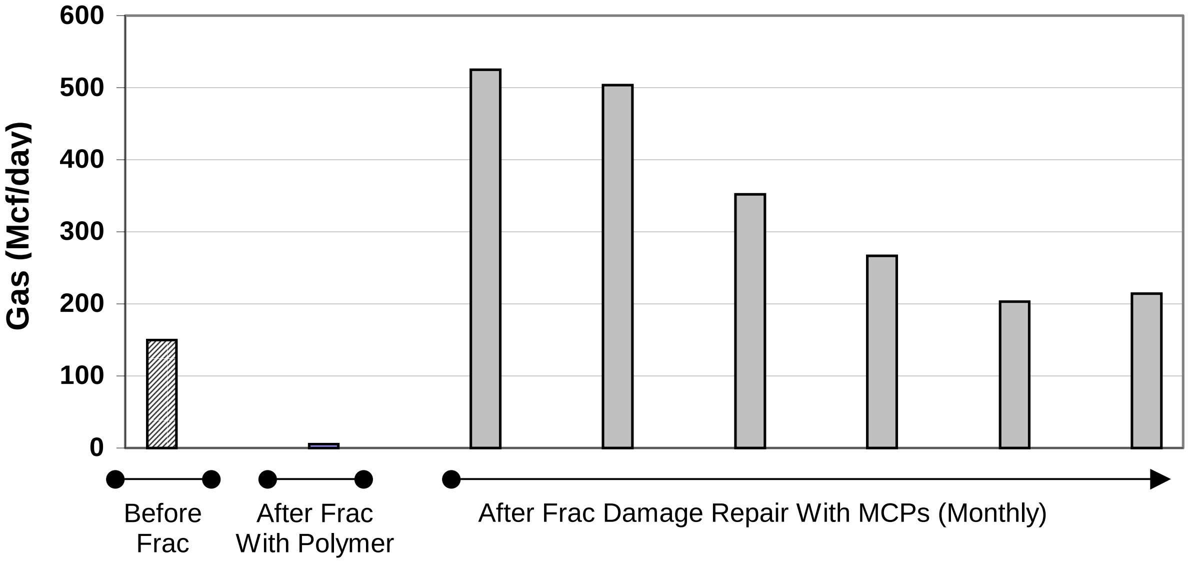


Figure 8. Production history for gas well treated with Microbial Culture Products to repair frac polymer damage.

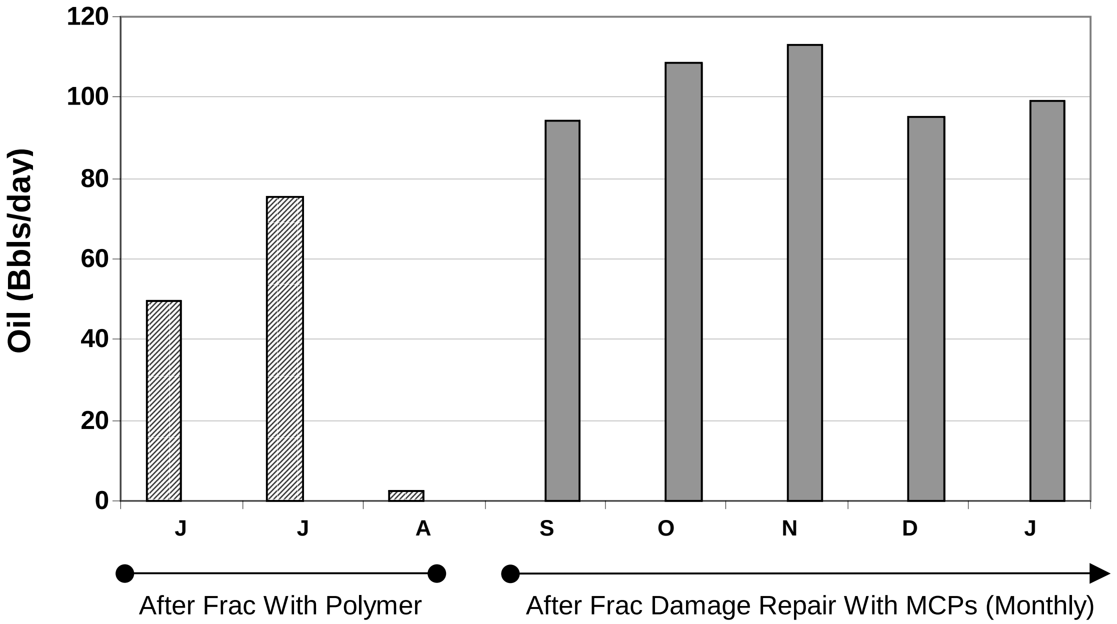


Figure 9. Production history for oil well treated with Microbial Culture Products to repair frac polymer damage.

Table 1. Typical MCP Treatment Protocol.

Task	Requirements	MCP Service Provider	Operator
Define Program Goals			√
Identify Candidate Wells	Production history Maintenance and service records	√	√
Baseline Data Gathering	Production rate Maintenance records Fluid sample acquisition		√
Fluid Sample Analyses & Treatment Recommendations	500 ml oil (wellhead) 1 liter water Frac fluids (Frac damage repair only)	√	
Treatment Program Design	Completion data or well diagrams Results of sample analyses	√	
Implement Treatment Program	Treatment program Mixing and pumping equipment (recommendations available)	√	√
Post-Treatment Monitoring	Production records Produced fluid samples (optional)	√	√
Gain Assessment	Production records Laboratory analysis results	√	√
Reporting		√	√