Impact case study template (REF3b)

Title of case study: Thermally Sensitive Polymers in enhanced oil recovery

1. Summary of the impact (indicative maximum 100 words)

Thermally sensitive polymers are injected into oil reservoirs to increase the recovery of oil. Experimental and theoretical modeling carried out at the BP Institute, University of Cambridge, has led to a new understanding of the behaviour of such polymers and ***increased their effectiveness in recovering oil, through improved design of the injection, and led to the discovery of a new reservoir monitoring technique to detect their effect on production. Optimising injection of polymer increases well production*** by over 1000 bbl/day and has generated annual revenues of over $US 300 million. This technology is also being applied to thermal energy storage systems.

2. Underpinning research (indicative maximum 500 words)

Research at the Cambridge BP Institute is focused on using experimental and mathematical modelling to understand the behaviour of multi-phase flows. One major area of work involves developing a better understanding of the factors controlling the evolution of flow in porous media; since the late 1990's this has included the influence of thermal conditions in oil reservoirs on enhanced oil recovery.

During the recovery of oil by injection of water, the layering or heterogeneity of the rock causes injected water to travel at different speeds through different layers. Water first arrives at the production well in the more permeable zones; water subsequently injected tends to short-circuit the remainder of the rock, preferring these high permeability pathways. This impedes oil recovery from less permeable zones in the reservoir which typically contain 25-75% of the oil in place, worth US$2.5 billion in a typical 100 million barrel oil field. To recover some of this oil, polymer additives are mixed into the injected water, thereby blocking up the high permeability zones once they have been swept of oil; in principle water subsequently injected will be diverted into the remainder of the reservoir, displacing more oil. In order to control the placement of the polymer in the reservoir, over the past ten years, BP have developed and are now deploying a thermally sensitive polymer, known as 'Brightwater'; this is designed to activate and viscosify within an oil field as the temperature rises above a specific value.

In order to optimise the use of the Brightwater polymer, Professor Woods and other researchers at Cambridge developed a research programme based on their fundamental research into flow and heat transfer in porous media (refs 1-6) which was carried out between 2000 and 2012. Given the high cost of the polymer, a key issue concerns determination of the optimal concentration and volume of polymer to maximise the sweep of oil. Since heat exchange between the fluid and porous matrix causes the thermal energy to migrate more slowly than fluid, the leading region of injected fluid is heated to the reservoir temperature; near the injection well, the rock is cooled to the injection temperature (refs 1,2). Since the density, viscosity and reactivity of the fluid change across such thermal fronts, the flow pattern and areal sweep of a reservoir also change (ref 3).

Since 2009, Professor Woods' work on the dynamic interaction of thermally sensitive polymers with these thermal fronts has been built from theoretical models and small-scale analogue experiments using PNIPAM (a microgel) in a bead pack. The work has revealed, firstly, an instability which arises when cold, polymer-laden injection fluid reaches the thermal front, cools and gels, lowering the permeability; this can lead to channelling and short-circuiting of the gel. Secondly, for a given polymer volume, it has identified the optimal polymer distribution in the injected water to maximise the diversion of the flow from a zone which has been swept of oil. Professor Woods has developed a new technique to monitor the onset of gelling of the polymer within the reservoir which enables real-time management of the polymer flood; BP have filed a patent to protect this invention (2012).

Members of the group working on this project and acting as co-authors on publications have included: Professor Woods, (Cambridge 2000- present), Dr Jupp (Cambridge 1996-2000), Dr Menand (Cambridge 2000 – 2003), Dr Nigam (Cambridge 2000 – 2003), Raw (Cambridge 2000-2001), Verdon (Cambridge 2005-2006), Dr Rayward-Smith (Cambridge 2008-2012), Dudfield (Cambridge 2011-present)

3. References to the research (indicative maximum of six references)

The fundamental research underpinning the technology and its applications has all been published in high impact, peer-reviewed international journals. *Those which best indicate the quality of the underpinning research are indicated (*)*

1) Jupp T.,and Woods, AW, 2003, J Fluid Mech., Reaction fronts in a porous medium following injection along a temperature gradient, 513, 343-361, doi:10.1017/S0022112004000199.
2) * Menand, T., Raw A., and Woods, AW, 2003, Geophys Res Lett, Thermal inertia and reversing buoyancy in flow in porous media, 30,1291-1293, doi:10.1029/2002GL016294.
3) * Nigam M and Woods, AW, 2006, J Fluid Mech; The influence of buoyancy contrasts on miscible source-sink flows in a porous-medium with thermal inertia, 549, 253-271, doi:10.1017/S0022112005007615.
4) * Verdon J.,and Woods, AW, 2007, J Fluid Mech., Gravity driven reacting flows in a confined porous medium, October, 588, 29-41, doi:10.1017/S0022112007007069.
5) Rayward-Smith W., and Woods, AW, 2011, J Fluid Mech., On the propagation of non-isothermal gravity currents in an inclined porous layer, 686, 250-271, doi:10.1017/jfm.2011.327
6) Dudfield P, and Woods, AW, 2012, J Fluid Mech., On the periodic injection of fluid into, and its extraction from, a porous medium for seasonal heat storage, 707, 467-481, doi:10.1017/jfm.2012.291.

The work on the Brightwater polymer at the BP Institute, has been funded through three University research grants:
(i) Enhanced oil recovery using Brightwater polymers (BP funded 2009-2012; £140k);
(ii) The Use of Brightwater polymer in thermal-energy water flooding systems (BP funded; 2011-2013; £140k);
(iii) an EPSRC KTN CASE PhD (2012-2016), with BP as the industrial partner.

4. Details of the impact (indicative maximum 750 words)

The BP Institute research results have had an important impact on BP’s use of the Brightwater polymer and the way in which it has been deployed in a number of oil fields throughout the world.

The research group's work has produced a direct impact on the design and operation of polymer floods in two principle ways. Firstly, the improved modelling capability now allows an assessment of the possible impact of the polymer flood, secondly it provides a novel and effective approach for monitoring a field during a polymer flood. This breakthrough has now been implemented by BP.

The models and analogue experiments developed by the Cambridge BP Institute have focused on the operation of the polymer as it flows through a reservoir, heats up and gels. These feed directly into models for selecting the optimal size and concentration of a slug of polymer to be added to the injected water to optimize the diversion of the flow away from swept zones of the reservoir in a given reservoir geology. Presentation of the model results to BP engineers, in December 2011, June 2012 and December 2012, has informed the design of polymer floods in specific oil fields. This new research underpins a new approach to optimising the distribution of a given volume of the polymer in the injected water and typically enables an additional diversion of between several % to several 10's % of injected water into low permeability rock. This increases oil production by several to several 10's %, which increases the value of the production by US $ 3-30 million per well per year. When applied to tens of oil fields, each with tens of wells, the value of optimising the technology increases to US $300-3000 million per year.

Prof Woods research has also led to the recognition that once the polymer gels, there are changes in the temperature of the fluid produced from the field. As a consequence, monitoring of well temperatures is now being used routinely as a real-time indicator of flow behaviour in certain fields. Such information enables real-time amendments to polymer injection to increase the effectiveness and inform decisions about the value of additional polymer treatment. Prior to this new approach monitoring the gelling of the polymer and hence assessing its impact was practically impossible. As a result of our work such monitoring can provide evidence of successful polymer flooding, leading to decisions to use additional polymer floods; the additional 1-10% oil production associated with this is worth $US 3-30M per well per year. BP filed a patent for this novel monitoring technique in 2012, with GB first filing number 1122027.4. The content is confidential.

As well as providing reports on the research and application developments, the research team in the BP Institute regularly interact with the polymer flood team in BP, headed by Dr Ian Collins of BP, and also reservoir engineers, to ensure the research is implemented and incorporated in BP's reservoir management and engineering processes. These meetings also ensure the research team focuses on challenges of direct impact to the field applications. Meetings with BP reservoir engineers, polymer chemists and enhanced oil recovery experts have been held on many occasions, including workshops at the BP Institute of the University of Cambridge during the months October 2009; March 2010; September 2010; December 2011; June 2012 and December 2012.

The Advisor on Chemical Enhanced Oil Recovery, BP Exploration Operating Ltd. will corroborate that: "*The research has identified how the flow interacts with polymers as they gel within porous rocks, and this is having a significant impact on the efficiency of water floods for enhanced oil recovery, through improved modelling capability and design of polymer* *treatments. In turn this is leading to improved field recovery."* "*In addition, the research has led to identification of a new monitoring technique, which has been developed by Prof Woods and which has been patented by BP*".

New results have also identified how such thermally sensitive polymers can improve the effectiveness of heat recovery in inter-seasonal heat storage by control of the flow fronts in complex permeable rock, and especially to inhibit buoyancy-driven slumping of the hot injected fluid. This enables 10's% more of the injected thermal energy to be recovered in the early years of operation, which is a key time to help the economic viability of aquifer thermal energy storage schemes. A typical well can recover fluid 10-20° C warmer if the dispersion is suppressed by a polymer bank; this leads to an additional heat recovery of 2-4 GW hrs per year, with a value of US $ 0.5-1.0 million.

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

The Advisor on Chemical Enhanced Oil Recovery, BP Exploration Operating Ltd.

The Geothermal Programme Lead at BP Alternative Energy, BP International Limited, will also corroborate the impact of this work.