Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot-Watt/Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Maximising Oil Recovery with Low Salinity Water Flooding

1. Summary of the impact

The data generated from research undertaken by ERPE has enabled BP to leverage an investment of $125M for full field implementation of *Lo-Sal*® EOR technology in the Clair Ridge Field, west of Shetland.

This research has provided BP with a step change in understanding of how to maximise oil recovery and production. Low Salinity Water Flooding has been shown to increase oil recovery by an average of ~16% when compared to standard "High Salinity" water flooding. Based on this work, BP made a strategic decision in September 2012 to use Low Salinity Water Flooding as their default position for field development, by adopting this significant development in water-flooding technology.

2. Underpinning research

The key researchers involved throughout the REF period were: Prof Sorbie and Dr McDougall, Mike Singleton (Senior Research Fellow), Robin Shields, (Research Associate) and Will Thomas (Experimental Officer).

The most important outputs from the research were the broadening and development of understanding over a period of fifteen years from 1995 onwards about the nature of wettability and its influence on oil recovery, and how that is affected by salinity. There were three key breakthroughs:-

- Identifying the impact of wettability on oil recovery through waterflooding
- An analysis of experimental data to increase pore-scale understanding of oil recovery
- Setting up the parameters around the impact of wettability change on oil recovery, which led to a viable model for Low-Salinity waterflooding.

Over the REF2014 period, ERPE built extensive experience in core flooding through the Joint Industry Project (JIP) on oil field scale. BP approached ERPE to collaborate on this issue as BP had been working on field application of the low salinity waterflooding over a period of years, but had been unable to obtain accurate and conclusive evidence of the underlying mechanisms of the process. Developing the understanding of the impact of wettability on oil recovery [1,2,3] and how it can be applied to experimental data to enable pore scale modelling was a step change in understanding the phenomenon.

Since January 2005, BP has provided ~£650k of funding for this exclusive study, the results of which have been predominantly reported to BP through confidential reports and data sets. There have, however, been 2 papers published, in conjunction with BP, on the subject which details certain aspects of the proposed low salinity mechanism and the application of it in the field.
In this project, many possible models and mechanisms for low salinity water flooding have been explored experimentally. This data obtained provided insight into some of the factors controlling the increased oil recovery observed when low salinity brine is injected into oil saturated reservoir core samples. Extensive chemical analyses were performed on the effluent showing the extent of interaction between the injected brine, the oil and the rock matrix. A paper from this work was awarded the Best Paper Award at the Society of Core Analysts Conference 2006 in Trondheim, Norway and later accepted for the Journal of Petrophysics in February 2008. [4]

To complement the extensive experimental dataset, a pore-scale theory of how the low salinity water flooding effect works was derived. The theory demonstrated how pore-scale effects resulted in a reduction of residual oil saturation during low salinity oil waterflooding. The understandings gained from the research [1,2,3] and the results from extensive chemical analyses [4] led to ERPE proposing the pore scale mechanism for *Lo-Sal*®. The theory was able to approximate the magnitude of the effect, and allow some clear, experimentally-verifiable predictions to be made [5].

3. References to the research

The references identified with * are the ones which best indicate the quality of the underpinning research.

[1] McDougall S.R.,. Sorbie K.S "The Impact of Wettability on Waterflooding: Pore-Scale Simulation" Society of Petroleum Engineers, Reservoir Engineering, vol.10, no.3,p208 - 213 1995 DOI:10.2118/25271-PA 85 Google Scholar (GS) citations

This paper identified the impact of wettability on oil recovery through waterflooding.

[2] Dixit, A.B., McDougall, S.R., Sorbie, K.S., "Pore-Level Investigation of Relative Permeability Hysteresis in Water-Wet Systems" Society of Petroleum Engineers Journal, vol.3 no.2, pp115-123,1998, DOI: 10.2118/37233-PA 44 GS citations
This paper provides an assessment of the impact of wettability on the phenomenon of relative permeability.

[3] *Dixit A.B.; McDougall S.R., Sorbie K.S., Buckley J.S. "Pore-Scale Modeling of Wettability Effects and Their Influence on Oil Recovery" Society of Petroleum Engineers Reservoir Evaluation & Engineering, vol. 2, No. 1, p25, 1999 DOI: 10.2118/54454-PA 75 GS citations
This paper analyses experimental data and develops the pore-scale understanding of oil recovery.

[4] * Lager A, K. J. Webb, Black C. J. J, Singleton M. Sorbie K. S "Low Salinity Oil Recovery - An Experimental Investigation" Society of Petrophysicists and Well-Log Analysts Petrophysics, vol.49, no. 1, 2008. http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPWLA-2008-v49n1a2 132 GS citations
This paper identified a clear picture of the potential mechanism of how low salinity waterflooding happens and what needs to be done.

[5]* Sorbie K. S. and Collins I.R. (BP) "A Proposed Pore-Scale Mechanism for How Low Salinity Water Flooding Works" Society of Petroleum Engineers Improved Oil Recovery Symposium, April 2010, Tulsa, Oklahoma, USA, DOI: 10.2118/129833-MS 17 GS citations
Theoretical examination of the parameters around the impact of wettability change on oil recovery.

4. Details of the impact

BP's decision to implement low Salinity waterflooding in the £4.5 billion Clair Ridge development was underpinned by ERPE research. The direct costs of implementing low salinity waterflooding include $125M for desalination facilities to create 'low salinity' water from seawater. BP justified this investment on the basis of 42 million barrels of additional recovery (equivalent to around $4.5 billion of additional income at today's oil price) – a significant increase in the estimated 640 million barrels of recoverable oil from waterflooding using seawater.

The decision to implement low salinity required a high level of confidence in the technique's success to persuade BP management and the field partners. That confidence was built on theoretical and experimental results provided by ERPE, and two field tests (a single well tracer test and a field trial in the Endicott field, Alaska). In the field trial at Endicott, low salinity water was injected in one well and the incremental oil production observed in another. Endicott proved up the laboratory trials at full scale. The trial involved an injector and a producer 1040 feet apart, and the incremental oil recovery was equal to 10% of the total pore volume in the swept area [3]. The confidence generated by the combination of the experimental dataset and verifiable pore-scale theory was sufficient for BP to move forward to a single-well tracer test, and a field trial, providing them with the 'pyramid of proof' that they required to take the technique all the way through the field deployment.

Without the theoretical and experimental results, the two field trials would not have happened, and low salinity would not have been implemented in Clair Ridge. According to BP's Chief Adviser on Low salinity for BP "*ERPE has made a significant contribution to the fundamental understanding of the mechanism by which Low Salinity Water Flooding increases oil recovery. Without such understanding and contribution from ERPE, BP would not be in a position to change their Water Flood strategy to a default base case position of Low Salinity Water Flooding."* [S1]

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Chief Adviser, Lo-Sal, BP Exploration. Will confirm that the work undertaken by ERPE provided BP with the high level of confidence required to invest in Lo-Sal, and without this research, BP would not have been able to change their strategy.

[S2] "Low Salinity Enhanced Oil Recovery - Laboratory to Day One Field Implementation – *Lo-Sal* EOR into the Clair Ridge Project", Robbana, Buikema, Mair, Williams, Mercer, Webb, Hewson, Reddick, Abu Dhabi International Petroleum Conference and Exhibition, 11-14 November 2012. DOI:10.2118/161750-MS This paper references the research undertaken at ERPE as the grounds for BP's decision making process. Reference 6 here cites the underpinning ERPE research, included in this case study as [4]"

[S3] "Demonstration of Low-Salinity EOR at Interwell Scale, Endicott Field, Alaska", Seccombe, Lager, Jerauld, Jhaveri, Buikema, Bassler, Denis, Webb, Cockin, and Fueg, BP. At the SPE Improved Oil Recovery Symposium, 24-28 April 2010, Tulsa, Oklahoma, USA. Reference 3 here cites the underpinning ERPE research, included in this case study as [4]"