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Technical Background on BioEnhanced Oil Recovery

Abstract

Dramatic advancements in scientific knowledge provide the foundation for a new method of chemical enhanced oil recovery, termed "BioEOR" by Transworld Technologies. The injectants utilized are simple, dilute and inexpensive chemicals that activate native microbes. In appropriate waterflood reservoirs, BioEOR is effective in increasing oil production via flow diversion, when deployed using untreated injection water. With all-in cost of resulting new oil being less than $6/bbl, resulting economics are positive, even when oil commodity prices are low.

Introduction

Throughout the world, mature waterfloods share one or more common features:

- High water production
- High pumping costs
- High oil-water separation costs
- Aging infrastructure
- Mechanical idling or abandonment of some producing and injection wells

There are several consequences for Operators:

- Low operating margins make the ongoing financial performance of these fields very sensitive to oil prices
- Opportunities to increase oil production via use of traditional chemical EOR methods are limited, due to:
    - high chemical costs
    - the need for extensive investment in water treatment and chemical blending facilities
    - in some cases, the need to replace inactive wells to re-establish regular injector-producer well patterns
- Weak short-term economics threaten remaining field life, increasing the risk of incurring near-term Asset Retirement Obligations, and reducing the field's chance of surviving until oil prices recover

BioEOR's potential for Operators of mature waterfloods

BioEOR can be simply summarized as:

> "Using modern biological understanding and methods, add simple chemicals to ongoing injection operations to improve waterflood performance at low cost by activating microbes already living in oil reservoirs"

When BioEOR is deployed, the result is increased production with minimal impact on field operating cost. For a mature field on waterflood, the effect on field life is shown on ***Figure 1***:

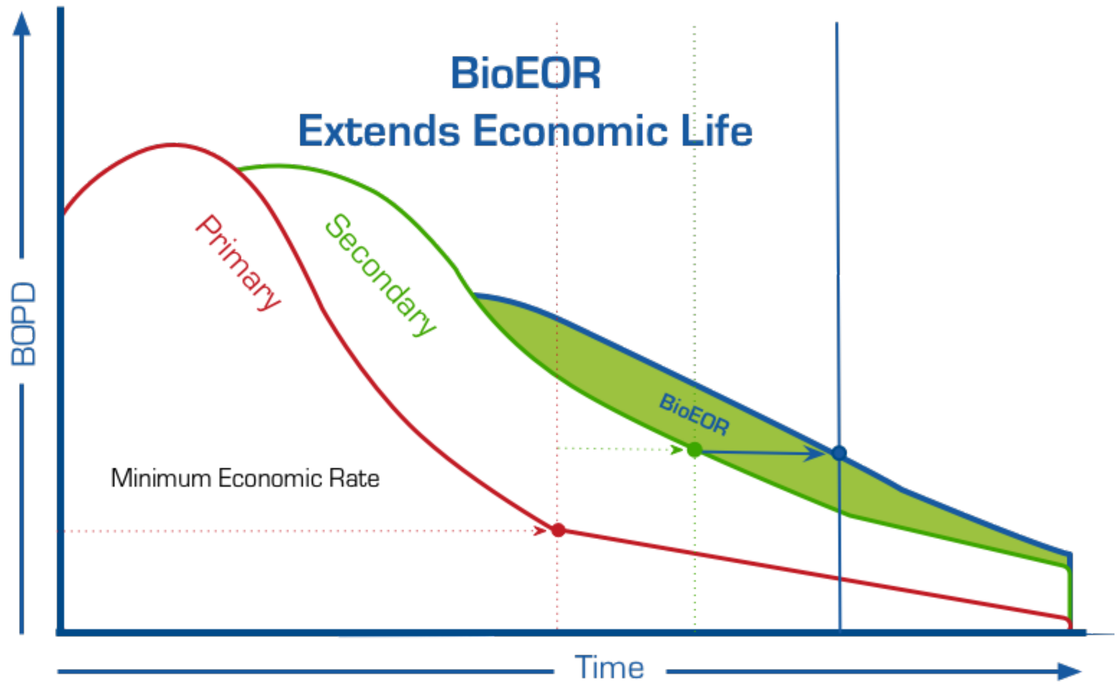

Figure 1. Impact of BioEOR on remaining economic life of a typical field now on waterflood

Field results provide the following metrics for BioEOR:

- All-in costs: less than $6 per barrel of new oil
- Oil production increases: +25% - 50%, with response starting around about six months from project commencement
- Sustained response: 3-4 years per treatment cycle (using one year of BioEOR injection)
- Impacts on existing field operations: minimal

These metrics are attractive in their own right. Additional benefits derive from the following:

- Low capital costs reduce the budget impacts and financial risks of BioEOR deployments
- Project functionality of the BioEOR technology *IS* dependent on factors accurately measured from samples and lab tests, and from field history:
  - geochemistry of formation and injection waters
  - biology of the microbial life already present in the target oil reservoir
  - lab responses of these microbes to various BioEOR injectant-formulation strategies
  - primary field production; water injectivity; and waterflood response
- BioEOR project functionality *IS NOT* heavily dependent on other reservoir characteristics, some of which are difficult to measure, and/or are susceptible to wide variation on a reservoir scale:
  - oil geochemistry
  - matrix rock: lithology; wettability
  - diagenetic pore-filling materials: presence; variable abundance; chemistry
  - reservoir rock uniformity: thickness; porosity; absolute and relative perms
  - well patterns: current geometries and regularities of injectors and producers

Scientific foundations of BioEOR

Microbes live in the water phases of many oil reservoirs. Their arrival may have occurred long ago, via transport by water movements in the subsurface over geologic time; or recently, via injection of waterflood makeup water taken from shallow aquifers; or often both. These microbes are a vital part of natural processes ("biogenesis") for cycling carbon, hydrogen and oxygen. Within biogenesis, by a number of inter-related steps, large hydrocarbon molecules are broken down into smaller compounds more easily transported back to the surface biosphere for re-use by plants and animals.

Orinoco (Venezuela) and Athabasca (Canada) are examples of oil biodegradation/biogenesis of methane carried out over geologic time, on basin scale, with extensive alteration of huge resources of crude oil. In many more reservoirs and locations around the world, the cumulative biodegradation of oil is not as dramatic, even though the microbes needed for the process are still present. These reservoirs present opportunities for commercial deployment of BioEOR.

Biogenesis is a complex yet orderly series of numerous biochemical reactions operating as a sequential "large molecule dis-assembly" process. Creation of methane, the smallest hydrocarbon, is the final stage. The process proceeds for logical thermodynamic reasons: the microbes gain energy by breaking down molecules, from larger to smaller. However, biogenesis is susceptible to interruption for various reasons related to transient geochemical phenomena and biological responses. If conditions in the reservoir change, and the complete dis-assembly process cannot continue, the process stops, and the microbes driving biogenesis become dormant. Research and field trials by Transworld in oil and certain coalbed methane reservoirs has laid vital foundations for the commercial potential of enhancing biogenesis, and improving production of hydrocarbons:

- Scientific understanding of the biogenesis process is mature, with many of the microorganisms needed to fully execute the process having been identified
- Careful procurement and handling of field samples, and DNA sequencing of the biology recovered, provide necessary vision of the complex microbial community present in the reservoir. A reliable assessment can then be made of the microbial community's ability to execute biogenesis if BioEOR is deployed, and the microbes are activated
- Lab studies using numerous chemical activators with multiple reservoir fluids have provided clear vision and an extensive database of those activators appropriate for stimulating various microbial communities and specific microorganisms
- Dormant microbes have been proven to respond in the lab to appropriate chemical activators, by increasing production of methane in easily-measured quantities
- Lab-determined activator formulations have been shown to work effectively in the field to accomplish the biological changes (activation; selective growth) needed to re-initiate biogenesis by the microbes already living within the reservoir
- The result of active biogenesis in a waterflooded oil reservoir is increased oil production

EOR mechanism

Field results (injectivity performance; successive tracer studies) have shown that BioEOR increases oil production principally through the mechanism of flow diversion. BioEOR expands the swept zone of a treated reservoir by improving areal and vertical sweep efficiency, so that the existing waterflood performs more efficiently.

Figure 2 shows a typical pore within the swept zone of a mature waterflooded reservoir. While residual oil saturation within the pore is a typical (and substantial) 35%, capillarity and flow-channel geometry will not allow this globule of oil to be displaced from the pore. Instead, injected water will flow around the globule before exiting the pore.

This pore and its entry and exit pore throats are large enough for habitation and transit by microbes. The microbes live in the water, but will tend to cluster near the outer surface of the oil globule.

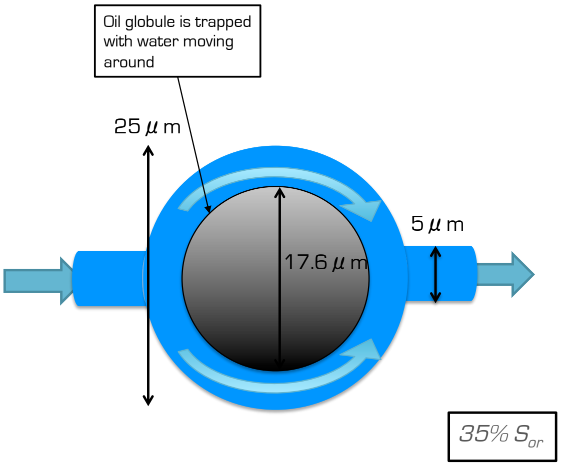

Figure 2. Typical pore within the swept zone of a mature waterflooded reservoir

When the resident microbes become energized after they absorb the BioEOR activators, renewed biogenesis will break down oil in the outermost (oil) layer of the oil globule, producing methane with several destinations:

- The first volume of new gas will saturate the limited solubility capacity of the water, where the microbes live
- The next gas volume will saturate the gas solubility capacity of the oil globule, via mass transfer of methane from the surrounding water into the oil
- Ongoing biogenesis and creation of new gas will result in creation of gas bubbles, since there is no longer a solubility sink available to store the gas

Figure 3 shows the spatial relationships involved. Because the oil is much denser in carbon and hydrogen than methane bubbles, conversion of only a small portion the oil globule's outer volume to methane results in formation of a large bubble, or possibly of a number of mid-sized bubbles. The bubble shown is sufficiently large to occlude the exit pore, and to divert water flow, even after accounting for new methane that becomes dissolved in water and oil prior to bubble formation.

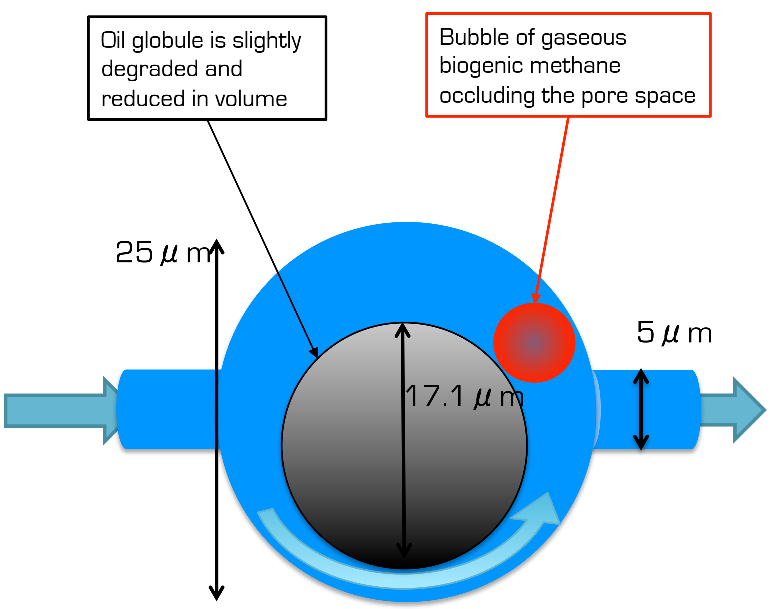

Figure 3. Fluids within the pore after reactivation of biogenesis via BioEOR

An alternative, less dramatic outcome could be for biogenesis to create only a small saturation of free gas within the pore, too small to completely occlude the exit pore. As shown by ***Figure 4***, a modest saturation of new gas will cause a disproportionately large reduction in water relative permeability, and hence diversion of some water flow. In this case, while some water will continue to flow through the pore, a portion of the former rate will be diverted.

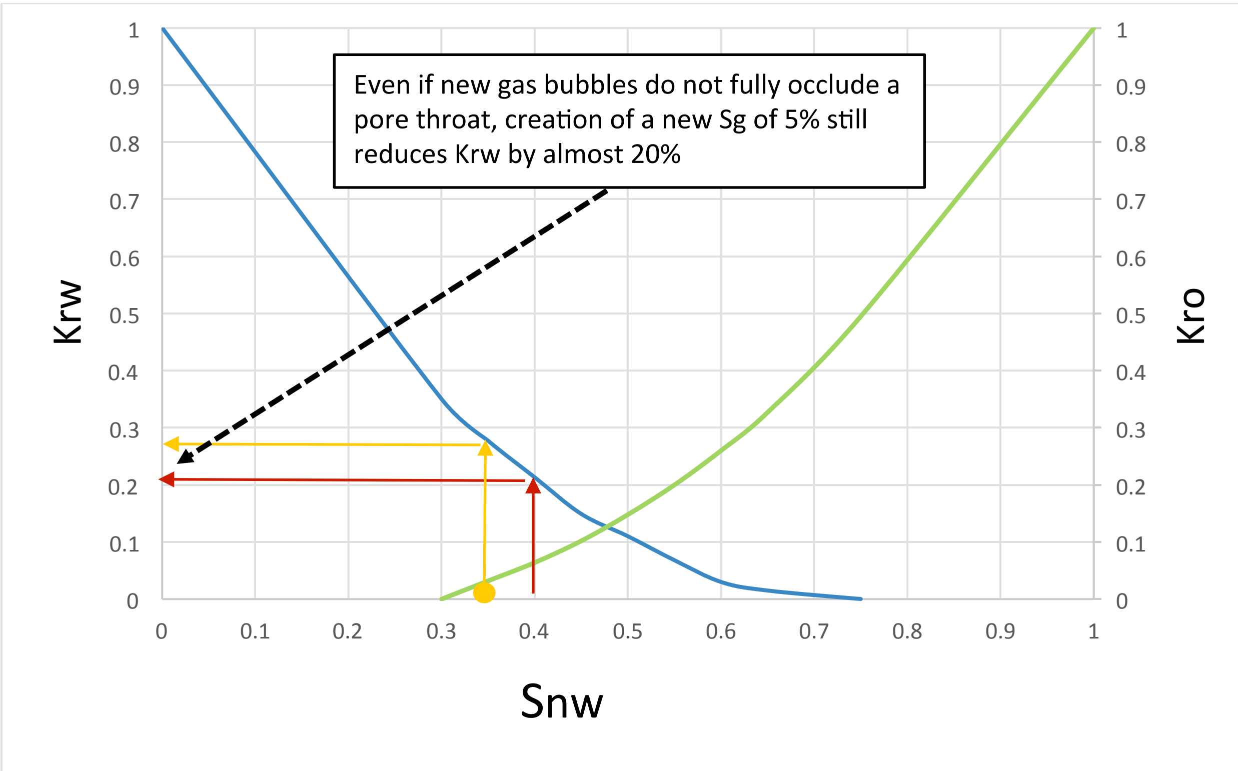

Figure 4. Effect on water relative permeability (and hence flow) of a small saturation of new methane *(permeability data from Cole (1969))*

Once formed within the pore, methane bubbles will be durable agents of flow diversion, for several reasons:

- Capillary forces will cause the bubbles to maintain their round shape, just as the capillary forces act on the oil globules
- In the chemically-reducing environment of the oil reservoir, there are no significant chemical reactions which might oxidize and consume methane
- There is no effective microbial consumption of methane (unlike the microbial degradation of polymer molecules)

As a result, once formed the methane bubbles create a flow diversion mechanism that persists for extended periods. ***Figure 5*** shows production performance of a BioEOR field trial in a very mature oil reservoir in the Ardmore Basin, Oklahoma. In this trial, BioEOR activators were injected for less than 4 months. Resulting improvement in oil production was observed for 3 years, until project termination. By extrapolation, it is estimated that the BioEOR oil-production response would have lasted for 4 years.

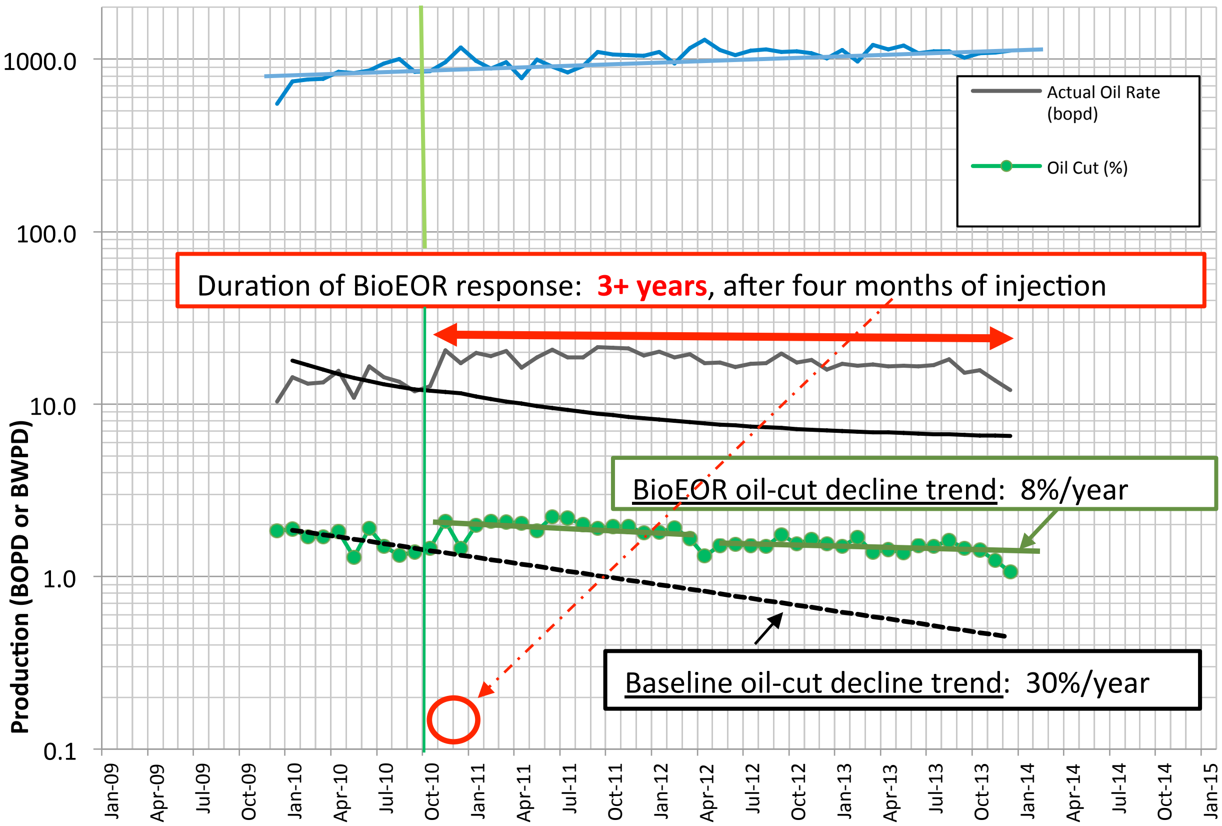

Figure 5. Duration of BioEOR production response (Ardmore Basin, Oklahoma)

<u>Deploying BioEOR in the field</u>

Transworld's science and databases are cutting-edge, and broadly patented. However, for deployment into the field on a commercial basis, the operational implications are straight-forward and field-ready, as follows:

- For a commercial deployment of BioEOR into an oilfield, the end product of all this research and detailed study is a custom recipe for a formulation of chemical activators appropriate for the microbes in the reservoir
- Years of extensive research has shown that the necessary activators turn out to be chemicals well-known in the industrial chemical business, and commercially available
- Technical-grade (least-expensive) versions of the chemicals are effective for field use
- Appropriate concentrations of activators in injected water are very low (less than 0.01% by weight), and cause no significant changes to the characteristics of water being pumped and flow-lined during ongoing water injection operations
- Aqueous formulation concentrates are easily handled and injected in the field, and are easily blended into injection water streams, with no requirement for water treatment
- The activation chemicals are so dilute as to be functionally unreactive: with each other; with compounds often found in reservoir waters; and with reservoir rocks
- Impacts on water injectivity are small, for several reasons:
  - activators are small, soluble, non-polymeric molecules with no plugging tendencies
  - microbial growth responses are low, because activator concentrations are low
  - BioEOR operates broadly in the swept zone of the waterflooded reservoir, and is not localized within the near-wellbore areas of injection wells

Production responses to BioEOR

Figure 6 shows recent production data for a small field in the Williston Basin, Montana currently receiving BioEOR activators. Baseline production trend and pre-project BioEOR response forecast are also shown. (The field has experienced downtime issues, as well as loss of injection source water; a number of the data points graphed have been corrected for these unrelated operational events). Injection of BioEOR activators started at the end of February 2015, and will conclude in March 2016.

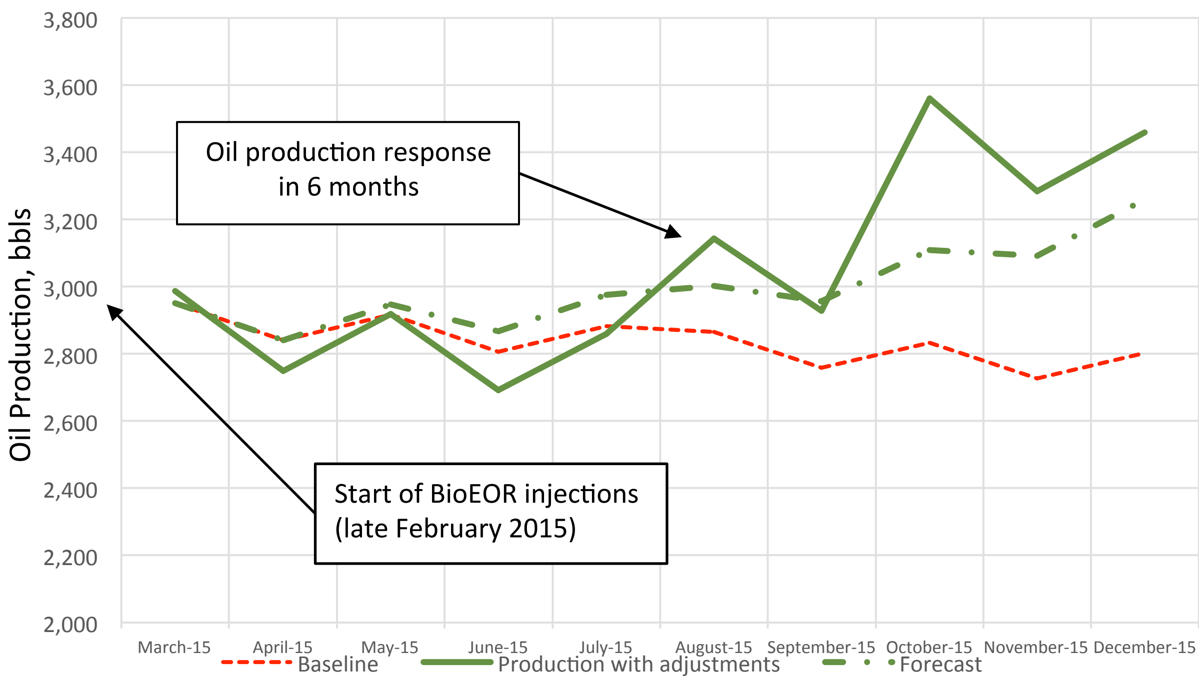

Figure 6. Oil production response to BioEOR (Williston Basin, Montana)

In this field, the elapsed time from first BioEOR injection to first oil production response was 6 months. The forecast BioEOR response was a 25% increase in oil production, to be achieved 14 months after first BioEOR injections. Actual response, adjusted for operational events, is better than forecast.

An active BioEOR project incorporates many aspects of ongoing technical assessment:

- Oil production (will increase, after an initial no-response period)
- Water injection (will be unchanged) and injectivity (will have a slight reduction, as injection water flow is diverted in the reservoir to less-transmissive rock with lower perm and higher oil saturation)
- Sampling of produced fluids (re activator consumption; water geochemistry; changes in biology; dissolved-gas content of produced water)
- Tracer studies (will see increased transit times vs baseline, as injection water flow is diverted)
- Lab studies working in parallel with injection in the field (for confirmation of field results)

For the Montana project, all of these biological science indicators confirm that microbial activation has occurred.

Transworld expects that production improvement will plateau, and then persist for several years (see ***Figure 7***). When response starts to decline, the field will be suitable for deployment of another round of BioEOR activators, because substantial saturations of residual oil will continue to exist.

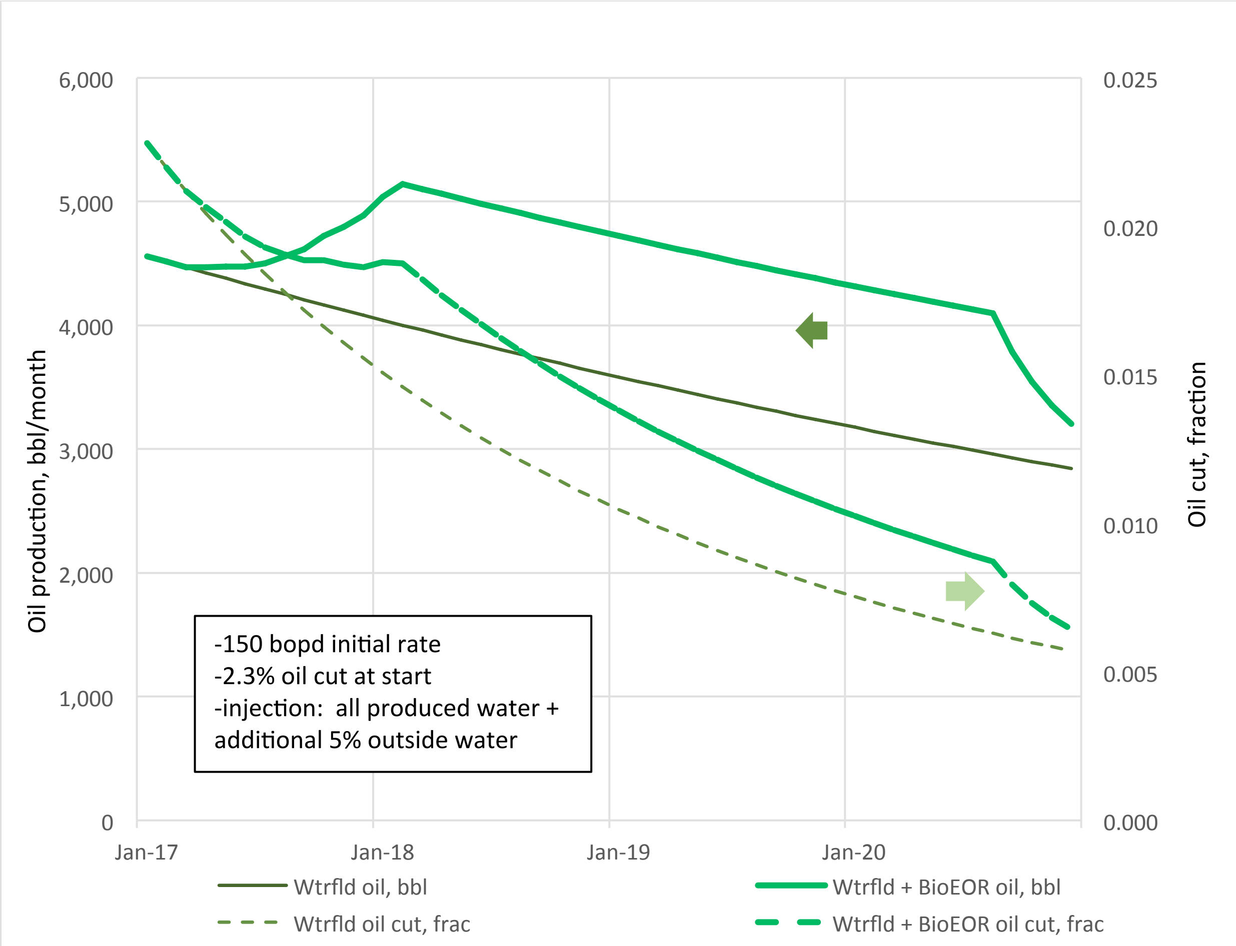

Figure 7. Model oil production and watercut responses to BioEOR in a typical small mature waterflood

Surface facilities needed for BioEOR

At ground level, a typical BioEOR project will include the following:

- A small enclosed module ("skid") with active tanks, dosing pumps, and blending manifold (see ***Figure 8***). All or a portion of the injected water stream is diverted into the skid, where the activators are added, before the water returns to the injection system.
- A shipping container used as a warehouse for tanks of aqueous activator formulations. The formulations are mixed off-site, and delivered to the field by trailer truck

Blending rates are in the range of 1 barrel of concentrated BioEOR formulations per 2,000 barrels of injection water.

Blending skids can be located adjacent to central injection plants, or near to injection wells if local-scale pilot operations are undertaken.

Initial lab testing during a project's design phase ensures that aqueous BioEOR formulations will blend into injection water without causing precipitation. Therefore there is no requirement of water treatment for softening or oil removal.

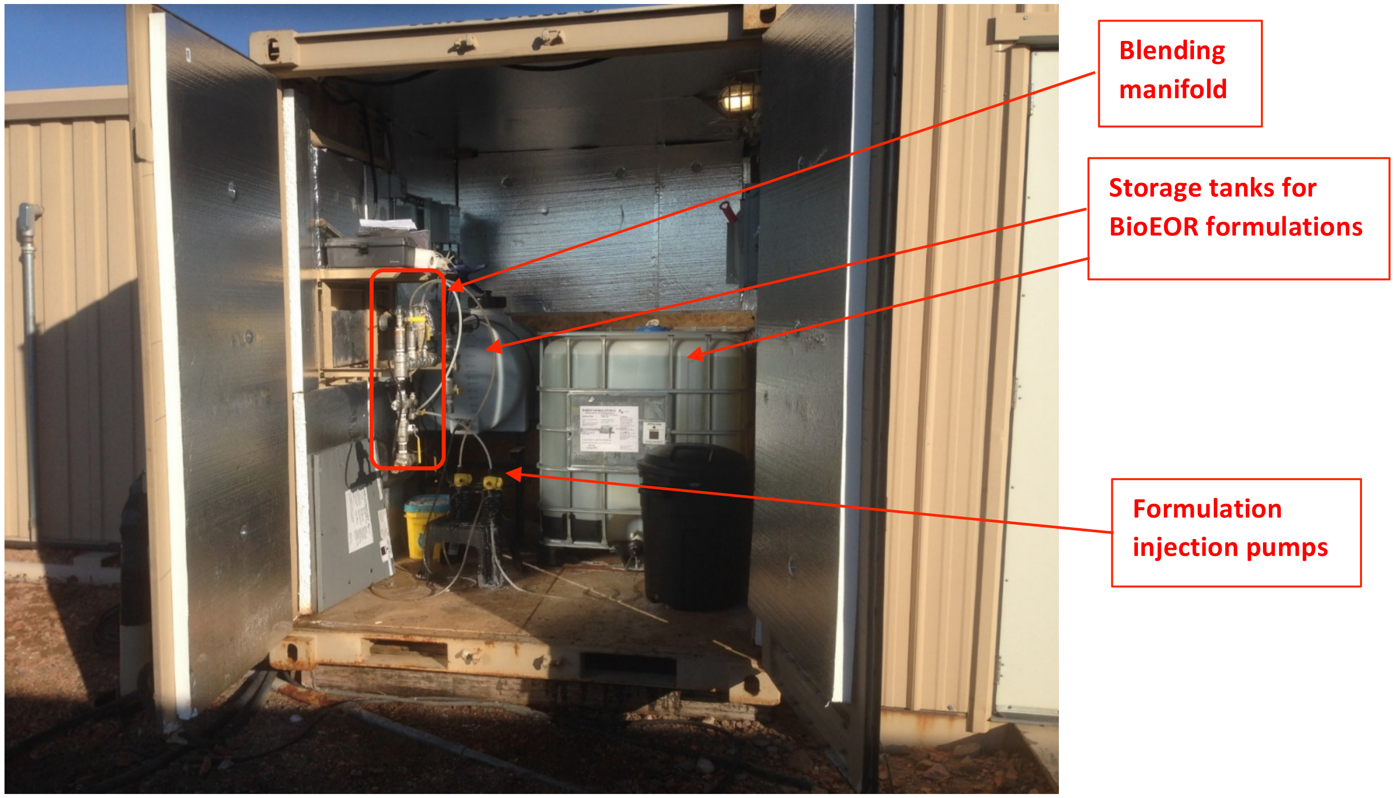

Figure 8. Activator injection module ("skid") working in the field

Project screening for BioEOR

Key project screening parameters are as follows:

- Mature waterflood property with the following characteristics:
  - historically successful waterflood response
  - ongoing oil production and water injection at commercial rates and stable trends
  - efficient recordation of production volumes, injection rates, and downtime
  - infrastructure in place for mechanical and electrical connection of Transworld's activator-blending facilities
- The presence in the reservoir of appropriate biology, capable of executing biogenesis after being re-activated
- Water chemistry that is supportive of biogenesis, and not of sulfate reduction
- Reservoir temperature below about 80ºC
- Prediction of commercial oil-production response to BioEOR, as the conclusion of the integrated evaluation of a field

Comparing BioEOR to other chemical EOR processes

Figure 9 shows a comparison of the characteristics of BioEOR chemicals, and of chemical costs per barrel of new oil. Input data for chemical costs was taken from Lake (2014) and from McCool (2012). BioEOR chemicals are far cheaper than surfactant-based chemical EOR processes per barrel of new oil produced. BioEOR activators are also less expensive than polymers.

	BioEOR activators	Polymer	Surfactant
Injected concentrations	Lowest		
Reactivity with rock	Very low	low	higher
Solubility in water	High	lower	high
Solubility in oil	Low		
Mechanical degradation	None	some	none
Cost $/lb.	Low	higher	much higher
Facilities required	Minimal	more	much higher

Figure 9. Comparison of chemical characteristics of various chemical EOR processes

Of equal importance, especially in mature fields, are BioEOR's small field footprint, and low infrastructure requirements.

In the field, BioEOR requirements are limited to the following:

- Mechanical connections to the field's injection water system for the skid
- Space on the ground surface for a temporary formulation storage warehouse, with access for delivery trucks bringing in pre-mixed formulations
- Sampling access at wellheads, usually via pressure bleed-off valves

BioEOR does NOT require:

- Water treatment
- On-site mixing of BioEOR formulations
- On-site laboratory facility
- Extensive and/or permanent storage facilities
- Modifications to wellbores
- Changes to field operating practices

Comparing BioEOR to microbial EOR processes

"Microbial EOR" processes have traditionally used various strategies to increase oil production, utilizing the biochemical processing power of microbial life to create desirable changes within the reservoir:

- Inoculation with commercial formulations of microbes having specific capabilities
- Feeding of inoculated and/or native microbes with injected carbon sources (such as molasses) and nutrients
- Changing the reservoir's chemical environment, from reducing to oxidizing

See Youssef (2009) and Patel (2015) for lengthy discussions.

The related EOR mechanisms involved have included:

- Residual oil mobilization, via microbially-created biosurfactants
- Flow diversion, via microbially-created polymers
- Flow diversion, via microbial growth
- Others

Field results have been mixed: some clear successes; some projects where results are difficult to discern; and some failures with dramatic problems (especially the plugging of injection wells due to explosive microbial growth) that have unfortunately created an enduring general concern about "MEOR processes" in the minds of some petroleum professionals.

Figure 10 summarizes crucial differences between BioEOR and many MEOR technologies:

	BioEOR: *activation* of microbes	**MEOR: *feeding* of microbes**
Original food source	Oil	Oil
Current activity level	Low	Low
Material provided	Simple ions	Complex chemicals, sometimes including carbohydrates like molasses
Species that respond	Key members of the complex community involved in methanogenesis	Any and all species who can utilize what has been injected
Microbial growth	Modest, controlled, and sustainable	Can be explosive causing plugging issues
Activity levels after injectates have been consumed	High	Low once again
Post-injection ability to utilize oil as the primary food source	High	Diminished

Figure 10. Differences between BioEOR and general MEOR technologies

A common characteristic of most MEOR processes is that their functionality is localized to near-wellbore areas. Therefore they are not effective on a reservoir scale, nor do they create results that are sustainable indefinitely after a treatment. As a result, frequent and ongoing treatment cycles will be required if strong production responses are desired over long periods.

The BioEOR process is entirely different:

- Agents of EOR functionality within the reservoir:
    - stimulation of native microbes, already broadly present in the reservoir and well-adapted to reservoir conditions, versus introduction of new microbes unfamiliar with the local reservoir environment

- Stimulation mechanism:
  - activation of microbes, so the microbes return to breaking down oil, versus the feeding of microbes using carbon sources not common in the reservoir
- Stimulation delivery system:
  - simple chemicals at dilute concentrations that are carried broadly throughout the swept zone, versus introduction of new microbes and/or complex chemicals at higher concentrations
- EOR mechanism:
  - flow diversion by a simple, resilient material (methane bubbles), versus changes to fluid saturations and mobilities caused by other materials (newly-created polymers; newly-created surfactants) which may be susceptible to adsorption, dispersion and microbial breakdown in the reservoir
- Scale of process operation:
  - process takes place throughout the swept zone, versus being localized close to the injection wells

	BioEOR: Microbial *Activation*	**MEOR: *Competitor***
Extensive Testing	6 - 8 Weeks	3 to 6 Months
Cost to Test	Included in Treatment Program	> $150,000 +
Field Requirements	Supportive Native Microbes + Active Injectors	Expensive Oxygenated Injection Systems & Water Treatment
Critical Species	Native Methanogens and Supportive Bacteria	Converted ***Aerobes*** and Supportive Bacterial
EOR Mechanism	Methane induced changes in Relative Permeability	Changes in Oil Wettability
Cost to Treat	Performance Based	Upfront Payment with Monthly Treatment Fee
Treatment Period	Up to 12 Months	Must Continue to Sustain Effect
Post-injection Performance	Prolonged once Activated	Declines Immediately Upon Discontinuance
EOR Performance	25% to 50%*	25% to > 60%**
Cost / Incremental Barrel	< $6 / Barrel	< $10 / Barrel***

* Estimated, amount is field dependent ** Multiple values according to literature *** Does not include infrastructure and testing costs

Figure 11. Commercial comparison of BioEOR to a competitive MEOR technology

Figure 11 presents a more detailed comparison of BioEOR to a modern commercial MEOR technology. From a general technical perspecive, the MEOR technology seeks to create significant chemical and biological changes within a small near-wellbore area, while BioEOR operates by making less-dramatic changes over a much broader volume of the reservoir. BioEOR is significantly less expensive, allowing Transworld to offer the technology to operators of waterfloods at zero upfront cost.

Summary
BioEOR presents operators of mature waterfloods with a new opportunity for increasing oil production at low cost.

The technology's EOR functionality is interlinked with microbes living in the reservoir. However in the context of field operations, BioEOR is a straightforward chemical EOR process:

- Key field operation remains water injection
- BioEOR chemicals are simple, soluble and dilute
- Reservoir distribution of BioEOR activator chemicals is broad, throughout the swept zone, as injected water moves through the reservoir
- No treatment of injected water is needed
- No new microbes are injected

Rapid advancements in biochemistry and microbiology have developed lab-based tests which provide reliable vision of BioEOR's future efficacy in oilfields under evaluation.

The combination of low cost and low risk can yield positive BioEOR project economics, even at today's depressed oil prices.

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