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MEOR From Lab to Field

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Abstract

Progression of Microbial EOR (MEOR) technology from the laboratory towards field trial is described. An overview is provided of evaluation steps and field trial risk management through laboratory testing and numerical simulation, together with assessment of operational factors which could impact a long-duration field trial.

Previously MEOR has often been applied in onshore operations which carry relatively low risk. Where MEOR is to be applied in high value wells or higher risk environments such as the arctic or offshore deepwater, a higher degree of assurance is necessary to mitigate technical risks and maximise economic value. It is also essential to have sufficient understanding of base performance to ensure appropriate application and interpretation of the EOR process. To ensure success of an MEOR process, there needs to be a sufficient understanding of the performance of the microbes and the relevant MEOR mechanisms operating in the specific reservoirs.

Multiple processes have been characterised and represented to enable improved understanding of a microbial technology and its potential field implementation.

This paper will focus on screening of candidate reservoirs, and the methodology adopted to upscale core-scale results to prediction of performance in the field. This will include the choice of simulation models used for mechanistic understanding at the core scale and prediction of performance at the reservoir scale. It will also discuss some of the field operational aspects which need to be considered for well selection for field trial, including injectivity and surveillance requirements. Potential constraints on application of MEOR in the field have been identified, assessed and mitigated where possible in order to maximise chances of success.

MEOR technologies are often poorly understood, which creates uncertainty and apprehension around their use. The approach described here has been used to reduce uncertainty in progressing towards field application of a novel MEOR technology.

Introduction

Many microbial EOR (MEOR) technologies and processes have been described and reviewed in the literature over the decades e.g. (1-3). This technology development is part of a significant EOR R&D effort by BP to improve recovery from its water flooded reservoirs which form a significant proportion of its portfolio (4).

MEOR processes can potentially be complex, involving multiple mechanisms which are generally poorly understood and not easily assessed or quantifiable. This can be offset by their generally low cost, leading to small financial risk in many cases. Where financial risk is greater in high value wells, or in more difficult areas to operate such as the arctic or offshore deepwater environments, a higher degree of certainty and commitment is required in order to progress from the lab stage to field trial and beyond.

While the current focus is on improving recovery from viscous oil production where recovery factors are relatively modest, there is also considerable scope to extend MEOR application more broadly to include conventional light oil which dominates the current global field portfolio.

Background to Milne Point Field, Alaska

The Milne Point field is located on the North Slope of Alaska in the US (Fig. 1).

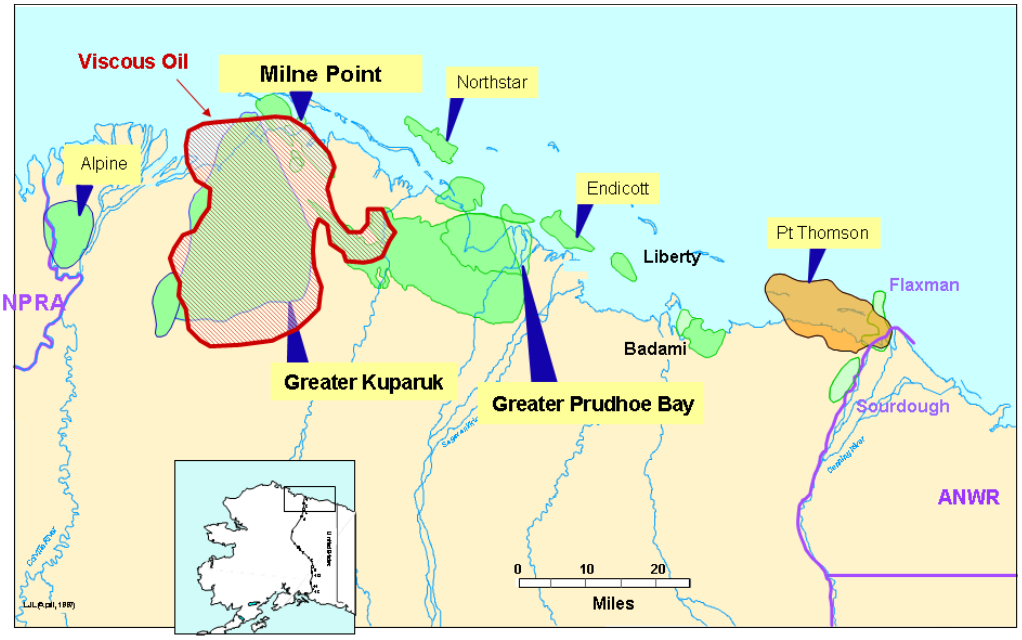

FIGURE 1 - Map showing location of Milne Point and other North Slope fields (Alaska state inset)

It contains a number of different oil reservoirs, of which the subject of this application is the viscous oil of the Schrader Bluff formation.

This formation is situated at a depth of approximately 4,000ft and consists of a stacked reservoir sequence containing biodegraded oil with variable fluid properties ranging from 14-21ºAPI (equivalent to 650 to 20cP reservoir oil viscosity). Saturation pressure is ~1,300psi and initial reservoir pressure was around 1750psi. Initial reservoir temperatures are low, in the range 75-85ºF. Surface injection water temperatures are higher, in the range 107-125ºF. Bottomhole injection water temperatures are in the range 85-103ºF after transit through 2,000ft of permafrost (Fig. 2).

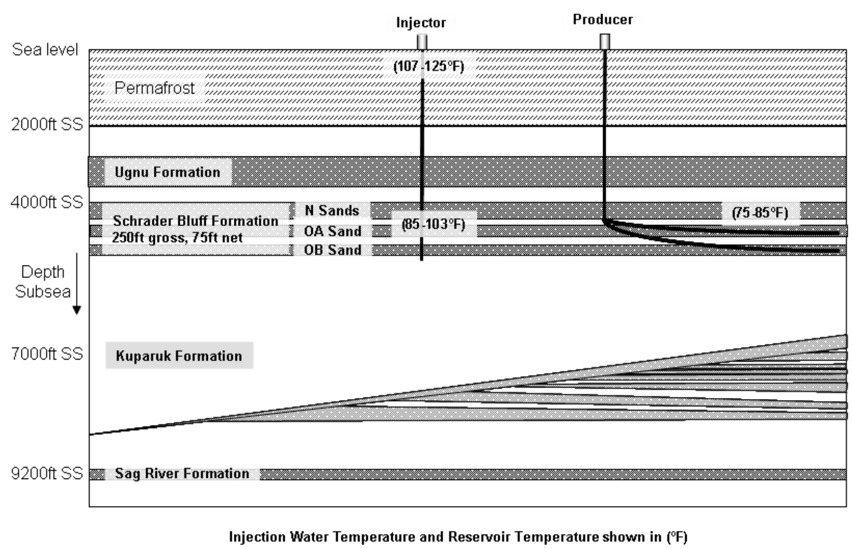

FIGURE 2 - Schematic Cross Section Showing Major Oil Reservoirs at Milne Point with Schrader Bluff Reservoir and Injection Water Temperatures

Brine chemistry analyses by IC and ICP from production, injection and power fluid water samples are shown below (5).

Table 1 – Analyses of Water Samples from Milne Point (concentrations in mg/l)

Species	Production Water	Injection Water	Power Fluid
Sodium	4965	5299	4186
Potassium	30	45	32
Calcium	50	71	48
Magnesium	27	28	37
Chloride	6141	7788	6516
Bicarbonate	2794	n/a	n/a
Sulphate	57	55	51
Phosphate	-	11	-
Acetate	210	n/a	n/a
Propionate	48	n/a	n/a
Butyrate	11	n/a	n/a

The lower viscosity reservoirs are developed primarily by waterflood with a mix of vertical and horizontal wells. The sands are poorly consolidated, and completion techniques use a degree of sand control to prevent major sand ingress. Expected recoveries under waterflood are around 20%, and with multi-billion barrels oil in place the Schrader Bluff represents a significant EOR target and is described further in (6).

Proposed MEOR Process

The biodegraded nature of the Milne Point viscous oil means that it does not readily provide a carbon source under anaerobic conditions in the reservoir. The proposed MEOR process is based on

- Waterflood diversion, through generation of biomass in higher permeability intervals to alter flood conformance
- Reduction in residual oil saturation, through microbially-induced interfacial activity

The treatment concept involves bioaugmentation i.e. injection of specialized microbes into the formation, supplemented by nutrients specific to those microbes. The microbes themselves are BSL1 organisms sourced from the Milne Point facilities.

Coreflood Evaluation

Several corefloods have now been carried out with the proposed MEOR microbe system with successful outcomes, more recently at full reservoir conditions, but using dead crude throughout. The MEOR Reservoir Condition Laboratory is shown in Fig. 3.

FIGURE 3 – MEOR Coreflood Facility

By its nature the viscous oil is difficult to handle experimentally due to its wetting characteristics. Volumetric measurements are therefore extremely difficult, and reliance had to be placed on the GASM (Gamma Ray Attenuation Saturation Monitoring) technique for accurate saturation determinations.

Factors which have influenced experimental design:

- Development of a non-damaging core cleaning protocol for the Schrader Bluff core involving a change to standard solvents used and use of a modified synthetic brine formulation to avoid formation damage.

- Use of iodide to measure in situ saturations real-time but without affecting microbe growth and performance.

- Use of a synthetic medium which mimics growth potential of real field brine but in trace quantities and without a large complex organics mix which could artificially elevate or modify growth potential.

- Representation of both initial inoculation and long-term phases of the MEOR process in a single reservoir condition experiment in a small rock volume at reservoir conditions with accurate saturation measurements

The essential principles of the coreflood methodology are to conduct a baseline waterflood in the absence of microbes, and then repeat it where necessary in the same core to check for relative permeability hysteresis. If relative permeability hysteresis were present, then it could mask the MEOR response or alternatively provide a false positive interpretation of saturation changes. If the saturation profiles are repeatable between consecutive floods, then there is confidence in the baseline waterflood response and saturation changes with throughput, against which an MEOR treatment flood can be directly compared on the same core material.

The use of iodide to measure saturations introduces an artificial component to the brine chemistry which can adversely modify microbe cell growth or even generate biocidal iodine if oxidized. Iodide can therefore only be used in the baseline floods and after the MEOR flooding sequence has been completed. It must be eliminated for the microbe stages of the coreflood. This means running without real-time saturation data during the crucial MEOR stages but enables an accurate snapshot saturation profile to be measured at the end of the MEOR flood to compare with the baseline. Final interpretation of the GASM data during the microbe/non-iodide stages of the flood allowed evaluation of the saturation profiles on a near-continuous basis.

The Schrader Bluff core contains reactive clays, particularly smectites. It was found that formation damage (loss of permeability) was occurring during cleaning and subsequent flooding of the core in preparation for the MEOR floods. The standard coreflood preparation protocol was modified to make the solvent cleaning phase less aggressive, allowing the reactive clays to remain protected by a thin oil film – kerosene and IPA were used as solvents instead of toluene and methanol. In addition, it was found that real formation brine and synthetic brine containing bicarbonate concentrations consistent with the field injection brine also caused formation damage, even when pH adjusted. Stable permeabilities were obtained when the bicarbonate concentration in the synthetic brine was reduced from 1,000mg/l to 100mg/l.

The MEOR system microbes were known to grow better in real field brine than in synthetic brine. In order to avoid the artificial use of high concentration media such as yeast extract to provide trace elements and vitamins for the microbes, a specific medium was provided to provide the missing nutrients at low or trace concentrations. The coreflood results are summarized in Table 2.

Table 2 – Summary of Coreflood Conditions and Responses

Coreflood	Conditions	Interfacial Response	Pressure Response
Clashach outcrop core	Ambient	Yes	Yes
Schrader Bluff core 1	Ambient	No	Yes
Schrader Bluff core 2	Ambient	Yes	Yes
Schrader Bluff core 3	Reservoir	No	Yes
Schrader Bluff core 4	Reservoir	Yes	Yes
Schrader Bluff core 5	Reservoir	Yes	As expected

Along with saturation and differential pressure measurements, periodic data was obtained on inlet and effluent brine chemistry (including volatile fatty acids and ammonium ions) and microbe population counts. This data plus other data from the project were fed into simulation studies for history-matching to obtain parameters describing the microbe activity and its interactions with the fluids and porous medium.

Simulation Models and Upscaling

Two types of simulation models of the MEOR process were worked with, utilizing commercially-available reservoir simulation tools – STARS and REVEAL. A complex hydrocarbon/microbe/nutrient reaction model was used in STARS to history-match sandpack and coreflood experimental data. A higher level multi-process model was used in REVEAL to assess performance at the field interwell scale.

The STARS model uses an approach similar to that described by Coombe and Vordoouw (7) in their model of microbial reservoir souring and its mitigation with nitrate or nitrite. The MEOR model is of the following form:

- Two types of microbes (with both planktonic and sessile components)
- Nutrient components
- By-product components
- Hydrocarbon components
- A method for transition between relative permeability curve sets describing the interfacial effect
- Methods for modifying permeability to alter waterflood conformance

The REVEAL model uses the polymer and surfactant flooding capabilities of the simulator to represent the two principle MEOR mechanisms. The polymer and surfactant components each mimic the overall effect of the generated and propagating biomass, with adsorption of these components representing the sessile microbe population.

The key difference between the two models is that the STARS model incorporates biomass growth directly as a function of nutrient injection, whereas the REVEAL model does this indirectly.

Linkage between the two models to complete the upscaling from lab scale to field scale was done through additional simulations with REVEAL at the core scale followed by comparative runs with an interwell distance scale model with both STARS and REVEAL. Watercut and injectivity responses were similar over the expected range of biomass/nutrient cases.

The high level REVEAL models could then be used to assess the relative importance of the different mechanisms of the MEOR process and their rate of response at the producers.

In order to capture reservoir heterogeneity (and subject to uncertainty around injector fracture growth – see discussion of Matrix Bypass Events) type pattern and indidivual injector-producer pair models were used for inter-well modeling of MEOR treatment performance. Full field models were not used as they would either be too complex for the high level simulation approach in terms of runtime or not capture sufficient formation heterogeneity. The models used reservoir layers of the order 2ft thick each. An example permeability heterogeneity profile for two adjacent wells with 1400ft separation is shown in Fig. 4.

Incremental oil profiles were then fed into economic models for commercial assessment.

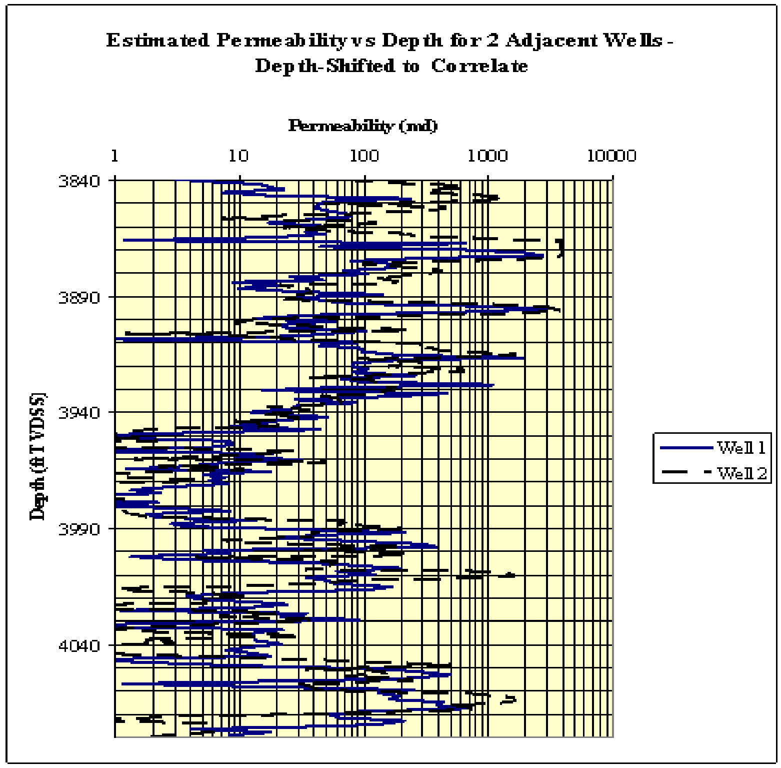

FIGURE 4 – Example Permeability Heterogeneity Profile for 2 Adjacent Wells

Analysis of Field Constraints

Multiple field operational risks can impact well operability, surveillance and the MEOR treatment itself. These include:

- Rate and watercut variability
- Injectivity impacts and voidage management
- Matrix Bypass Events
- Issues with Injection Water
- Corrosivity Assessment
- Screening for other Potential Analogue Fields

These are discussed in the following sections.

Rate and Watercut Variability

In order to determine the success of an MEOR field trial at liquid production and injection well rates of around 1,000bpd and with rate and watercut variability/uncertainty of 20% or more, it is essential to install a multiphase meter to have more frequent rate measurement compared with use of a mobile test separator.

Injectivity Impacts and Voidage Management

Injection of microbial nutrients in to the reservoir can result in significant changes to well injectivity, even if the well is normally injecting above (thermally-altered) fracture pressure. Wells which are already injecting at fracture pressure limits may therefore not represent good MEOR candidates if voidage replacement has to be maintained, as the rapid change in injectivity may not be immediately compensated for by a drop in water production at the offset producers. A voidage gap could result, leading to loss of producer performance.

Consequently, well selection needs to focus initially on wells which have wellhead pressure headroom to accommodate injectivity change. At Milne Point, the many injection completions were narrowed down to the final potential candidates for MEOR on this basis.

Matrix Bypass Events

Matrix Bypass Events (MBEs) are thought to be caused by injection well fractures and/or wormholes growing with time, eventually linking up with offset producers. This can result in sand production at the offset producers, water cycling and even shut-in of the affected wells. Some of the current Schrader Bluff wellstock have been affected by MBEs of varying degrees of severity, presenting significant risk to successful EOR application.

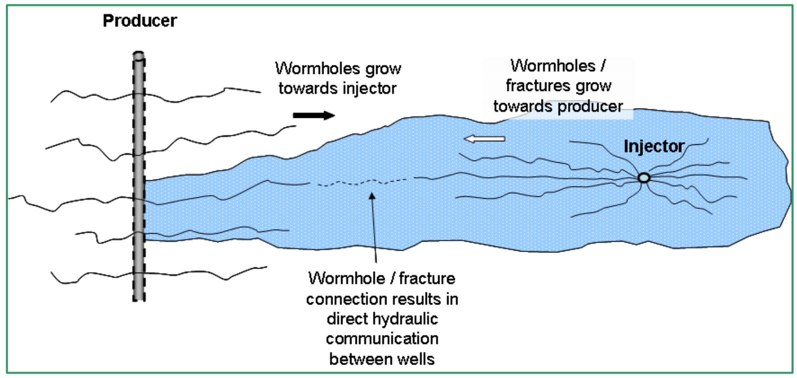

FIGURE 5 – Schematic of Matrix Bypass Event Mechanism

To enable low MBE risk wells to be selected for field trial, the likelihood of an MBE occurring over the medium term needed to be estimated. One way of doing this is to estimate the size of the void volume associated with MBE events in the form of a fracture. These injectors have been injecting above fracture pressure of the formation so the first approach was to see if the MBEs could be adequately explained by injector fracture-type behaviour without having to infer any direct association with wormholes generated by sand production at the producer.

The timing of a known MBE event in an injector-producer pair was matched to a calculation of a fracture length equivalent to the interwell distance using the methodology described by Slevinsky (8). The single match parameter Fd (the damage factor) obtained from this match was then used to calculate fracture lengths in other injectors around the field and found to correspond well to bursts of sand production and known MBE events at offset producers in many cases. Injection wells with offset producers having no known MBE events also tended to have shorter calculated fracture lengths in comparison with the wells that did have MBE events, giving confidence in the validity of this approach. The risk appears to increase significantly above 70% of the interwell distance – whether this represents the true impact of producer-generated wormholes or is just a feature of the statistics is not known.

This approach enabled an assessment of MBE risk for all the wells in the field to be made over the medium term i.e. sufficient to cover the duration of an MEOR field trial. In turn, this enabled wells to be selected as potential field trial candidates with some confidence that they would be unlikely to suffer a catastrophic MBE during the course of the trial. An unfortunate but logical consequence of this is that these lower MBE risk wells are also likely to have less wellhead pressure headroom to allow for injectivity change, and better waterflood conformance, therefore taking longer to respond to an MEOR treatment.

Issues with Injection Water

In addition to brine salinity, composition and temperature considerations, production chemicals are added to injection water which may impact survival of the microbes both before and after they reach the reservoir.

Brine salinity and chemistry are not a risk to the proposed MEOR system microbes as they were originally sourced from the field and are adapted to these conditions. The concentration of sulphate in injection water is low and there is no reservoir souring although sulphate-reducing bacteria (SRB) are present.

Reservoir temperature does vary across the field, and perhaps more importantly, the injection water is actually hotter than the reservoir. It is important that the microbes are not exposed to high injection water temperatures for long during transit from the surface to the reservoir where conditions are more benign after the water transits through 2,000ft of permafrost.

Corrosivity Assessment

Introduction of microbes or microbial nutrients into an injection system is intended to change the microbe populations and/or increase microbial growth in the reservoir at least. If applied on a long-term semi-continuous basis there is a risk that corrosion rates may be adversely impacted by an MEOR treatment.

A long term sandpack experiment was carried out to assess whether there was any tendency for the MEOR microbes to increase system corrosivity, using both corrosion probes and coupons. No significant increase in corrosivity was observed.

Screening for other Potential Analogue Fields

Screening has been carried out to see if there were other fields in the portfolio that could potentially offer field trial candidates with properties and conditions analogue to the Milne Point Schrader Bluff but in a lower risk environment with less risk of MBE impacts.

The screening criteria were:

- Injection water salinity <35,000-50,000mg/l TDS
- Injection water temperature <104ºF
- Reservoir temperature <104ºF
- Injection water pH slightly acid to alkaline
- Rock type sandstone
- Mineralogy preferably smectitic
- Permeability typically >50-100md
- Oil type viscous
- Brine type low sulphate, low hardness

Conclusions

1. A methodology has been described for evaluation of an MEOR system with respect to a high risk environment, covering coreflood, through simulation to addressing field operational risks.

2. Coreflood methodologies have been modified to account for factors such as brine chemistry which may affect microbe performance and/or modify core properties.

3. Reservoir simulation tools have been selected to reflect the scale of application and enabling understanding of the process and assessment of performance potential at the reservoir scale.

4. Key operational factors affecting MEOR potential and field trial evaluation have been assessed.

5. Appropriate surveillance monitoring techniques have been identified to ensure that the MEOR response can be adequately quantified.

6. Matrix Bypass Events in particular have been successfully quantified to assure well candidate selection is appropriate for a long-duration field trial.

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