Impacts of BioEOR Technology in Rabbit Hills Field, Montana

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Executive Summary

BioEOR injections were conducted by Transworld Technologies Inc. (TTI) at the Rabbit Hills Field in north-central Montana from February 2015 to March 2016, for the purpose of improving the performance of the existing waterflood. The field's subsequent performance has demonstrated that BioEOR was successful.

This very mature waterflood was selected for BioEOR deployment based on the suitability of field conditions and history with key aspects of the technology:

- The reservoir waters were chemically compatible with microbial habitation, and with the work of microbes actively converting oil to methane.
- There was a pre-existing habitation of suitable microbes within the reservoir, who were capable of carrying out bioconversion, after they had been activated and stimulated by BioEOR.
- It was possible to design of a suitable robust formulation of BioEOR activators, that could be injected into a broad expanse of the reservoir and then be utilized by the BioEOR-associated microbial species.
- There was a past history of successful waterflooding within the field.
- Field conditions and operations were stable.
- There was potential for significant production uplift.

Field data provides the following assessment of BioEOR's impacts, after adjustments for unrelated operational upsets:

- After an initial lag period of five months, oil production capacity ramped up over another five months, reaching a plateau 31% above pre-BioEOR baseline.
- This plateau has been maintained for 14 months, and is ongoing.
- If as expected this plateau is maintained for another 22 months before production capacity ramps back down to pre-BioEOR baseline, a total of 32,400 additional barrels of oil production capacity will be attributable to BioEOR.
- Within the reservoir, the flow patterns of injected water were changed, as BioEOR created a distributed phase of methane bubbles that expanded the waterflood's swept zone.
- Water injection pressures increased slightly and slowly, reaching 2.3% above pre-BioEOR baseline pressure levels.
- No change was seen in the properties of the oil produced from the field.

Chemical and biological analyses of produced-water samples showed the following:

- There were no changes to the chemical properties of the produced water.
- The BioEOR activator chemicals were consumed in the reservoir.
- No biologically related events were seen. The reservoir was not "soured" beyond baseline conditions. No evidence was seen of large blooms of microbial growth, either in production behavior or in samples.
- Analyses of the biological changes which occurred in the microbial communities living in the oil reservoir show that microbial responses to BioEOR activation were orderly, and consistent with microbiological understanding.

Introduction to BioEOR

In nature, vast numbers of microbes live in the harsh, anaerobic environment of the Earth's subsurface. They obtain their energy through chemical reactions, including the breaking down of large hydrocarbon molecules. As a result, elements such as carbon are re-packaged into mobile forms, and thus made available for migration and potential re-use in the aerobic biosphere of the Earth's surface.

Microbial hydrocarbon conversion occurs naturally and globally on a huge scale. However, it is a complex process, involving numerous linked biochemical reactions and microbial species. Bioconversion is susceptible to slowing down and halting if biological or geochemical imbalances occur, either through exhaustion of necessary chemical inputs, changes in the functionality of one or more microbial species, or if upsets occur through geological events such as altered groundwater flows.

Bioconversion of oil has influenced the density and composition of over 50% of Earth's oil inventory (Head *et al.*, 2003). However, Transworld's sampling of numerous oil reservoirs has indicated that, in almost all cases where microbes are present, current conditions are not suitable for active bioconversion of oil:

- Chemical deficiencies exist, either due to depletion of key compounds needed by the microbes, or through the presence of process inhibitors at sufficiently high concentrations.
- Microbial populations are inactive, and unable to execute bioconversion unless important biological changes occur.

BioEOR is a chemical EOR process. BioEOR seeks to increase oil production in certain mature waterfloods and waterdrive reservoirs with appropriate existing conditions by stimulating the metabolic activity of resident microbes via providing dilute chemical activators. These activators re-invigorate the microbes, and stimulate the resumption of bioconversion of oil. In an oil production context, the BioEOR process operates as follows:

- Ongoing waterflooding delivers the activators to microbes already living within water-swept rock.
- Microbial respiration, using oil as the substrate (food), creates a gas saturation within the swept zone that diverts injected water into new, unswept rock.
- Expansion of the swept zone increases oil recovery.

Selecting and managing BioEOR projects

At the project level, a BioEOR project requires five baseline conditions:

a. Pre-existing habitation within the reservoir of a living community of microbes, adapted to the local conditions, which includes the presence of various key species needed to execute the symbiotic natural process that converts crude oil to methane.

b. Geochemistry of water and, to a lesser extent, of oil, that are suitable for the biodegradation process to take place, and to be accelerated by BioEOR.

c. A history of successful waterflooding.

d. Suitable current operating conditions: injection rates; voidage replacement; spacing of active injection and producing wells; stable operations; remaining economic life lasting at least several years.

e. Accurate measurement and recordation of operating parameters and downtime.

BioEOR's effectiveness is assessed technically in several ways:

- Minor changes in injectivity, observed within weeks at water injection wells.
- Changes in oil production, via improved oil cuts and improved oil displacement efficiency.
- Changes in tracer transit times, via comparing post-deployment data to a baseline survey.
- Certain changes to microbiology, and to a lesser extent to geochemistry, observed through a time series of chemical and biological samples taken from producing wells, starting prior to process deployment and continuing for several years after first injection of activators.

In the field, BioEOR involves the following actions:

- Controlling the blending ratio of the aqueous BioEOR activator solution, by adjusting pump rates as needed to match injection-water rates. *(weekly)*
- Monitoring injection well pressures, and ongoing injectivity re units of water injected/units of injection pressure. *(weekly, then monthly)*
- Sampling produced water for geochemistry and for biology, to ensure that the injected activators are being consumed, and that no unusual chemical or biological responses to BioEOR activators are occurring. *(quarterly, decreasing over time to annually)*
- Sampling produced water in key wells for tracer arrival. *(twice/week for several months during two tracer campaigns during project life)*

Rabbit Hills Field Case Study

Field History

Recently, BioEOR has been deployed into Rabbit Hills Field, Blaine County, Montana, located on the Montana shelf near Havre. BioEOR injections were conducted from February 2015 through March 2016, to supplement ongoing waterflood operations.

Oil production at Rabbit Hills is from the Jurassic Sawtooth (sometimes called "Bowes") formation, at a depth of 4,100 feet. The field was discovered in 1972. Waterflooding commenced in 1996, and successfully increased oil recovery. The field is now mature, and economically marginal. Cumulative production is about 2.6 million barrels of oil. Legacy Reserves has owned and operated Rabbit Hills since 2012.

Current oil production is 85 bopd at 7% oil cut, prior to corrections for operational upsets.

<u>Development</u>

Rabbit Hills Field was developed on 40-acre spacing. The field has 9 oil producers and 2 water injectors. A loose ring of dry holes helps define reservoir boundaries. Additional wells produce from separate Sawtooth reservoirs about one mile south. Legacy Reserves is also operator of a number of these outside wells, and uses their produced water to supplement re-injection of the waterflood's produced water.

As water production rates at Rabbit Hills increased during primary production, water disposal was needed, which encouraged unitization and commencement of waterflooding. The field's two water injectors were apparently selected for that service based on their (low) ranking as oil producers. These wells are diagonal offsets to each other, on the eastern side of the pool, at locations distant and asymmetric relative to most of the field's producers.

Geology and reservoir

At Rabbit Hills, the Sawtooth formation was laid down in a braid-plain depositional environment proximal to a marine shoreline, with complex lithology that includes clastics and several kinds of carbonates in proportions that vary from well to well. Reservoir thickness varies from 9 to 26 feet.

Cores indicate wide variability of perms for various lithofacies. From a study of four cores, Porter *et al.* (1998) report porosity and permeability averaging 15.1% and 79.6 md (ranging from 0.17 md to 469 md) for the field's bioclastic limestone facies, while "…the variably intermixed ooid limestone and quartz sandstone have a combined average porosity of 10.6% and average permeability of 13.7 md." Obviously, significant variability in lithology, porosity and permeability exists within the waterflooded interval.

BioEOR seeks to exploit the presence of matrix heterogeneity (ie. the presence of unswept rock). In addition, BioEOR is agnostic to lithology. Therefore the stratigraphically-complex reservoir rock at Rabbit Hills is well-suited to the BioEOR process.

Rabbit Hills oil has a gravity of 19^{o} API. Dynamic viscosity is 40 cp. Most wells produce black oil, however several produce a tight emulsion of oil, water and minor gas sometimes termed "chocolate mousse" in the technical literature.

Production performance

Production peaked at about 700 bopd in 1991, during primary production. Current production is about 85 bopd at 7% oil cut for the field. Production and oil cut trends will be discussed below.

As might be expected, waterflooding is most mature in the eastern area of the field, near the two injectors. Here, 4 producers make only 20% of the field's oil at 3.3% oil cut. The 5 wells around the field's northern and western rim produce 80% of the oil at 11.8% oil cut.

The two injectors are both operating comfortably within their regulatory maximum injection pressures. Legacy, as operator of other wells to the south (completed in separate Sawtooth pools) in addition to the waterflood, gathers the outside water by flowline and truck to the unit for injection. This outside water is a vital part of waterflood operations, representing 23% of total injection rates when BioEOR injections started in February 2015. Accounting for subsequent losses of injection water, due to mechanical failures in both waterflood and outside wells, was an important aspect of production loss management ("PLM") calculations needed for performance analysis.

Economics during the BioEOR project period

Rabbit Hills Field is a mature waterflood, with high water cuts, high lifting costs, and low operating margins. In addition, the field has more challenges:

- Limited opportunities to control costs through economies of scale, due to its small size, and its location in a remote area hosting little oil production
- A lack of nearby oilfield services, exacerbating downtime due to the costs and time associated with mobilizing workover rigs and pumped services to the field
- Bad crude oil pricing, as much as $22/bbl below the WTI benchmark, due to its heavy gravity, and its location in a region where crude oil pricing is tied to the weak WCS index

After oil prices collapsed in 2014 and 2015, Rabbit Hills Field was operated at a loss for some time. Cost-control responses, plus a spate of uncommon downtime events, reduced oil production. Once again, PLM analyses have been made to determine the field's true production capability in response to BioEOR.

BioEOR deployment at Rabbit Hills

Initial screening

Transworld staff acquired anaerobic produced-fluid samples from four wells in the Rabbit Hills Field in August 2014, using specialized equipment and techniques. These samples captured produced water and live microbes in native conditions, upstream of production chemicals and central facility heating.

The biological assessment of Rabbit Hills was encouraging for BioEOR. DNA sequencing showed that the groups of microbes required for BioEOR were all present (Figure 1A). The bacterial community (Figure 1B) was comprised of a diverse group of solubilizing, fermenting, and metabolite-generating bacteria. The archaeal community (Figure 1C) included representatives of species capable of generating methane via three different pathways, along with additional metabolite-generating groups.

DNA sequencing indicated the presence in low concentrations of some sulfate-reducing bacteria. It is likely that some past microbial creation of H_2S has occurred, since a trace of H_2S is present in the minor volumes of solution gas produced at Rabbit Hills. However, based on previous laboratory and field tests, conditions at Rabbit Hills made it unlikely that more H_2S would be created.

Initial screening also showed that bacteria were more abundant than archaea in the Rabbit Hills reservoir prior to BioEOR. To biodegrade oil, various microbes with different tasks in the metabolic pathway must work harmoniously and simultaneously, with their functionalities being properly balanced. At Rabbit Hills, both vigor and balance were lacking. The necessary biological pieces were in place, and they had functioned effectively in the past, since the oil at baseline was already partially biodegraded. However, prior to treatment, the microbes were not capable of renewed activity.

Chemical analysis of produced water was used to determine if elements required for biological growth and function were at levels that are predicted to be necessary to support a biological community at concentrations required to execute BioEOR.

Initial sampling indicated that Rabbit Hills water did not have sufficient concentrations of key elements required for cell energetics and protein building (nitrogen, phosphorus), or of trace elements required to produce enzymes (manganese, copper, cobalt, and others) needed for the cells to perform their biochemical hydrocarbon-breakdown reactions. From this data, a BioEOR treatment formulation was designed, by which the missing elements could be delivered to the microbes living in the reservoir.

Chemical analysis of produced water also investigated the possible presence of compounds that would prevent BioEOR creation of methane. Sulfate was found to be present, however concentrations were low, as were concentrations of sulfate-reducing bacteria in the community. In addition, no iron as iron (III), nitrate, or nitrite were detected, and salinity was at low concentrations suitable for many species of microbe. In total, the geochemistry of Rabbit Hills water was found to be suitable for BioEOR.

Engineering review of the historical performance of Rabbit Hills confirmed that waterflooding operations had been successful, and that then-current injection rates and voidage replacement were suitable. Operations and conditions in the field were observed to be orderly, and very clean. The field’s low well count reduced the importance of accurate measurements of fluid rates and oil cuts at the well level. Finally, minimal historical downtime had been reported in production reports submitted to Montana Board of Oil and Gas.

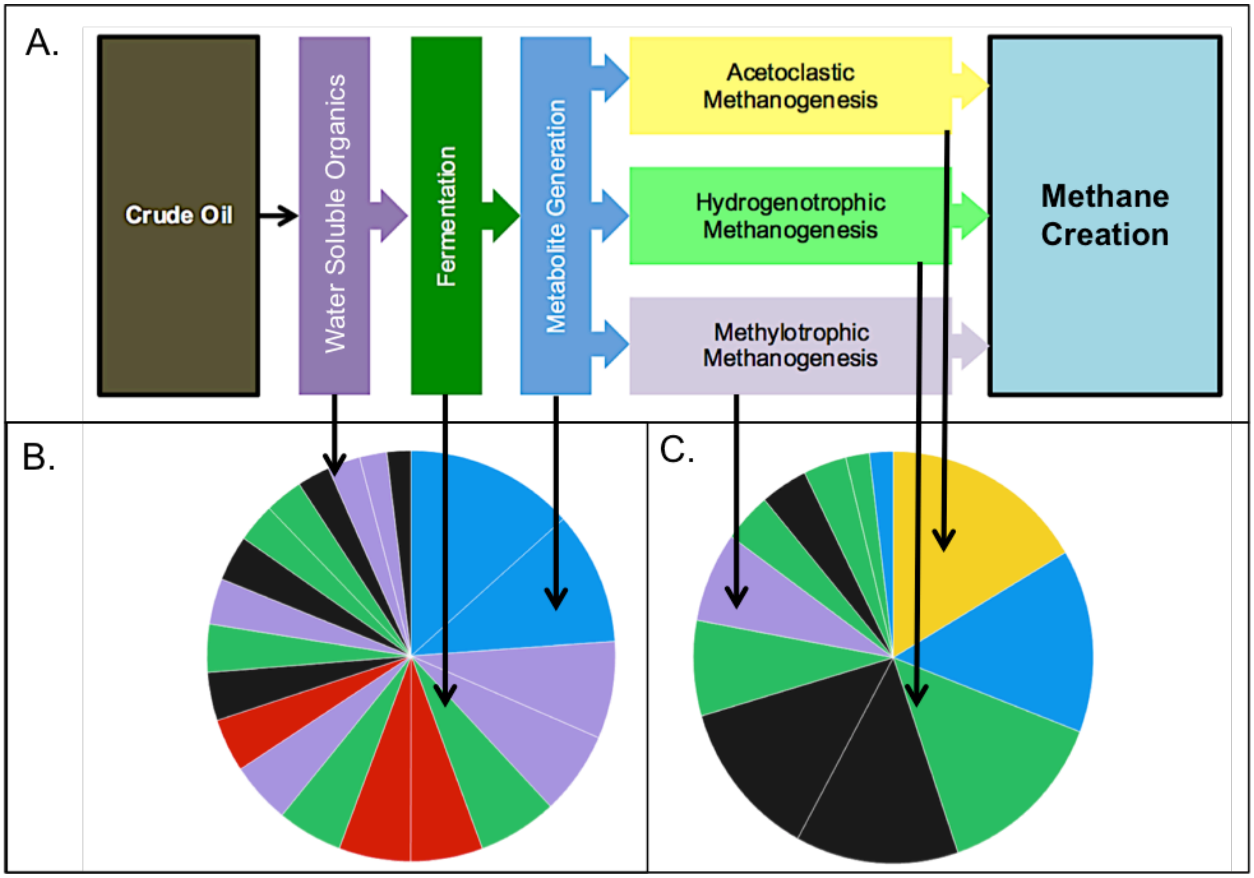

Figure 1. Stepwise biological conversion of crude oil into methane.

A: A metabolic model of BioEOR creation of methane from crude oil. **B**: Field averaged Bacterial community of Rabbit Hills Field prior to treatment. In red- Sulfate reducing bacteria, in black, aerobic bacteria. **C**: Field averaged Archaeal community, prior to treatment.

Baseline sampling

A baseline sampling program was conducted at Rabbit Hills in February 2015, prior to the start of BioEOR injections. It was seen that only minor changes had occurred to geochemistry and microbiology since the initial screening samples of August 2014. To summarize, for both groups of samples, the following observations were made:

- The biological community had present all of the members required for the BioEOR production of methane.
- Ratios of the microbes present from the kingdoms of bacteria and archaea indicated the BioEOR metabolism could not function efficiently unless stimulated.
- Chemical elements that are required for growth and metabolism for microbes were at too low of concentration to support bioconversion of oil to methane, pre-BioEOR.
- In reservoir water, compounds capable of inhibiting biodegradation, or of supporting other unwanted chemical reactions, were absent or present at tolerably low concentrations.

Between times of initial screening and baseline sampling, additional laboratory tests were conducted to confirm that the BioEOR activator formulation designed for Rabbit Hills was effective in stimulating methane production**.**

Production baseline

In 2014 there was a sharp increase in water injection rates, which had impacts on oil production (Figure 2), oil cut (Figure 4) and waterflood performance metrics (Figure 5). These changes have all been incorporated into baseline forecasts of oil production and water injection.

Tracer surveys

Slugs of tracer were launched from each injection well during February 2015, just prior to the start of BioEOR injections. Fluorescent dye was used, because of its chemical inertness, and the ability of Transworld's lab to detect it in produced water samples at concentrations down to 10 parts per billion.

The baseline tracer survey provided good vision of tracer transit times in the highest water-cut wells, which are located near the injectors. For the more distant producers along the field's northern and western edges, this tracer survey provided transit-time data that was less crisp, but still useful.

A second tracer survey was launched in April 2016, just after injection of BioEOR activators had concluded. A comparison of transit times is discussed below.

Design and injection of the activator formulation

BioEOR functions through the delivery of chemicals, needed by microbes living in water in the reservoir, but limited in availability there. Designing an appropriate formulation requires two steps:

- Determination of which chemicals are needed by the microbes, as discussed above
- Ensuring that the chemicals will in fact be delivered to the microbes. BioEOR operates over a broad area…the entire expanse of the swept zone. Therefore the activator chemicals must stay in solution for some time, as injected water moves significant distances. Numerical models and lab tests are used to design the formulation, and to confirm that precipitation will not occur, either in pre-blending storage in the field, or after blending into the injection water; and that no adverse chemical reactions will occur within the reservoir that could affect produced-water quality.

In the field, activator formulation is blended into waterflood injection water at slow rates. Resulting activator concentrations in injected water are low, consistent with the goal of aiding living microbes. Other production-enhancement processes, which seek to alter reservoir rock, or to broadly adjust reservoir chemistry, require much greater injected-chemical intensity (pressure; volumes; reactivity).

At Rabbit Hills, baseline injected water had a TDS of 9,600 ppm. Once the activator formulation had been blended in, the injected water had a TDS of 9,700 ppm when injected into the reservoir.

BioEOR deployment at Rabbit Hills involved the temporary installation of two Transworld treatment units ("skids"), one on the suction side of each injection pump. The same aqueous BioEOR activator formulation was pumped from each skid, at blending rates appropriate for the ongoing injection rates of each injection well. One well, Federal Rabbit #2, had baseline injection pressures closer to Maximum Injection Pressure. Its activator blending rates were initially reduced, and were then increased to design level once the injection pressure increase was observed to be low and steady.

Activator injection operations, including mobilization to the field and de-mob later, were low-impact and uneventful.

BioEOR results at Rabbit Hills:

Production and operational impacts

<u>Production</u>

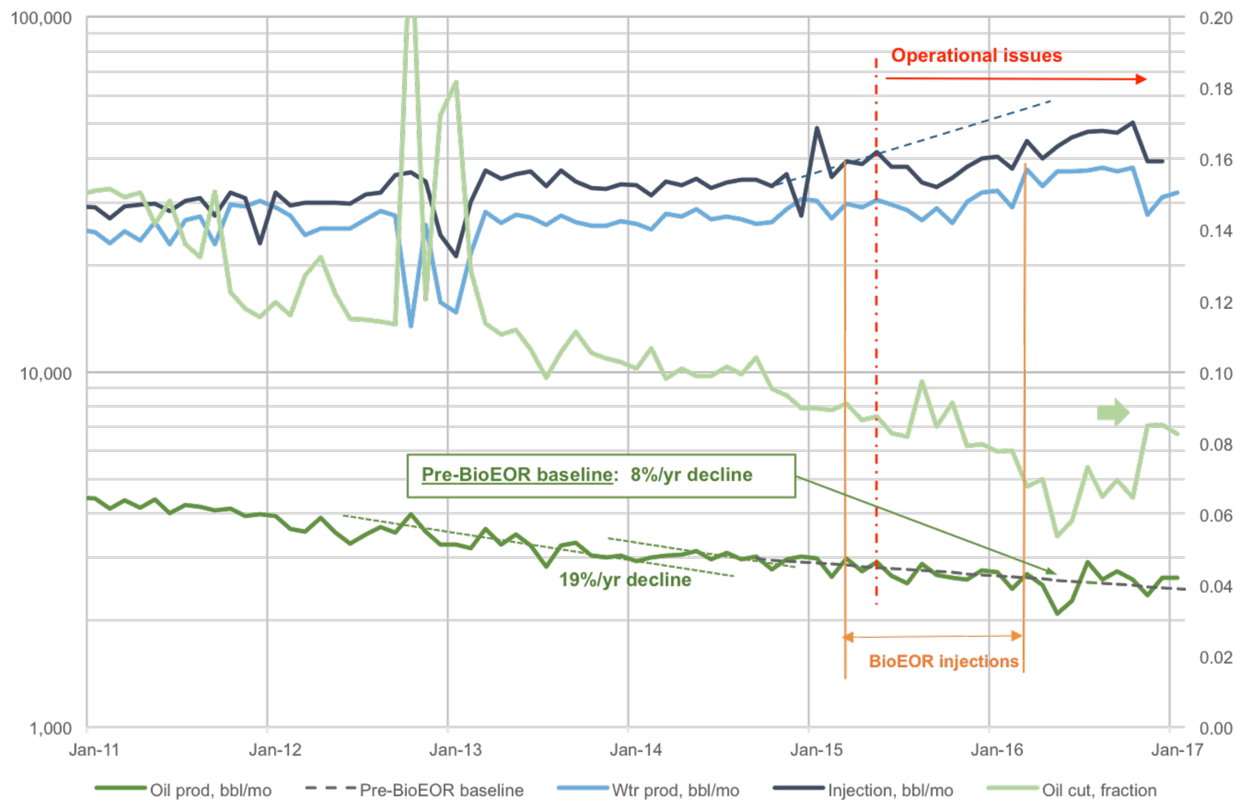

Figure 2. Recent production and injection history of the Sawtooth reservoir, Rabbit Hills Field.

Figure 2 shows reported oil production at Rabbit Hills from January 2011 through December 2016, and the pre-BioEOR baseline trend. Also included are annotations concerning significant events in the field.

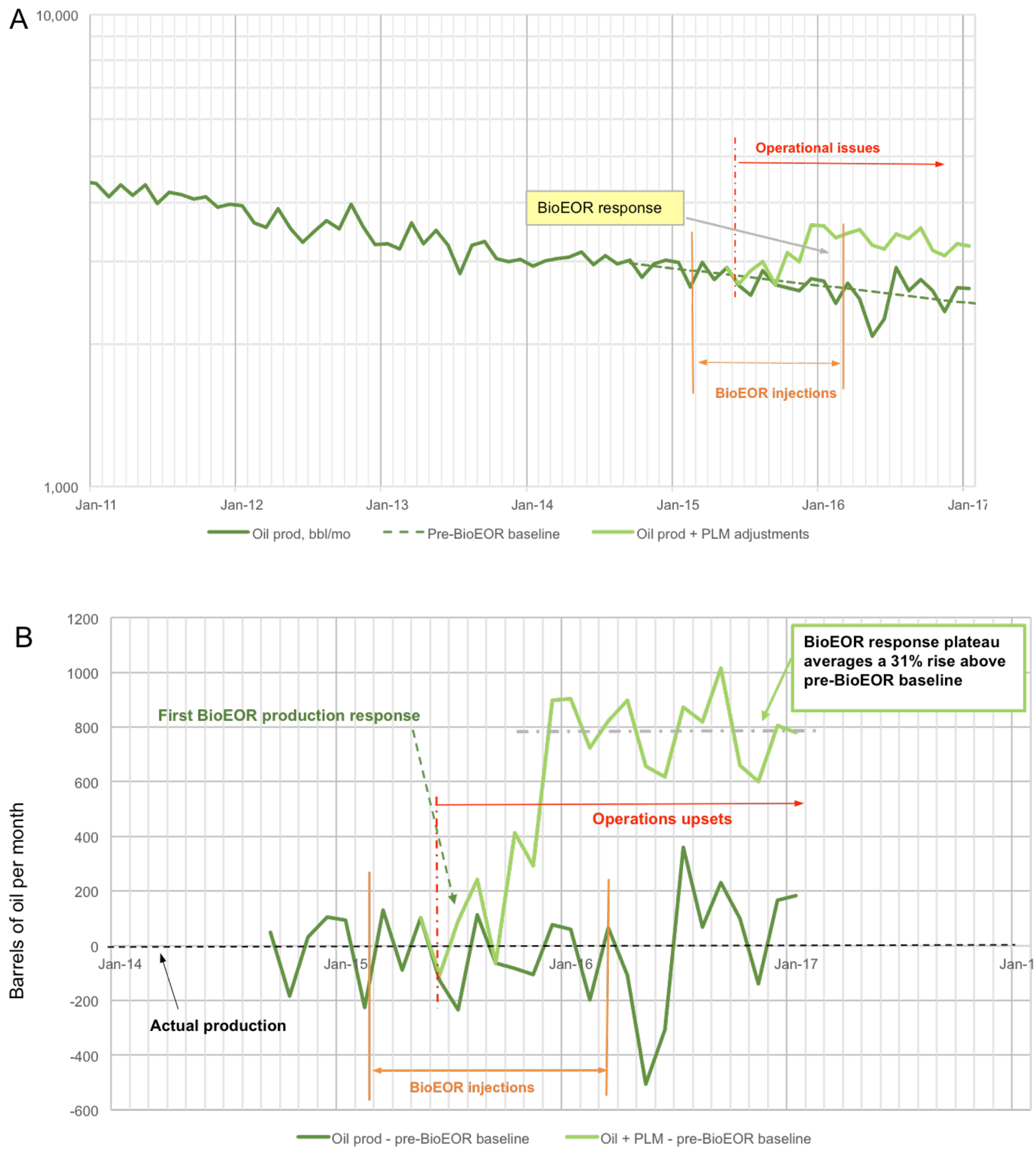

Figure 3. Response of Rabbit Hills oil production capacity to BioEOR.

A: Production capacity and actual production compared to pre-BioEOR production baseline. **B:** Quantification of oil production response to BioEOR (oil production per month).

Figures 3A and B show PLM-adjusted production capacity versus the baseline forecast. PLM methods were applied to deconvolve the impacts of reported downtime and reduced water injection volumes. Figure 3A and B present actual field production over time, and the reservoir's production capacity in response to BioEOR.

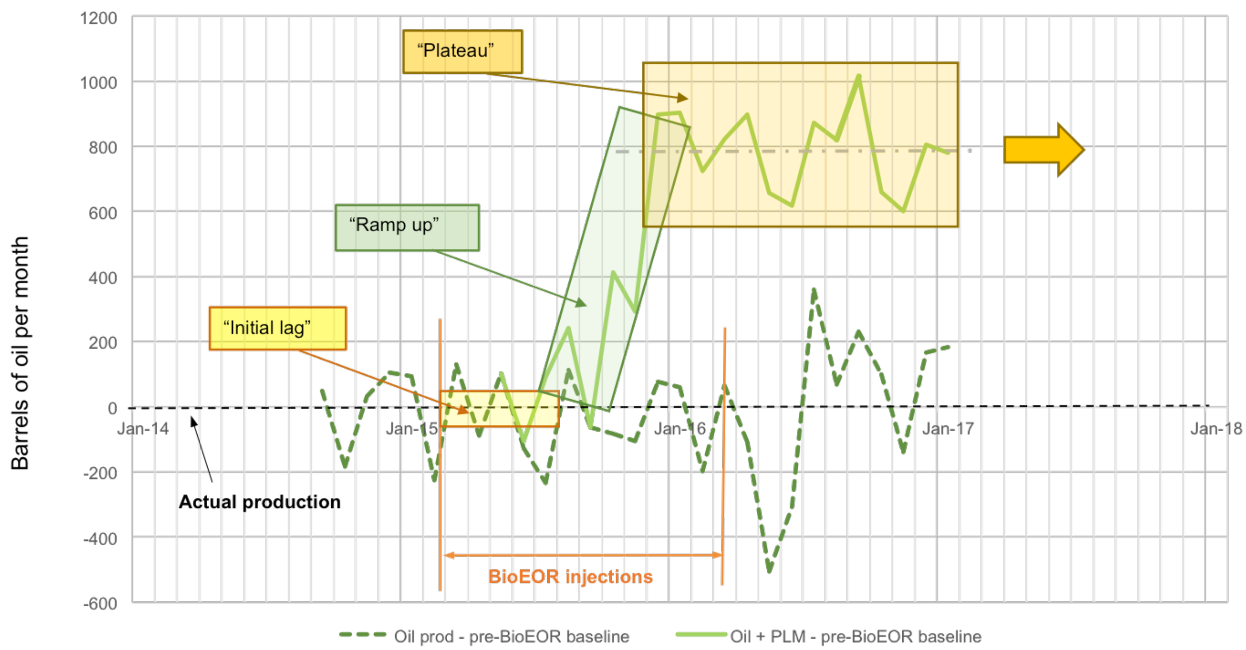

Figure 4. Stages of production response to BioEOR at Rabbit Hills Field.

Several phases of response are observed, and highlighted on Figure 4:

- An initial lag period, lasting 5 months, between first injection of BioEOR activators and first production response. During this time, the activators were being transported out into the swept zone. There, microbes were taking up the activators, and they were responding to the chemical stimuli: via the re-ordering of the microbial communities, as process-important species became more common; by increasing their activity; and through controlled growth in the numbers of microbes. New methane was created in the aqueous phase, and was initially dissolved there. As the water moved down-gradient toward lower-pressure producing wells, and more gas was continually created by newly-activated microbes, there reached a point where the (low) solubility of methane in water was exceeded. Most of the new methane exsolved, to form the bubbles which were the flow-diversion agent within the swept zone
- A ramp-up period, once again lasting 5 months, as injection was diverted from former flowpaths, the swept zone was steadily expanded, and new oil was contacted and displaced for production
- A plateau period, where the waterflood was now processing a larger, quasi-stable swept zone. At Rabbit Hills, this period has been underway for 14 months, and is ongoing. TTI expects the plateau to last for 3 to 4 years, based on the results of a small earlier BioEOR pilot project in the Ardmore Basin, Oklahoma. During this period, there will exist a dynamic balance between creation of new saturations of methane gas, the dislocation or breaking-down of other methane bubbles, and recovery of oil from newly-swept reservoir.

TTI expects that a ramp-down period will finally follow the plateau period, completing the BioEOR response cycle. No evidence of the ramp-down is seen so far.

The total time cycle for this project's BioEOR deployment is projected to be 51 months:

- 5 months of initial lag (observed).
- 5 months of ramp-up (observed).
- 36 months of plateau (14 months already observed; 22 more months projected).
- 5 months of ramp-down (projected).

Waterflood performance metrics

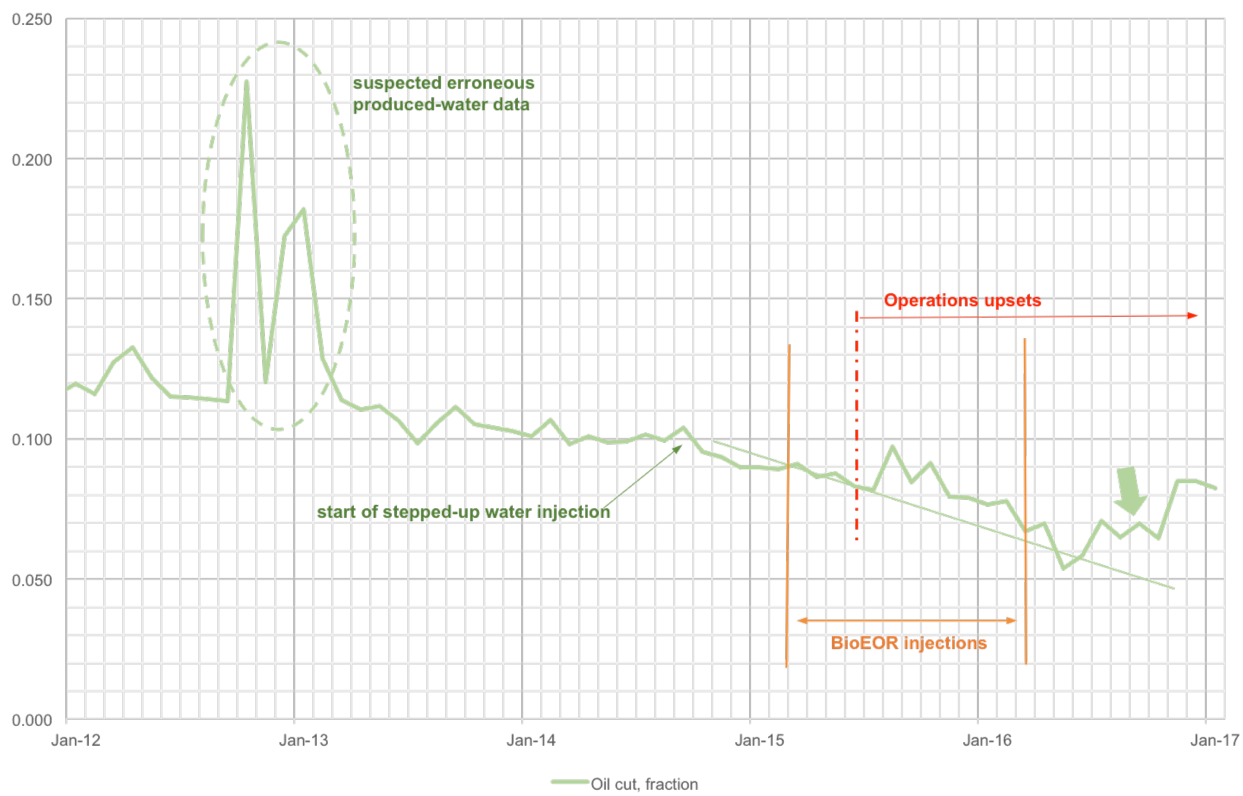

Figure 5. Oil cut at Rabbit Hills Field: recent performance and response to BioEOR.

Figure 5 shows field-wide oil cut trends over time. Included are annotations of important recent events in the operation of the field. It can be seen that BioEOR response caused a step-rate increase in oil cut, consistent with the additions of water injection into (and oil displacement from) newly-contacted rock.

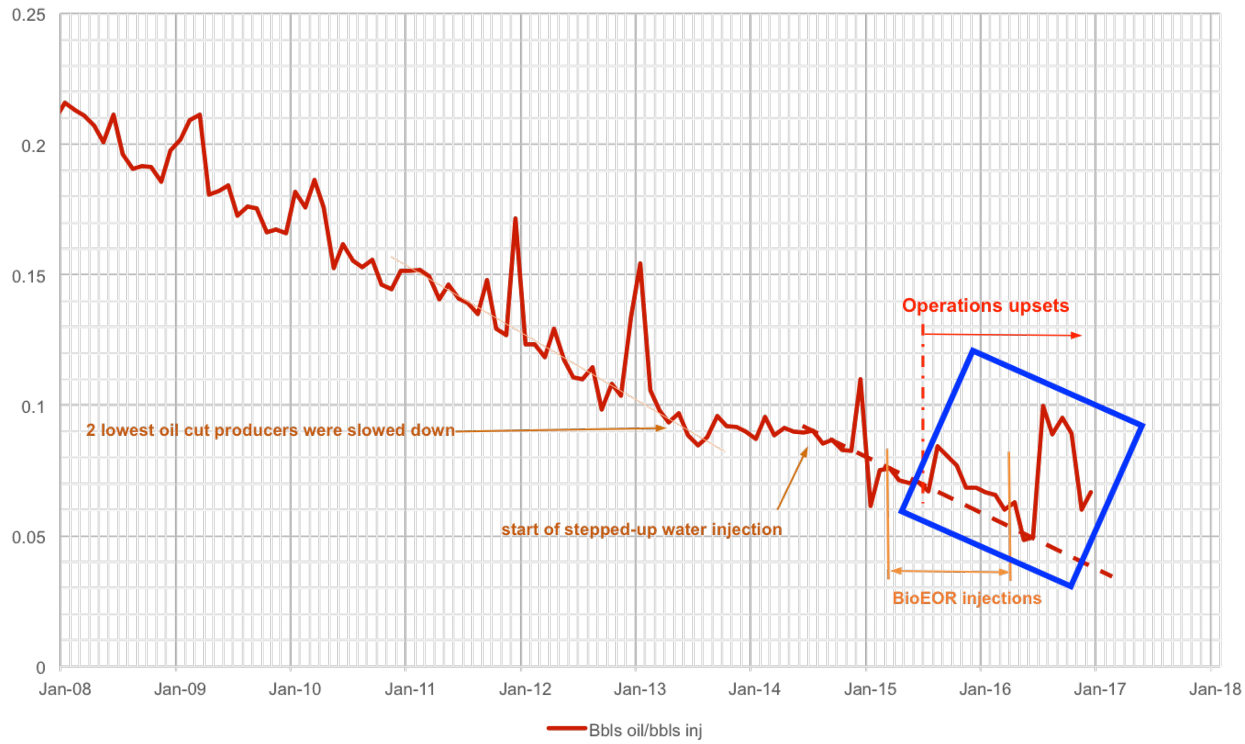

Figure 6. Oil produced per water injected performance at Rabbit Hills Field.

Figure 6 shows similar waterflood-efficiency trends over time via the "oil displacement index", or ODI, calculated for these analyses as barrels oil produced per barrel water injected. ODI was used for the PLM calculations related to lost injection volumes.

Water injection pressures, and water injectivity

Figure 7 shows the recent history of injection volumes, injection pressures, and the resulting calculated injectivity for the Federal Rabbit 2 injector at Rabbit Hills. Injection data at Rabbit Hills has a lot of chatter, so the data shown has been averaged over one-week periods for smoothing. The annotated trends correspond to the time periods used in production baselining.

Unfortunately the operational events causing the loss of injection water began soon after the start of BioEOR injections, which of course overprinted the injection-related field data. However, the following observations can be made:

- The volume of lost injection water was very significant.
- Minor increases in injection pressure, and reductions in injectivity, were visible within a few weeks of the start of BioEOR injections.
- These changes were not sudden or dramatic, as might have been expected if a near-wellbore plugging phenomenon had been at work.
- Injection pressure increases, amounting to 25 psi or about 2.3% of baseline injection pressure at the Federal Rabbit 2 well, have been reasonably stable for 1.5 years.

These observations are consistent with a shifting of injection flow within the reservoir, from the mature swept zone to previously-unswept rock.

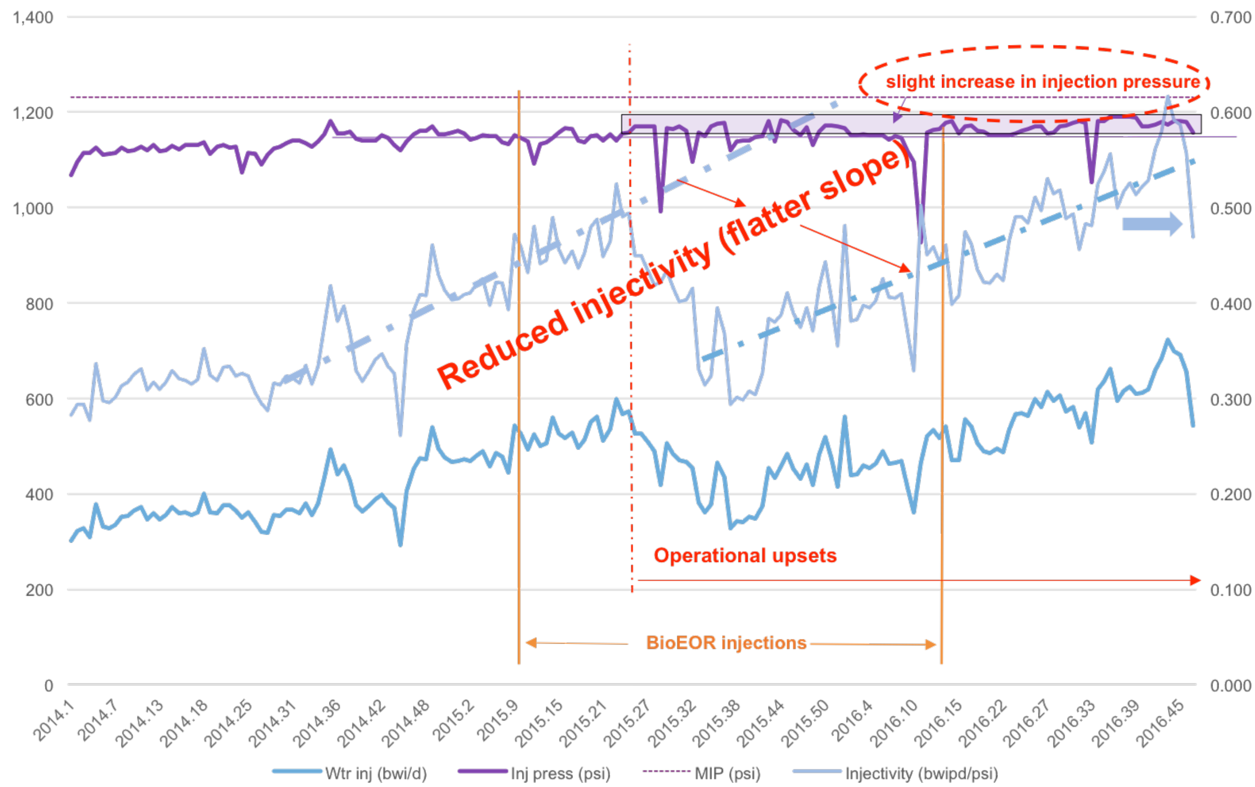

Figure 7. Water injection performance of the Federal Rabbit #2 well.

Note: time units are year.week.

Tracer transit time, and implications for modified water flow paths within the reservoir

Figure 8 shows transit time data from Tracer Study 1 (baseline) and Tracer Study 2 (post-BioEOR injections, 14 months later) for the area of the Rabbit Hills Field surrounding the two water injection wells.

BioEOR had two impacts:

- Time to first arrival of tracer doubled, from 19 days to 43.
- Width of the tracer wave (i.e. number of days between first arrival and last detection) more than doubled, from 23 days to 59.

Once again, both of these observations are consistent with the re-direction of injected water from “fast rock” (the original swept zone, with high perm and high water saturation) to “slower rock” (lower perm and/or lower water saturation).

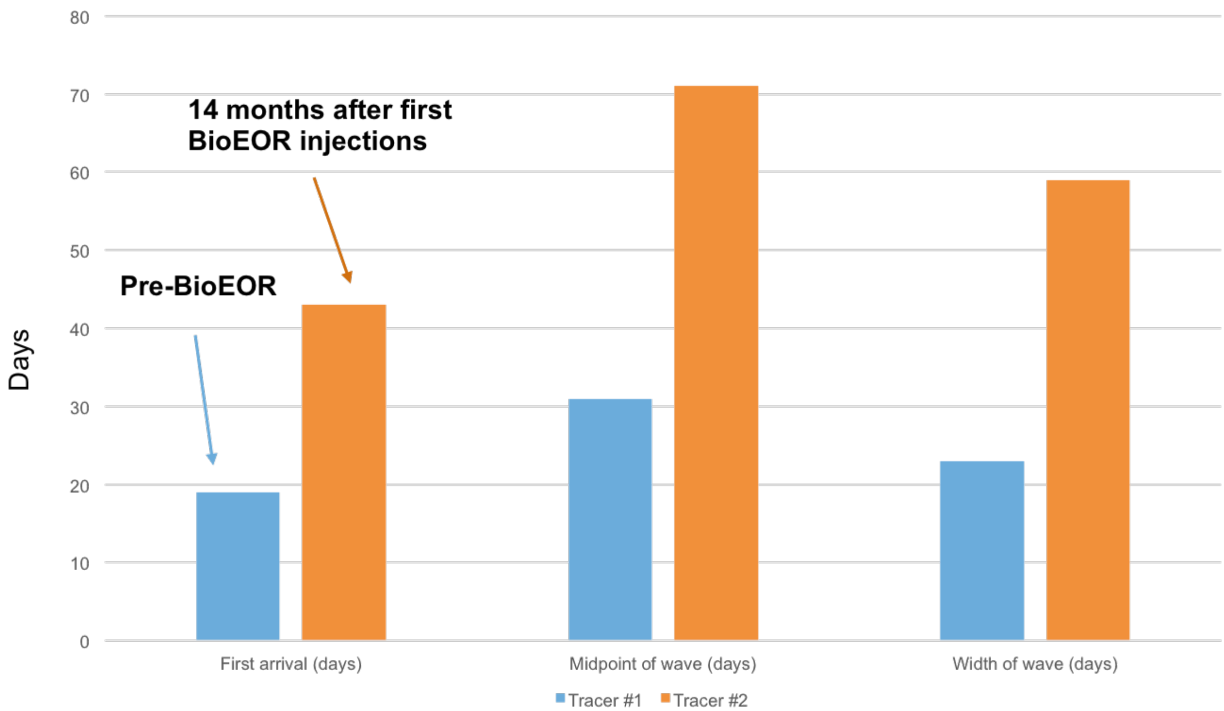

Figure 8. Comparison of tracer arrival times in producing wells offsetting injection wells.

Microbiology and geochemistry

Vision of biological changes over time is obtained through consistent analysis of a time series of produced-fluid samples, and observation of how the biology present in each sample has changed over time in response to BioEOR stimulation.

For the Rabbit Hills BioEOR project, excellent insight into just how BioEOR changed the microbiological life and activity within the reservoir can be obtained from an examination of a key well: Flynn Trust 41-18, a high watercut oil producer that offsets both water injection wells.

<u>Baseline Evaluation of Flynn Trust 41-18</u>

Prior to treatment, the biological community was primarily made up of various species that biodegrade large molecules. Fewer than 50% of the Archaea present were methanogens [Archaea is a kingdom of life, similar to but distinct from bacteria. Methanogenic species are the most commonly recognized species within Kingdom Archaea, however other species exist here too.] The methanogens that were present used acetate as a carbon source, so this metabolite's concentration was low. Many archaeal species present did not contribute to the production of methane as a terminal metabolite. Overall microbial cell density was low, as should be expected for a pre-stimulated reservoir. The fraction of archaea to bacteria was also very low, indicating the methanogenic population was depressed by lack of solubilized metabolites. Typical changes in microbial population take place on a logarithmic scale, however a change of cell concentration of 10^9 would be required to cause blockage due to cell density alone.

> *<u>Process status description</u>: <u>upstream</u> bioconversion capability (the presence of large numbers of cells utilizing large oil molecules) was well represented at pre-BioEOR baseline. However, the <u>downstream</u> parts of the process (those responsible for breaking down smaller molecules to methane) were weak, and were acting as a barrier to the functionality of the overall process*

Early Treatment phase: April-July 2015

During this phase, methanogens that utilize acetate increased in concentration, as did a species that produces acetate from carbohydrates. The acetate concentration increased as a result; the overall process was now successfully bioconverting both large and mid-sized molecules to small-sized methane precursors. The increased activity in this metabolic pathway resulted in more members of the biological community that were producing methane. A species that produces hydrogen and carbon dioxide from benzoate also increased in its abundance, causing a corresponding increase in numbers of hydrogenotrophic methanogens that use these metabolites to make methane. Because of these shifts in microbial demographics and activity, two pathways were now active for producing methane in support of effective BioEOR. Cell density slowly increased. The fraction of archaea increased exponentially, indicating a significant increase in precursor metabolites for the methanogenic pathway.

> *Process status description: BioEOR activators had awakened the downstream (smaller-molecule) bioprocessing capability of the overall microbial community. Not only was methane now being created; the functionality of the downstream section of the process was now more robust, since it was able to convert small molecules to methane using two different chemical process pathways.*

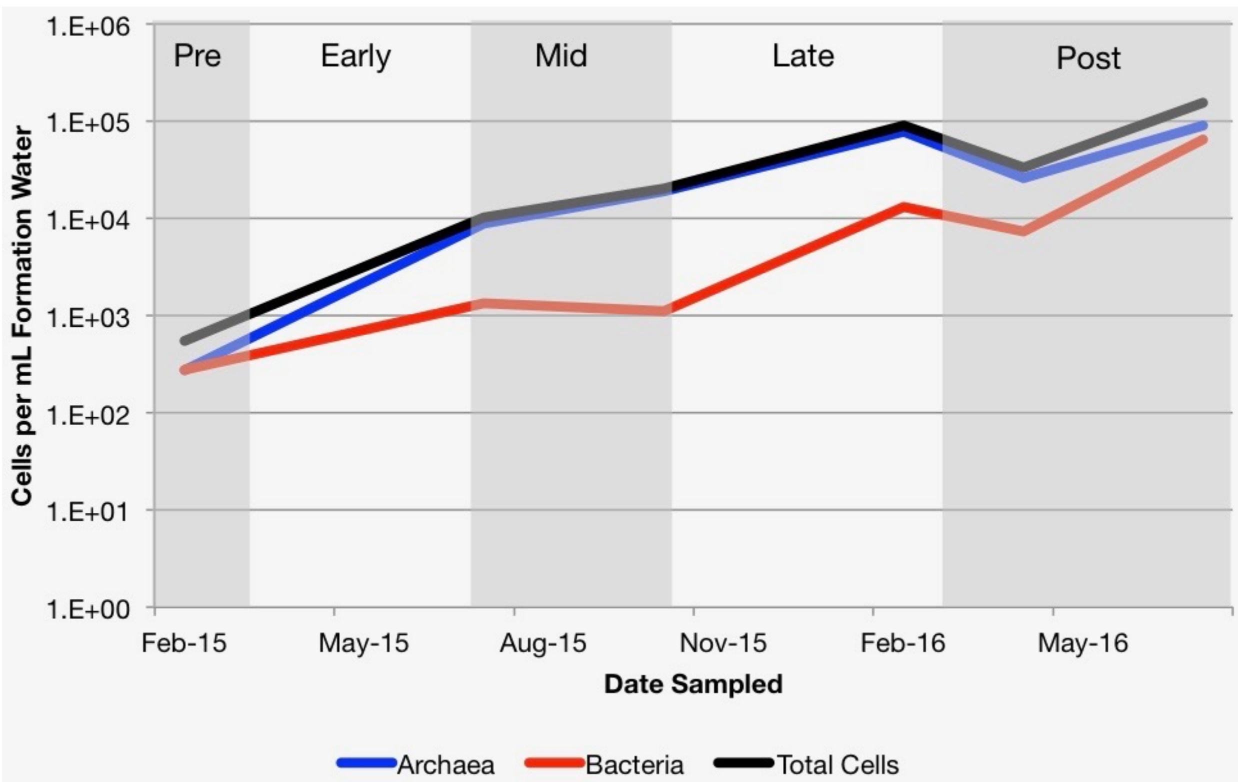

Figure 9. Cell concentrations of the 41-18 well prior to, during, and after BioEOR treatment.

Mid-Treatment phase: July-October 2015

Cell density continued to increase, and the fraction of archaea in the population increased 10 times from the early treatment phase. Acetate began to be depleted as methanogens catabolized it. At low concentrations of acetate, a different metabolic process called acetate oxidation becomes more entropically favorable, and in the 41-18 samples a species that performed acetate oxidation dramatically increased in concentration, becoming the most common bacterium. The metabolic products of this species are hydrogen and carbon dioxide. With two different species producing hydrogen and carbon dioxide, the hydrogenotrophs became the most common archaea. An acetogen also increased as a major part of the bacterial community, and reverted some of the hydrogen and carbon dioxide to acetate. This process is much more energetically favorable than the breakdown, but can only happen at high dissolved gas concentration.

> <u>Process status description</u>: *the complex bioconversion process, which breaks down C_{40}-sized molecules (oil) all the way down to C_1 (methane), was coming into dynamic balance. The baseline understaffing of downstream Archaea has been partially fixed; we now have many more of these microbes at work, so that they can better keep up with the upstream microbes (Kingdom bacteria) who are creating smaller metabolites from oil. Various species are actively responding to changes in the concentrations of their preferred feedstocks. The result is much-improved efficiency of carbon flow, from large molecules (oil) to small molecules (methane)*

<u>Late Treatment phase: October 2015 to February 2016</u>

A decrease in the presence of the acetate oxidizer and acetogen species during this period indicates that acetate concentrations have stabilized at a new higher level than prior to treatment *(mid-stream part of the process is now working better)*, and acetate is now continuously consumed by acetoclastic methanogens *(the downstream part of the process is now fully functional, too)*. Abundances of species that produce hydrogen and carbon dioxide (other than the acetate oxidizer) have stabilized, and hydrogenotrophic methanogens remain the most common archaea. As a result, the metabolic pathway to methane generation is more linear *(the various process-pathway alternatives have been sorted out, with the best becoming dominant)*. Rapid growth of the archaeal fraction of the community continued *(ongoing increases in staffing in this part of the process, in dynamic response to the accelerated carbon flows)*. The bacterial fraction of the community began to increase in population as well, but not at the same rate.

> <u>Process status description</u>: *the complex bioconversion process, that had achieved full functionality in the mid-treatment stage, is now finding ways to improve its performance, and to expand. The upstream part of the process (bioconversion of oil) remains strong; ongoing improvements are once again concentrated in the downstream part of the process. Fixing of the bottlenecks in the downstream process now allows the upstream species to become more numerous, expanding overall processing rates.*

From October 2015 to April 2016, the 41-18 well had detectable nitrogen in the form of ammonium ions well above the field baseline in produced water. Ammonium ions were injected as part of the treatment formulation, and were a major activation component. In the lab, ammonium ions move through porous silica-based media much more slowly than other, less reactive molecules. In the field, this slow velocity corresponds to predicted transit time 8 to 10 times slower than a chemically-neutral tracer. Detection of slow-moving ammonium in 41-18 samples indicates that the flow pathway between injectors and the 41-18 well had been fully exposed to the treatment chemicals. During the remainder of treatment, no other element included in the formulation appeared in any of the other wells, indicating full utilization in the reservoir.

<u>Post Treatment phase 2/2016 to date</u>

The post treatment phase currently matches the simplified metabolic pathway observed in the late treatment phase. A small increase in species that biodegrade large molecules may indicate a demand for more metabolic precursors to be used by these processes. Cell densities continue to trend upward slowly. Archaea appear to be reaching a steady state of around 2 logs of increased cell growth when compared with baseline measurements. Bacterial cells are now increasing significantly, which could be an indication of increased demand for metabolites in the methanogenic pathway.

> <u>Process status description</u>: *The bioconversion process at Rabbit Hills is now in balance. The entire process system, converting large hydrocarbon molecules (up to C_{40} in size) to methane (C_1) is stable, and functioning well. The changes now observed relate to overall process rate expansion, and not to rapid localized changes in metabolite concentrations or abundances of individual species associated with process restructuring and stabilization.*

Table 1: Bioconversion Process Changes under BioEOR

	Measurement	**Pre-treatment**	**Early**	**Mid**	**Late**	**Post-treatment**
Metabolites (est. in reservoir)	[Acetate]	Stable	**+**	**-**	**+**	No change
	[Hydrogen]	Low	**+**	**++**	**+**	No change
	Large Dissolved Organics	High	**-**	**-**	No change	**+**
Biological Community Members	Acetoclastic Methanogens *Methanosaeta*	Medium	**+**	**+**	No change	No change
	Hydrogenotrophic Methanogens *Methanobacterium* *Methanoculleus*	Low	**+**	**+++**	No change	No change
	Acetate Producer *Thermatoga*	Medium	**+**	**-**	No change	**-**
	H_2/CO_2 Producer *Sporatomaculum*	Medium	**++**	**-**	No change	No change
	Acetate Oxidizer *C. Contubernalis*	Low	**-**	**+++**	**- -**	No change
	Acetogen *Morella*	Very Low	**+**	**+++**	**- - -**	No change
	Large Molecule Degraders *Pseudomonas* *Xanthomonas* *Pseudoxanthomonas*	High	**- - -**	No change	No change	**+**
Cell Counts by Kingdom	Archaea	Low	**+**	**++**	**++**	**++**
	Bacteria	Low	**+**	No change	**+**	**++**
	Total Cells	Low	**+**	**++**	**++**	**++**

Conclusion on the Impact of BioEOR at Rabbit Hills

BioEOR was successful in stimulating oil production. During a period when Rabbit Hills Field experienced serious operational upsets and downtime, BioEOR kept the oil production on the pre-BioEOR baseline trend. When the effects of these unexpected operational events are deconvolved by applying production loss management (PLM) analysis, a production capacity increase of 31% above baseline trend is shown.

At injection wells, minor increases in injection pressure and injectivity were seen, consistent with diversion of injected-water flows to previously unswept rock. Tracer studies confirmed that travel times between injectors and producers have increased.

No reservoir problems related to the injection of treatment chemicals was observed either chemically, biologically, or operationally.

- Produced water from the reservoir had the same TDS and general water characteristics as before treatment.
- Souring due to an increase in sulfate reducing bacteria, or a change in reservoir pH due to acid producing bacteria was not observed in the reservoir.
- No blooms or massive increases in microbial populations were observed.
- Almost all chemicals injected for BioEOR have remained in the reservoir.
- Injection pressures increased in a stable and trendable manner, due to flow diversion over a broad area (the swept zone). Dramatic changes in injection pressure, indicative of plugging or blockages near the wellbore, were not seen.

Projections of Project Success matched actual observed results.

- Transworld's forecast of production uplift (6 month initial lag; then 25% uplift in daily rate) was reasonably accurate in predicting PLM-adjusted production response (5 month initial lag; then 31% uplift)
- Initial screening correctly identified the Rabbit Hills reservoir as being a suitable BioEOR environment, with supportive geochemistry, and an existing habitation by a function-capable microbial community
- Biological and chemical surprises were not expected, and none were observed.

References:

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