

Intelligent Well Technology: Incorporation of Smart Controls in Injection Wells to Enhance Sweep Efficiency and Maximize Oil Recovery

Philip Asante-Mireku¹, Kwabena Okyere-Nyako², Joel Teye Tetteh³

BSc Students, Department of Petroleum Engineering, Kwame Nkrumah University of Science and Technology,
Kumasi-Ghana^{1,2,3}

ABSTRACT: This paper takes a look at application of Intelligent Well Technology (IWT) in water injection, how the use of IWT can reduce injection inefficiencies like viscous fingering and how the inclusion of smart controls in Injection Well (IW) is justified, based on improved oil recovery and net present value (NPV). This was achieved by the use of a reservoir simulator to model an Intelligent Injection well by placing Inflow Control Valves (ICV) at vulnerable zones with high possibility of viscous fingering. Reactive Control Strategy (RCS) was adopted to help control the movement of the injected water as a displacement fluid to delay viscous fingering and hence increase oil recovery. The effect of the IWT in improving the efficiency of the waterflooding process was very evident with a 22.8% increment in Field Oil Efficiency (FOE) experienced in 20-year life of the field by incorporating ICV in the injection well. The Net Present Value (NPV) also saw a 17.63% increment in this same period. The displacement pattern was maintained at an almost “piston-like” pattern throughout the waterflooding process with the use of the IWT. It was also realised that the efficiency of the Intelligent Injection Well varied under varying reservoir conditions and hence may not be applicable for certain reservoir conditions. For water-wet systems and damaged formation (positive skin), IWT performed poorly but in case of permeability and porosity variations, the effect of the IWT on the injection well was felt.

KEYWORDS: Intelligent Well Technology, Enhanced Oil Recovery, Reservoir Simulation, Waterflooding, Reactive Control Strategy.

I. INTRODUCTION

With the advent of new technology aimed at improving oil recovery from production wells to meet the growing global demand of crude oil to fuel global energy needs, the shift from conventional vertical wells to Intelligent wells seem imminent. The need to control and monitor the ease of flow of formation fluids towards production wells or injected fluids in dedicated injection wells to obtain close to uniform sweep in heterogeneous reservoirs has encouraged much research. Intelligent wells (IW) are believed to be the most important among a series of technological breakthrough aimed towards adding reserves. (Dyer et al, 2007).

Intelligent well completions employ localized pressure restrictions (ICVs) to balance the production profile along the length of the well completion by splitting it into two or more sections. This is aimed at maximizing net oil while delaying gas or water breakthrough.

This paper aims at showing how intelligent injection of flood fluids can enhance sweep efficiency and maximize oil recovery. Sweep efficiency in a recovery process is a measure of how well the injected fluid has come in contact with the available pore space in the oil-bearing zone.

In this paper, commercially available tools are employed for this purpose. The reservoir simulator Eclipse is used to model and control the ICV action in the injection well by the use of the ACTIONS Eclipse keyword.

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II. THE PROBLEM

Complex flow situations are encountered in the reservoir due to heterogeneity in multiple production zones. Injection of fluids to sweep formation fluids towards producing wells are affected by such heterogeneity in most cases resulting in Viscous Fingering (VF) and subsequent by-passing of oil in the reservoir.

This effect seriously impacts well productivity and influences the degree of depletion and the overall recovery efficiency of the oil reservoir and can make waterflooding or similar recovery technique less profitable due to early water breakthrough.

III. STUDY OBJECTIVES

The objective of this work is aimed at showing how intelligent wells can be used to enhance sweep efficiency in a reservoir and maximize oil recovery as well as assess the economic viability of its incorporation.

These objectives will be achieved by:

1. Monitoring the effects of reservoir conditions on IW during fluid injection.
2. Developing an injection control strategy to enhance sweep efficiency by incorporating IWT.
3. Determining the economic viability of using intelligent control strategies in injection wells as against conventional wells (CV) for various reservoir conditions.

IV. OPTIMIZING CONTROL IN INJECTION WELLS

The injected fluids during water or polymer flooding from dedicated injection wells may reach the producing wells without touching a large region of the reservoir, thus resulting in a low recovery factor. (Asadollahi, 2012) The installation of ICVs in IWs needs to be optimally set in order to ensure maximum hydrocarbon recovery from the well. Control strategy can be characterized as:

1. Reactive control: Yu et al (2000) studied various types of smart completions in a simple reservoir with an oil rim bounded by a gas cap and an aquifer. Reactive strategy comprises of an action on the downhole valves upon water or gas breakthrough. In a reactive strategy no action was undertaken before some changes in the well measurements was observed.
2. Proactive control: these are well operating strategies that do not start at the moment of gas or water breakthrough but in an earlier stage in order to prevent or delay it as much as possible. Typically, these scenarios require a great knowledge of the reservoir than reactive control scenarios. Within proactive control strategies, two main types can be distinguished, with each requiring different knowledge on the reservoir properties. In the first kind of strategy, optimization of the valve settings is done based only on wells performance at the current time or forecasted well performance for a short period (Seputelli et al., 2003). Second, the entire production life of the reservoir is intended for the optimization, in which a reservoir model is needed to maximize the benefits, mainly NPV, from a reservoir. The latter approach is known as long-term or recovery optimization (Asadollahi, 2012)

V. WATERFLOODING CASE STUDY

Collins *et al* investigated the effect of IWT on Agbami deepwater field which is located offshore Nigeria. The technology was installed on both production and IWs on the field, so as to alleviate the issues created by the complex stratigraphic architecture and subsurface uncertainty of the reservoir. The project provided real time monitoring or surveillance and the control necessary for field performance and recovery optimization. It ensured judicious reservoir management by the integration of surveillance plans and production management practices in producing from multiple zones. Between August and November 2010, approximately 10 million BOPD was incrementally added.

Al-zahrani *et al* of Saudi Aramco Oil Company examined the installation of an IWT Supervisory Control and Data Acquisition (SCADA) system on a Haradh Increment-III (HRDH-III) field in Saudi Arabia. The SCADA system was

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applied for real time monitoring and remote control of surface and downhole tools from the control station. This eliminated the need for engineers to control or regulate the IW from the well site, while optimizing hydrocarbon production. It was noted that IWT application (multilateral drilling, ICVs and sensors) maintained peak production values, reduced water cut to the barest minimum (less than 3%), and increased field performance.

VI. THE SIMULATION MODEL

The conceptual model used contains 50x1x15 grid cells in the X, Y and Z directions respectively, a total of 750 cells, of which all are active (**Figure 1**). The physical dimensions of these cells are 5600ft x 1800ft x 150ft. It consists of 3 distinct geological zones, each containing 5 layers. The top layer has the largest permeability and porosity values, with the other two having lower porosity and permeability values. The top of the reservoir is located at a depth of 8000ft with an initial reservoir pressure of 4500psi. The model has no underlying aquifer or gas cap.

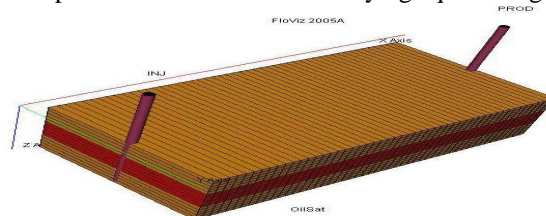


Figure 1: Reservoir model with vertical well configuration

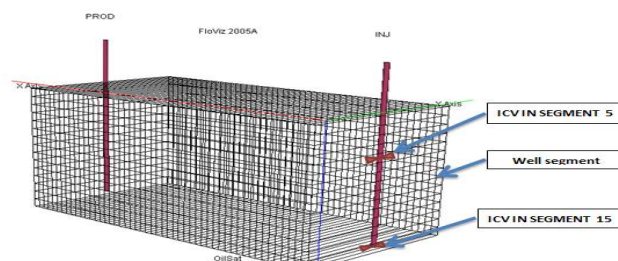
An 8150ft vertical well is drilled at both ends of the reservoir model and completed in the target zone on interest of 150ft using 0.67 in ID production and injection tubing. This is used to represent the base case. Field oil production and injection is set for 20 years at production and injection rates of 2500bbl/day and 3000bbl/day respectively.

VII. CONVENTIONAL WELL DESIGN

There was no form of control for fluid flow during water injection. Water was injected into the reservoir at a surface rate of 3000 bbl/day.

VIII. INTELLIGENT INJECTION WELL

The optimum conventional well design was used as a base case to be compared with the IW cases. The injection well is connected to 15 grid blocks in the *Eclipse* model. These grid blocks are segmented such that is divided into 6 segments with 2 segments in all three reservoir layers. The segment performance is studied in order to locate where ICV should be placed. Two zones are identified, zone one (segment 5) and zone two (segment 15) as having the highest segment water flow rate. A two zone well completion was thus designed (**Figure 2**), each zone being controlled by an ICV (ICV1 and ICV2). A sensitivity study with respect to the number of ICV's confirmed that the chosen 2 ICV completion design was optimum. The intelligent well equipment and its installation will incur an estimated US \$ 10 million.



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Figure 2: The segmented reservoir model showing valve placements

IX. THE SIMULATION METHODOLOGY

The conceptual model enables the separate phases to flow with different velocity in the reservoir. Flow through the ICV (modelled as a constriction with a specified cross-sectional area) imposes an additional pressure drop. The condition that triggers this action, as well as the action itself, have both to be specified by the ACTIONS keyword in Eclipse. The action chosen is based on the production profile of a particular segment (representing flow from a particular zone). The time (e.g. each simulator timestep, in this case 20 years in 240 timesteps) at which the simulator checks whether the condition is exceeded was also specified.

ICV action is modelled by introducing an extra pressure drop (calculated from the reduced choke dimensions with the sub-critical choke model) into the ICV segment when certain conditions are met. In this case, the segment with the highest Segment Water Flow Rate (SWFR) is commanded to shut off after every timestep. The actions of the ICVs are then studied under varying reservoir conditions, namely varying permeability, wettability and varying skin

X. CONVENTIONAL INJECTION WELL PERFORMANCE

Oil production for the conventional injection well (CI) and conventional production well (CP) saw a decline due to viscous fingering and subsequent by-passing of oil. Oil production saw a decline from 1000 stb/day to 800 stb/day in the first four (4) years, and had reached 700 stb/day in ten (10) years as shown by **Figure 3**. Water production, as indicated by field water production rate also rose from 0 to 300 stb/day in ten (10) years. There was a sharp rise in water production between the 2- 6 years of production, which was as a result of accelerated viscous fingering and by-passing of oil. Cumulative water production at the end of the simulation (20 years) was 15.2 MMSTB and cumulative oil production was 60 MMSTB. The cumulative water production represented 20.21% of total fluid production. It was thus observed that the conventional injection well yielded lower sweep efficiency from the field (**Figure 4**).

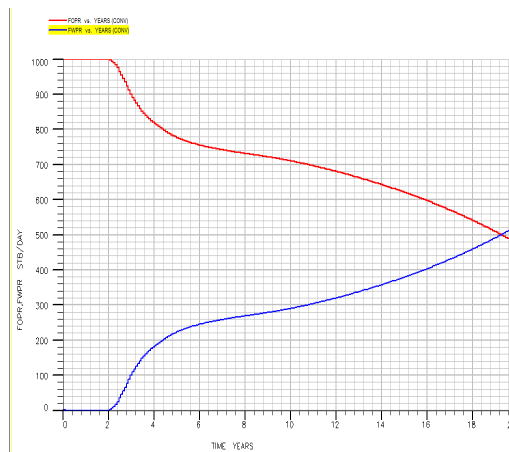


Figure 3: FOPR and FWPR obtained by using the Conventional Injection Well for 20 years

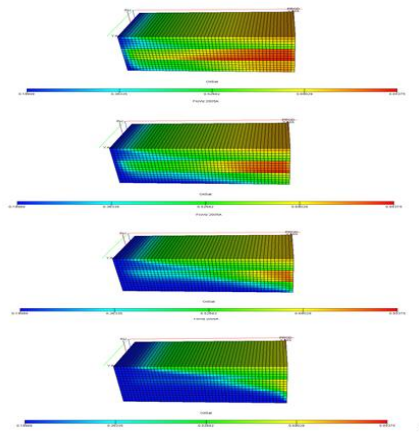


Figure 4: Water Injection profile of Conventional Injection for 5, 10, 15 and 20 years

XI. INTELLIGENT INJECTION WELL PERFORMANCE

Oil production rate (FOPR), was maintained at 1000 stb/day for a little over four (4) years and had only declined to 900 stb/day in ten (10) years as shown in **Figure 5**. There was little or no water production within the first four (4) years of injection and production, and gradual rise to 100 stb/day of water production in the first ten (10) years.

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This was due to the open-close action of the interval controls valves (ICVs) on the Intelligent injection well, which control the rate of water injection into the formation layers and control the effect of viscous fingering, while delaying water breakthrough and by-passing of the oil. **Figure 6** shows the fluid flow profile obtained using the interval control valves in segment 5 and 15. **Table 1** compares the field oil efficiency, oil production rates and cumulative production for both the conventional and intelligent well completions.

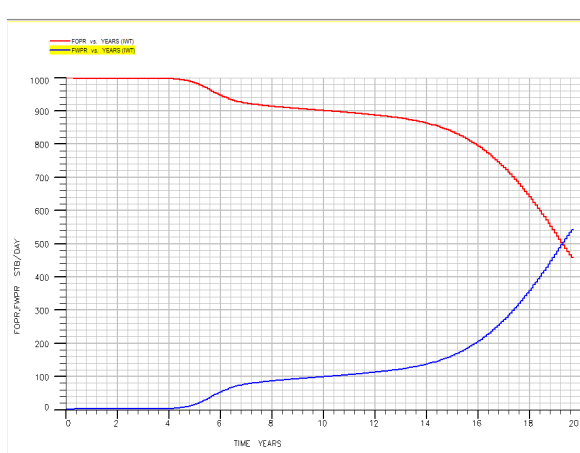


Figure 5: FOPR and FWPR obtained by using the Intelligent Injection Well for 20 years

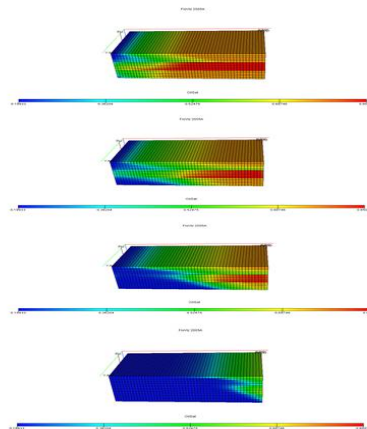


Figure 6: Water Injection profile of Intelligent Injection for 5, 10, 15 and 20 years

PARAMETER (20YRS)	CW	IW
FOPT(MMSTB)	5.2	6.29
FWPT(MMSTB)	1.98	0.908
FOE	0.58	0.7
FOPR(AVG)	728.24	873.33
FWPR(AVG)	267.72	122.62
FLPT(MMSTB)	7.2	7.2
FOPT/FLPT	0.724	0.87
NPV(MM\$)	57650.75	67812.61
%ΔNPV=17.63%		

Table 1: Base case comparison of well performance for conventional and intelligent injection

The performance of the intelligent injection well was analysed under various reservoir conditions. Here, the parameters were grouped under dynamic and static parameters, for the analysis to be done: Static parameters such as absolute permeability and porosity, and dynamic parameters such as relative permeability and skin.

XII. POROSITY AND ABSOLUTE PERMEABILITY

The porosity and absolute permeability values of the base case were altered by a multiplication factor of 0.5 and 2 to obtain the low and high values of porosity and permeability. The performance of the Intelligent Injection Well (IW) was then analyzed. From **Figure 7**, it is noticed that there is greater field oil efficiency (FOE) in the first nine years of production using the Conventional Injection well. However, it is noticed for the rest of the twenty (20) years that, the FOE obtained in using the Intelligent Injection Well increased beyond that of the Conventional well for the low permeability and porosity case, where the porosity and permeability values were decreased by a factor of 0.5. FOE obtained for CW was 0.71 as compared to 0.75 for the IW. This represents an increase of 5.6%.

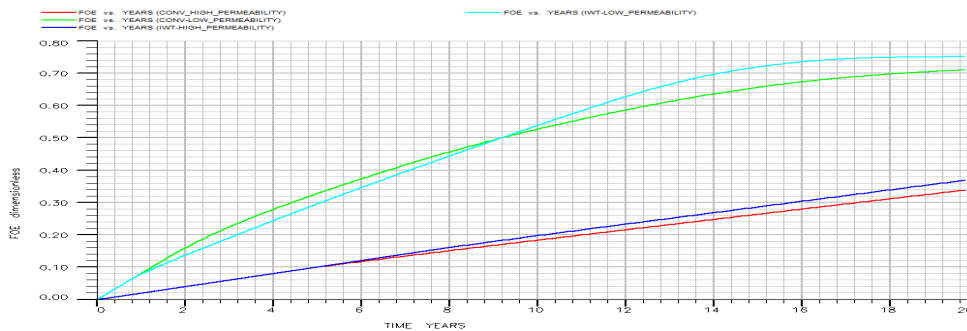


Figure 7: FOE performance for CW and IW under high and low permeability for 20-year production period

XIII. RELATIVE PERMEABILITY

Here, two cases were represented; a water-wet reservoir system, and an oil-wet reservoir system. Oil is able to flow more readily in a water-wet reservoir than in an oil-wet reservoir. It is observed that IW performed better in the oil-wet system with an FOE of 0.64 as compared to that of the CW with an FOE of 0.48, representing 33.33% increment (**Figure 8**). From this, it can be inferred that, though water breakthrough occurs much earlier in oil-wet systems, the IWT was able to delay water breakthrough, hence producing a higher FOE than that of the CW. This makes IW more suitable for oil-wet systems. On the other hand, the CW performed better in the very water-wet system than that of the IW with an FOE of 0.64 for CW and 0.45 for IW representing a decrement of 30%. This may be due to the fact that there was more by passing of water, therefore, reducing the FOE. In scenarios like this, the CW is the preferred option.

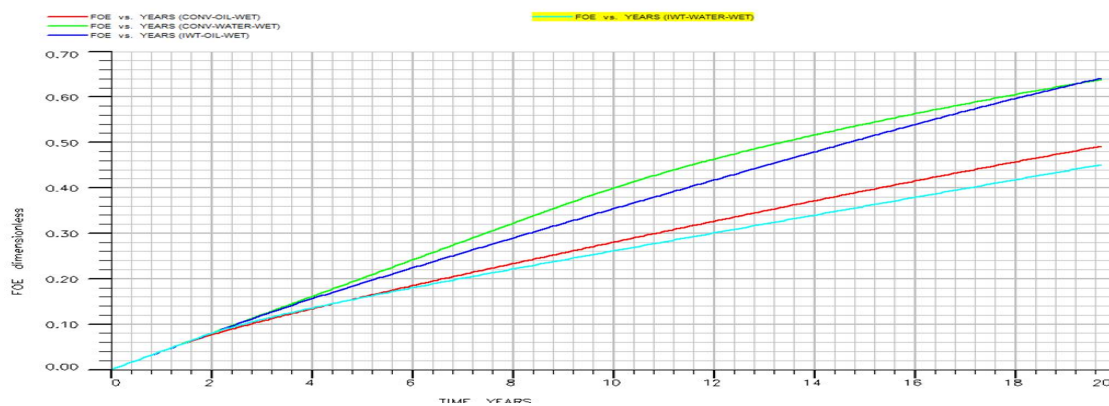


Figure 8: The effects of relative permeability on FOE for CW and IW for 20-year production period

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XIV. SKIN

The performance of the Conventional Injection Well and the Intelligent Injection Well were analyzed under the conditions of positive and negative skin and compared to that of the base case. From equation 1, it is seen that oil flow rate varies linearly with skin. Therefore, a negative skin, representing a stimulated well is expected to perform better than a positive skin,

$$S = \left(\frac{k_e - k_a}{k_a} \right) \ln \left(\frac{r_a}{r_w} \right) \dots \dots \dots (1)$$

It is observed that in the case of positive formation damage, the conventional well performed better in terms of FOPR as compared to the IW (**Figure 9**). This can be attributed to the extra flow restrictions that a reactive control strategy also imposes on the injection well aside the resident low permeability around the injection well. Hence less oil contacts the oil in the formation pores, resulting in less oil recovery. When the well is stimulated however, an improved oil recovery is observed: an FOE of 0.72 as compared to base case intelligent well completion FOE of 0.7. (**Figure 10**)

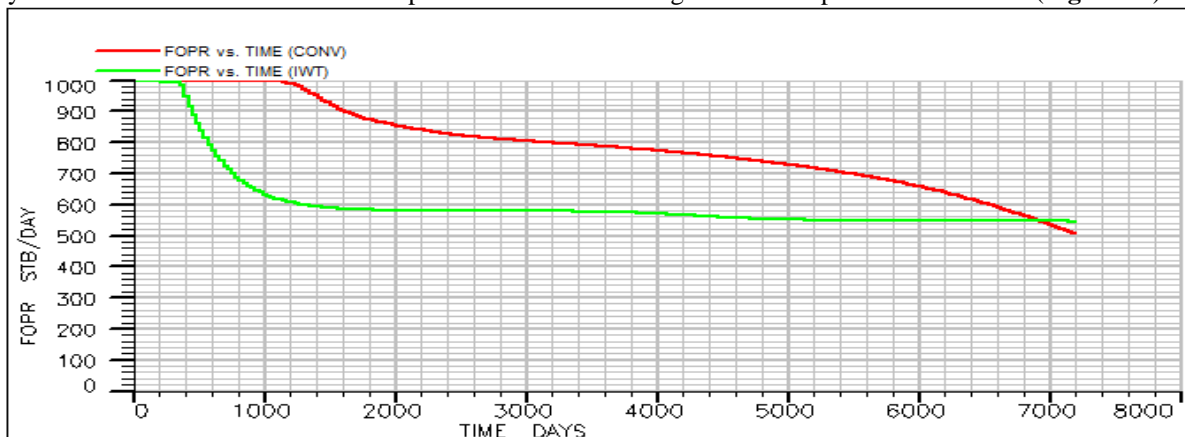


Figure 9: FOPR for positive skin scenario

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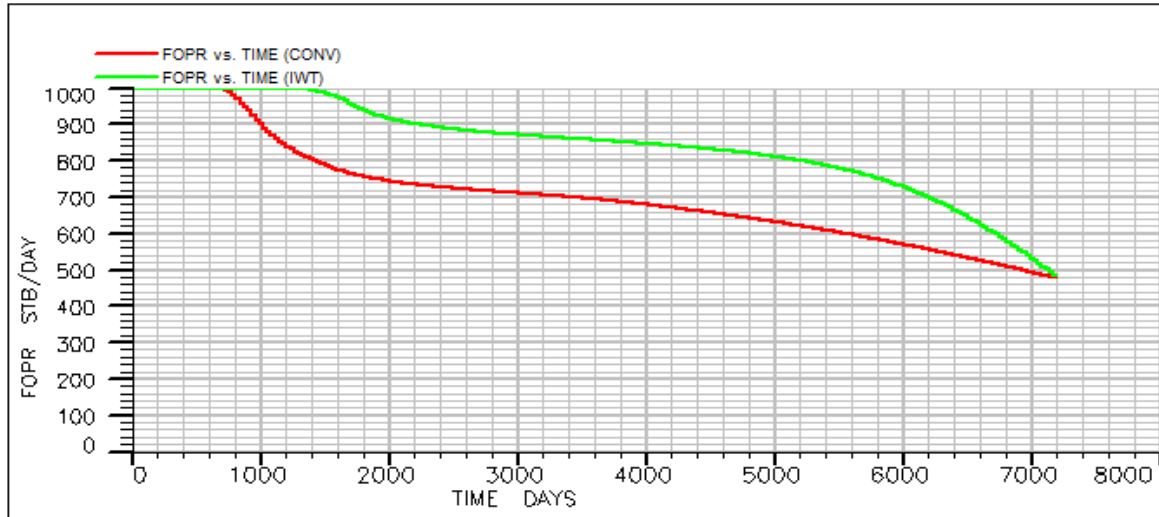


Figure 10: FOPR for negative skin scenario

XV. ECONOMIC ANALYSIS OF INTELLIGENT WELL PERFORMANCE

A comparison of NPV of the intelligent injection well is then assessed to justify it economically. The FOE of the two well configurations are obtained after varying static and dynamic parameters. For the static parameters, absolute permeability and porosity are assessed whereas for the dynamic parameters, skin and relative permeabilities are assessed.

	FOE	NPV(\$MM)	%Increase in NPV [(NPVIW - NPVCW) / NPVCW] * 100%
CW	0.58	57650.75	17.63
IW	0.7	67812.61	

Table 2: Economic performance of BaseCase

	FOE		NPV(\$MM)		% Increase in NPV [(NPVIW - NPVCW) / NPVCW] * 100
	CW	IW	CW	IW	
Low perm case	0.61	0.75	41925.39	43491.4	3.7
High perm case	0.34	0.37	64389.46	68684.2	6.67

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Table 3: Economic performance of IW under varied permeability

	FOE		NPV(\$MM)		% Increase in NPV [(NPVIW---- NPVCW)/ NPVCW]*100%
	CW	IW	CW	IW	
Low perm to oil	0.49	0.64	48592.11	62011.11	27.6
High perm to oil	0.63	0.45	65633.24	45481.96	-30.7

Table 4: Economic performance of IW under oil- and water-wet conditions

	FOE		NPV(\$MM)		% Increase in NPV [(NPVIW---- NPVCW)/ NPVCW]*100%
	CW	IW	CW	IW	
Positiveskin	0.63	0.48	62446.4	46803.53	-25.05
Negativeskin	0.61	0.72	60612.78	69120.11	16.7

Table 5: Economic performance of IW under positive and negativeskin

XVI. CONCLUSION

Oil sweep efficiency was effectively improved using intelligent injection well technology as well as an observed increase in oil recovery. An increase in oil recovery resulted in a subsequent increase in NPV justifying its economic viability.

From the derived results from this study, it can be concluded that intelligent injection wells under the appropriate control strategy could reduce viscous fingering and allow greater efficiency of waterflooding recovery technique.

We also realised that the efficiency of the Intelligent Injection Well varied under varying reservoir conditions and hence may not be applicable for certain reservoir conditions. For water-wet systems, IW was less efficient than CW. This is as a result of further injection flow restrictions encountered using the reactive control strategy for the valve system. It is therefore more preferable to use an intelligent injection well in an oil-wet system. Also, a damaged formation (positive skin) performed poorly with the Intelligent Injection well and better with a stimulated well. This is

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can be attributed to flow-limitations due to both the valve system and formation damage. It is therefore recommended to stimulate a damaged formation well before using the Intelligent Injection well.

From sensitivity analysis to determine the behaviour of IW under various reservoir conditions, it can be seen that stimulation further improves the action of IW.

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