

RESERVOIR CONDITION EXPERIMENTAL STUDY TO INVESTIGATE MICROBIAL ENHANCED OIL RECOVERY (MEOR) IN THE DEEP RESERVOIR ENVIRONMENT

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ABSTRACT

This paper describes an experimental study, comprising a series of reservoir condition core floods, which when combined with appropriate up-scaling simulation allow the determination of microbial enhanced recovery (MEOR) in an oil reservoir.

The experimental methods described combine both single and novel dual core flood techniques to generate data applicable to the deep reservoir environment, thus enabling an improved prediction of Microbial Enhanced Oil Recovery.

Initial studies (not covered by this paper) at both ambient and reservoir conditions, used conventional single core floods to demonstrate that MEOR could provide additional oil production. The potential for bio-diversion of flow was also demonstrated. However, the single core flood experimental design was such that results may have only been applicable to the near well-bore region in an actual reservoir.

The result of a new study to investigate MEOR using a dual core propagation technique is described. Advanced reservoir condition core flooding hardware, procedures and in-situ gamma attenuation saturation measurement techniques have been modified to enable the propagation of microbial behaviour to be investigated.

Two cores, at full reservoir conditions, were connected in series such that the effluent from the first core (representing the near well-bore region and inoculated with microbes) was injected directly into the second core (representing the deeper reservoir environment and not inoculated). The successful demonstration of propagation of the MEOR effect was through additional oil production from the second core when compared to previous baseline control floods. The intention of this paper is to describe the novel reservoir condition dual-core laboratory technique developed and to present qualitative results for one study

The experimental data from all these experimental studies has been input into a detailed simulation study to upscale the results and enable field MEOR performance to be predicted. This study showed that propagation of the interfacially active microbe can produce additional oil in the deep reservoir environment. There is also strong indication from the core flood and using an associated NMR analysis that the propagated region showed a change in wettability towards a more water-wet state.

INTRODUCTION

Many microbial EOR (MEOR) technologies and processes have been described and reviewed in the literature over the decades. This technology is part of the suite of technologies being developed under the Pushing Reservoir Limits R&D initiative aimed at keeping BP at the forefront of creating and deploying EOR technology in support of our leading edge recovery factor.

A study has been performed to investigate Microbial Enhanced Oil Recovery (MEOR) using a dual core flood propagation technique. This was performed at reservoir conditions on a specifically designed and constructed facility, Figure 1. This work continued on from a previous successful demonstration of MEOR [1]. Additional oil production was shown at both ambient and reservoir conditions. The potential for bio-diversion of flow was also demonstrated. However, the previous experimental design was such that results may have only been applicable to the near well-bore region of a reservoir. This work further developed an understanding of the processes involved, particularly whether the MEOR effect propagated to the deep reservoir environment.

The intention of this paper is to describe the novel reservoir condition dual-core laboratory technique developed and to present qualitative results for one study.

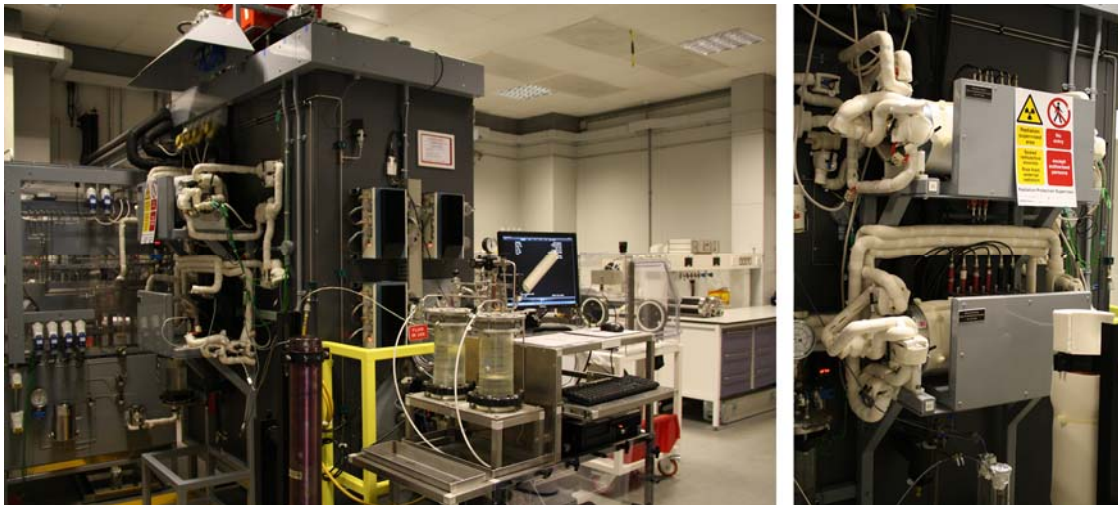


Figure 1: BP MEOR Laboratory

EXPERIMENT OVERVIEW

A dual core experiment was designed such that two separate cores, at full reservoir conditions, were connected in series with the effluent from the first core (representing the near well-bore region) injected directly into the second core (representing the deeper reservoir environment). Only the first core was inoculated with microbes, followed by a constant flush with brine containing feed nutrients. Upon equilibrium growth being established, indicated by a constant effluent microbe population, the effluent from this core was then flowed directly into the second core. This effluent was used to perform a waterflood from initial water saturation (S_{wi}) to remaining oil saturation (ROS) in the second core. The ROS result was compared with a previously performed Control Flood that had no microbes present. A lower ROS value was obtained, which indicated an MEOR benefit.

EXPERIMENT PREPARATION (PRE-MEOR)

Test Conditions And Fluids Used

This test was performed at full reservoir conditions, at a pore pressure of 124barg, an overburden pressure of 172barg and a temperature of 33°C. The oil used was reservoir crude oil, dewatered to 0.2% volume, which had a viscosity of 49cP at test conditions. Simulated brine was used, based on the reservoir brine composition, but with a reduced bicarbonate content to help mitigate clay damage. Three variations of this brine were prepared; standard brine, brine containing iodide to aid with gamma attenuation saturation monitoring (GASM), and brine containing some additional microbe feed nutrients. Brine had a viscosity of 0.77cP at test conditions.

Near Well-Bore Region

A single, long Clashach sandstone plug was used to represent the near well-bore region. A core length of 231mm was used to maximise the residence time of the brine within the growth zone region during MEOR flooding. Following cleaning, the plug was raised to reservoir conditions and the absolute brine permeability and pore volume were measured, shown in Table 1. This core was then ready for inoculation with microbes.

Deeper Reservoir Region

Material from reservoir preserved whole core was selected. This material was highly unconsolidated and required core plugs to be cut frozen using liquid nitrogen. Two plugs were cut parallel to observed bedding planes. They were then mild miscible cleaned using kerosene and iso-propan-2-ol (IPA) in a flood rig. This non-standard cleaning technique was developed to reduce permeability damage due to high clay content. Once cleaned, characterisation measurements were performed and similar results obtained for each plug. A composite was constructed using a CT scanner to ensure good alignment of bedding planes between the two plugs. Figure 2 presents a volumetric CT image of the final composite, within which some shells fragments were apparent.

The composite was loaded into the MEOR reservoir condition facility with frits installed at each end face. End frits were installed for this unconsolidated core to prevent fines / sand grain migration into rig flowlines which may have potentially lead to line blockages. The composite was degassed with undersaturated fluid at a nominal pore pressure, then raised to test conditions and absolute brine permeability and pore volume measured. A summary of the composite characterisation data is given in Table 1.

Table 1: Characterisation Data

<u>Deeper Reservoir</u> (Reservoir Composite)		<u>Near Well-Bore</u> (Clashach Plug)	
Length	164mm	Length	231mm
Diameter	3.75mm	Diameter	3.79mm
Bulk Volume	182mL	Bulk Volume	261mL
Pore Volume	55mL	Pore Volume	34mL
Effective Porosity	30%	Effective Porosity	13%
Kw (Sw=1)	111mD	Kw (Sw=1)	148mD

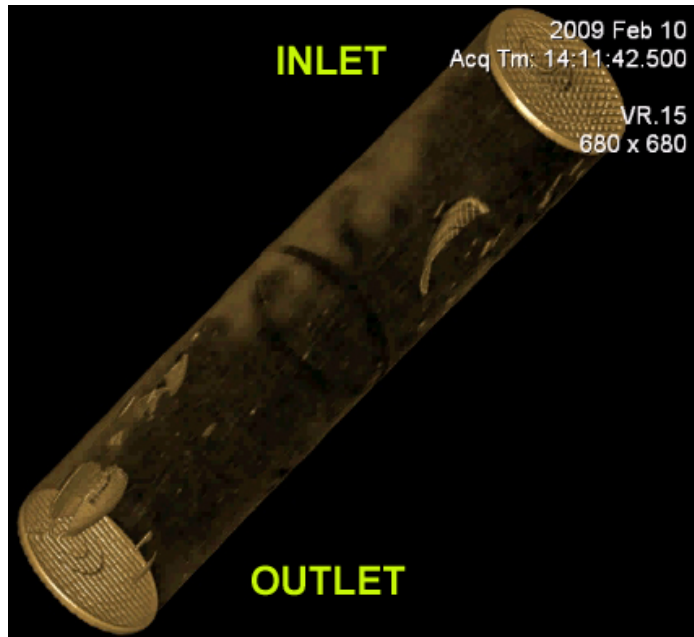


Figure 2: CT Volumetric Image of Deeper Reservoir Composite

Control Floods

Control floods were performed for the core representing the deeper reservoir. These formed the basis for conclusion of a successful demonstration of MEOR propagation. Figure 3 shows a flowchart of the core preparation stages and subsequent Control floods that were required.

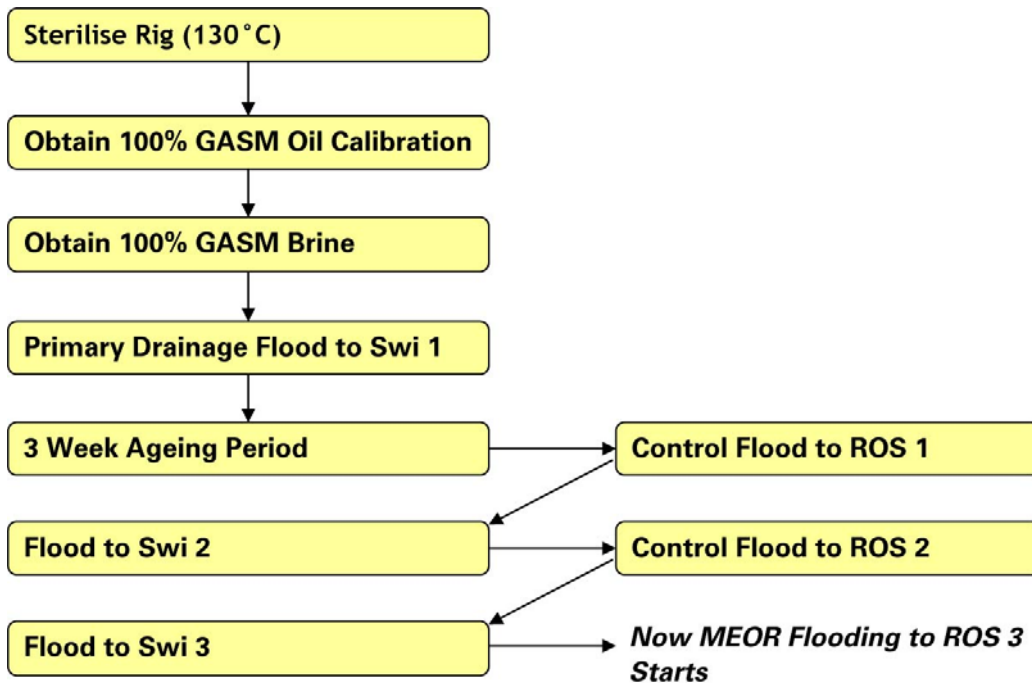


Figure 3: Deep Reservoir Core Preparation and Control Flood Sequence

To ensure that the study investigated the MEOR benefit of only the targeted microbes, it was essential to ensure that all equipment was sterilised prior to use and remained uncontaminated throughout the experiment. This was achieved by heating the entire rig, all equipment and both cores to nominally 130°C for a period of 24hours, prior to cooling to the required study temperature of 33°C.

GASM gave real time fluid saturation and distribution within the core. This was a key component to this MEOR study as the viscous nature of the reservoir oil used rendered mass balance measurements inaccurate (from observed and physically measured volumetric oil production). GASM calibrations had to be obtained at the start of this study as microbe growth and potential biofilm generation was considered to be a potentially irreversible effect.

The next stage was a primary drainage to initial water saturation (Swi1) performed through viscous oil drive with the actual study oil. This technique was necessary to maintain an uncontaminated system and to keep the up-front GASM calibrations valid (the core had to remain unmoved within the rig throughout the entire study). Following a 3 week ageing period, the deeper reservoir core underwent a secondary brine flood to remaining oil saturation (ROS1). It was then returned to Swi2, again through viscous oil drive.

Some evidence of saturation hysteresis was observed between the Swi1 and Swi2 drainage profile and end point distributions. This was to be expected given the different conditions; with one drainage started from 100% brine saturation with the core in a cleaned state, and the other from ROS with the core aged. A flood cycle to ROS2 and back to Swi3 was performed to achieve repeatable saturation histories, which was necessary to ensure that any MEOR benefit was subsequently highlighted. This completed the deeper reservoir core preparation. The flood to ROS2 was taken as the control flood for comparison with subsequent MEOR flooding, shown in Figure 7. To ensure all flood stages could be directly compared, a consistent flowrate was used for all drainages (chosen to maximise pressure drop across the core) and a consistent flowrate was used for all waterfloods (nominally equating to 1ft/day)

Fluid saturation results for the Swi drainages are shown in Figures 4 and 5 and control flood results are summarised in Table 2. The gradient in Swi distribution, with increasing brine saturation towards the core outlet face, is consistent with expectation due to viscous oil drive to Swi being necessary for this work.

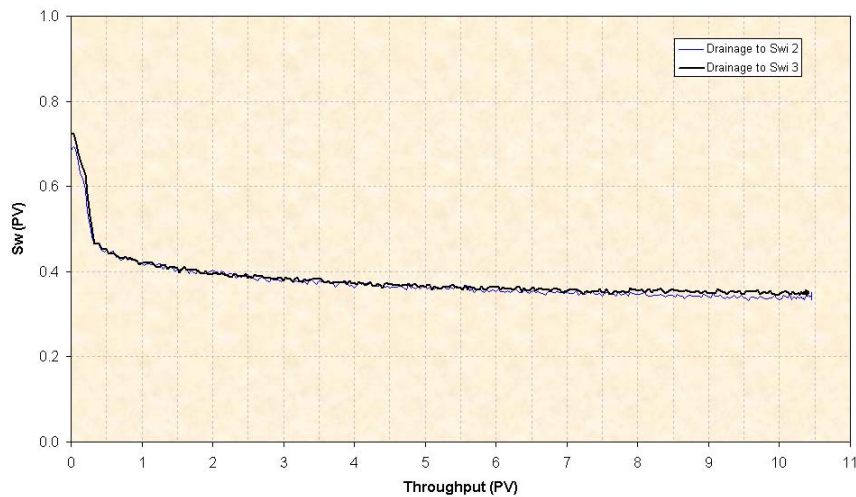


Figure 4: Average Water Saturation during Drainage to Swi

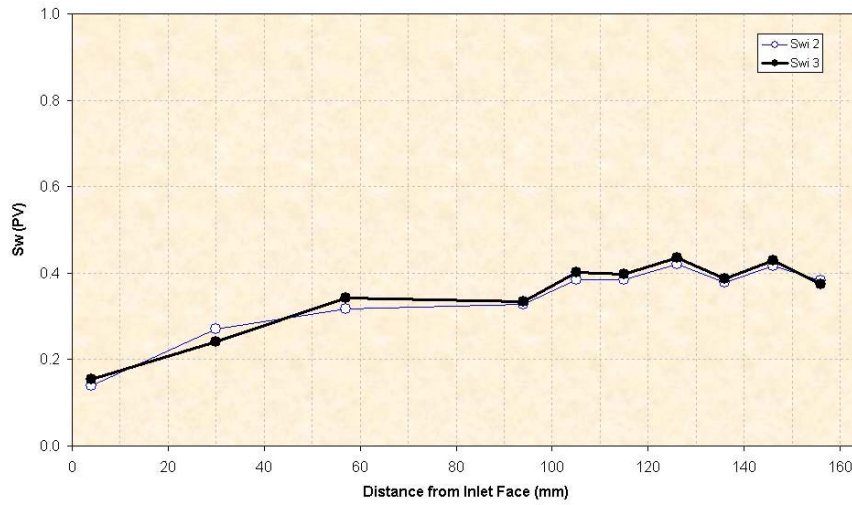
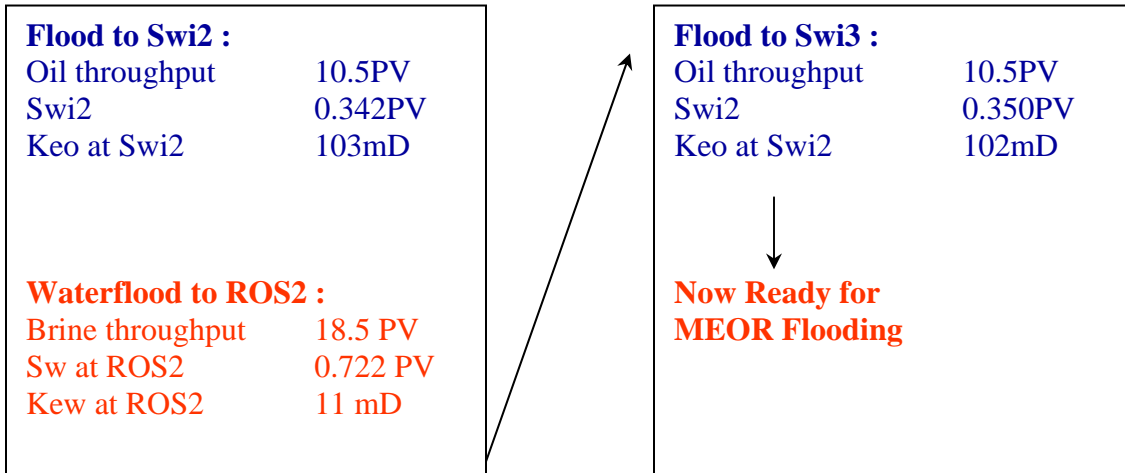


Figure 5: Swi End Point Water Saturation Profile

Table 2: Summary of Control Flood Results



MEOR EXPERIMENT PROCEDURE

Figure 6 shows a simplified schematic of the flow circuit and feed vessels used for MEOR flooding.

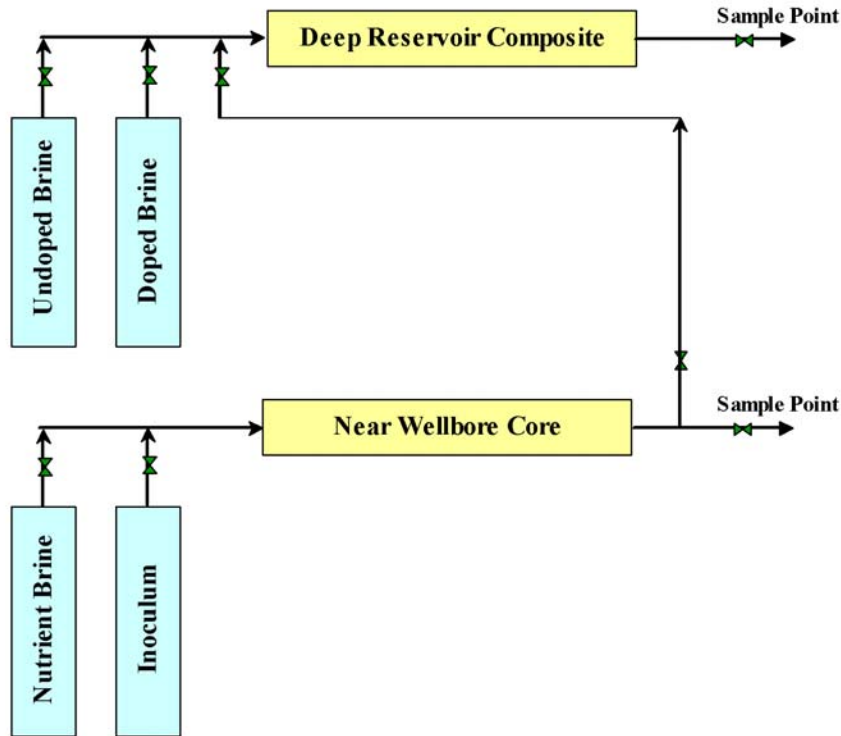


Figure 6: Simplified Flow Diagram for MEOR Flood Sequence

The following 10 steps detail the dual coreflood experiment. Steps 1 and 2 established an equilibrium microbe growth zone and steps 3 to 10 investigated the MEOR propagation.

1. Near well-bore inoculation. A flood using a high concentration batch of microbes. During this stage effluent from this core was directed out of the rig to a sampling station.
2. Near well-bore nutrient brine flood. No further microbes were injected from this point onwards. All inoculum (step1) was flushed from the core and flow continued until an equilibrium growth zone at reservoir conditions was established, indicated by a constant microbe population in the effluent collected at the sampling station. This core now represented the near well-bore region within the reservoir. It is important to note that to maintain equilibrium conditions within the growth zone, the low rate nutrient brine flow continued uninterrupted right through to the end of the experiment. Effluent from this core was either injected into the deep reservoir composite or diverted out of the rig to a sampling point.
3. Deep reservoir undoped brine flood. A short flood using undoped brine to remove iodide from the core (present in the initial Swi saturation and may be toxic to microbes).
4. Linked Flow. MEOR flooding of the deeper reservoir composite by direct injection of well-bore core effluent (1ft/day). This was achieved by linking the outlet of the first core to the injection point of the second core.
5. Deeper reservoir shut-in period. A zero flow period (5days) to increase the residence time of the well-bore effluent within the deeper reservoir (radial flow in a reservoir causes flowrate in this region to be lower than in the well-bore region).
6. Linked Flow. As per Step 4. Consistent flowrate.
7. Deeper reservoir endpoint 1. Doped brine flow via the deeper reservoir composite to determine the ROS end point from GASM measurement.
8. Linked Flow. As per step 4. Consistent flowrate.
9. Deeper reservoir shut-in period. As per step 5. Consistent shut-in period.
10. Deeper reservoir endpoint 2. As per step 7.

MEOR RESULTS AND DISCUSSION

The two effluent sample points allowed for continuous monitoring of fluid effluent (either directly from the near well-bore region, or during linked flow, from the deeper reservoir region). Effluent underwent real-time microbial analysis throughout the experiment before sterile filtration and freezing in preparation for chemical analysis upon completion of the study.

Qualitative illustration of fluid saturation changes obtained during MEOR flooding in comparison with the preceding control flood is shown in Figure 7. MEOR saturation data was analysed throughout the entire flood sequence irrespective of whether doped brine was absent or present. Gaps in the MEOR flood data occurred when a mix of doped / undoped brine was present, which invalidated GASM analysis due to representative calibrations being unattainable.

MEOR flooding demonstrated additional oil production over the control flood and also a potential change in wettability. Incremental production appeared to start at approximately 5PV total throughput, which included the “non-MEOR” initial throughput of 2PV (step3), and stopped draining at 10PV which may have indicated a potential change in wettability to a more water-wet state. Oil saturation in the control flood continued to drain throughout flooding.

Observations from NMR relaxation time analysis (MARAN Ultra 2MHz NMR equipment) from the dual core experiment and other single core and sandpack experiments showed that a change to more water-wet conditions occurred as a result of the microbial activity. This was consistent with the flattening of the incremental oil recovery response, compared to the steadily draining character of the baseline flood representative of more mixed-wet conditions.

This dual core reservoir condition experimental study was representative of both initial inoculation and long-term phases of the MEOR process within a reservoir. The work has successfully examined and demonstrated the propagation of microbial activity to the deeper reservoir environment. Quantitative MEOR responses, not provided in this paper, were subsequently used in the simulation study to define potential reservoir benefits.

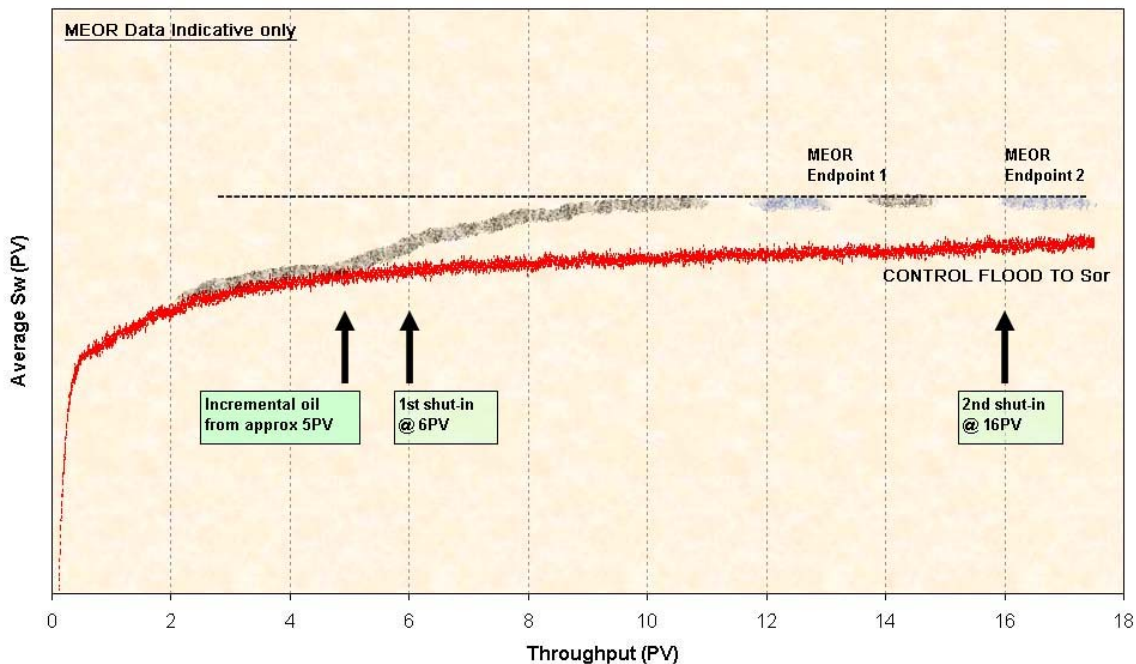


Figure 7: ROS Flood Profiles - Fluid Saturation Trends

SIMULATION

The simulation tools and upscaling process have been described [1]. In summary, commercial simulators REVEAL and STARS were used to model the MEOR process with different levels of complexity. To model the dual coreflood experiment described here, both cores were represented in STARS in a single run by representing the connection between the two cores with an alternating transmissibility multiplier of 1 or 0, with 1 allowing flow through to the downstream core, and 0 preventing it.

Together with the previously obtained results from single coreflood experiments, matching the incremental recovery profiles from the dual coreflood allowed quantification of the kinetics and magnitude of the MEOR recovery process. Upscaling comparison cases between STARS and REVEAL simulators provided linkage between the different forms of the MEOR process used in each simulator, by producing similar watercut and injectivity responses.

Field-scale simulation studies could then be carried out with the improved representation of the MEOR process using the lower complexity MEOR model in REVEAL to predict long-term performance with more detailed reservoir grids capturing the reservoir heterogeneity.

CONCLUSION

Improved experimental representation of the MEOR process through the use of the dual core methodology allows the prediction of MEOR performance via reservoir simulation to be studied with greater confidence.

- Coreflood methodologies have been modified to account for factors such as brine chemistry which may affect microbe performance and/or modify core properties.
- Development of a non-damaging core cleaning protocol for the preserved reservoir material 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 fluid saturations real-time but without affecting microbe growth and performance.
- 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.

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