OPTIMIZATION OF WATER INJECTIVITY AND OIL RECOVERY THROUGH LATERAL RADIAL DRILLING INTO THE RESERVOIR

BY

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CERTIFICATION

This is to certify that this research work, "**Optimization of Water Injectivity in The Reservoir Through Radial Drilling Technology in The Niger Delta**" was carried out by I, **Onyejiaka, Uchenna Nonyerem,** with Registration Number **20174078068** in partial fulfilment for the award of the degree of M.Eng. Petroleum Engineering in the Department of Petroleum Engineering of Federal University of Technology, Owerri.

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DEDICATION

This thesis report is dedicated in a special way to the Almighty God, the fountain of all knowledge.

In His great benevolence, He opened my mind to innovative thinking. He deserves all the glory.

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TABLE OF CONTENTS

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: LITERATURE REVIEW

CHAPTER THREE: MATERIALS AND METHOD

CHAPTER FOUR: RESULTS AND DISCUSSIONS

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The efficiency of water injectivity into the reservoir is greatly reduced by poor reservoir permeability and near well bore damage. However, the aim of this study is to evaluate the possibility of improving oil recovery during water flooding by using radial drilling technique which has the capacity of achieving longer perforation length than the conventional perforation operation. Perforation length up to 100 m (330ft) into the fresh formation beyond damaged zone can be obtained with radial technology. Eclipse simulator, version 100 was used to model the lateral radial drill and conventional perforation into the reservoir. The key project indicators that were studied are injectivity index, displacement efficiency, recovery factor and water cut using different radial drill configurations. It was observed that water injectivity was improved with radial drill case with the increasing length and number of radials as compared to the conventional wellbore perforation case. There was a progressive increase in recovery factor with increase in number radials irrespective of the radial length. Also, the water cut from the producer well was increasing as the number and length of the radials were increasing. Therefore, radial drilling is seemingly a promising technology that can be used to improve water injectivity and hence maximize oil recovery in a water flooding scheme.

Key words: Water Injection, Oil recovery, Water flooding, Reservoir, Permeability

CHAPTER ONE

INTRODUCTION

1.0 Background of the Study

Secondary oil recovery is aimed at augmenting the in-situ reservoir energy. It is often started when the natural energy of the reservoir is no longer capable of delivering the reservoir fluid to the surface. In that case water or gas (mixture of both) could be injected into the reservoir to improve oil recovery. Nonetheless, it is important to take cognizance of so many factors which could limit the process efficiency during fluid injection. In water flooding; fluid compatibility, formation heterogeneity, early water fingering, permeability damage resulting from suspended particles and clay swelling are some of the challenging factors.

Poor water injection is usually a problem associated with tight formations (Pang and Sharma, 1997). Tchistiakov, (2000) reported that this problem could be intensified in a formation with swelling type of clay such as classic shaly sandstone. Clay swelling is accompanied by release of tiny clay particles from the pore. These loose clay particles are usually redeposited on the pore throat thereby causing severe injectivity problem (Miniawi *et al.,* 2007, Yi, 2001). The two methods that have been traditionally used to improve water injectivity into reservoir are hydraulic fracturing and matrix acidizing. While the former is being limited by environmental concerns and difficulties in achieving the targeted fracture length, the later could be difficult to implement in in clay rich sandstone formations due to the complex reactions between hydrofluoric acid (HF) and the rock minerals (silicates, feldspars and chlorites). Also, in a high temperature environment, damage resulting from secondary precipitation hinders the application of matrix acidizing (Wang *et al.,* 2012).

Water injection is commonly used during secondary recovery phase. It involves drilling injection wells into a reservoir and pumping in water through the perforations of the well, into the formation for different reasons including reservoir pressure maintenance, EOR (water flooding) or for water disposal. When water is injected for pressure maintenance (primary recovery), it acts as a voidage replacement process that supports reservoir pressure to keep flowing hydrocarbons into the wellbore. Normally, it is assumed that oil recovery during water injection is equivalent to volume of water injected. Therefore, the injectivity of water is an important economic variable to the success of pressure maintenance in the reservoir.

Water injectivity simply put, is the pressure differential between the injector and the producer wells and it is measured in bbl/d/psi (Aodus *et al.,* 2016). The traditional method of carrying out water injection through the perforations restricts to an extent the water injectivity in the reservoir. These restrictions can be as a result of sand production and formation damage which reduces the vertical and areal sweep efficiency of the injection process. With the introduction of radial drilling technology, these problems can be mitigated.

Radial drilling technology is an unconventional drilling technology that makes the use of jet energy of fluids with high velocity to drill laterals with different geometries in both conventional and unconventional reservoirs (Ahmed, 2017).

This technology is able to make a right turn in a cased wellbore and penetrate some distance into the formation forming radial laterals with radius 20 to 50mm and length of 10-100mm (Liu *et al.,* 2017).

These radials distributed in one or more layers, can pass through the damage around the wellbore, and penetrate into the virgin formation from the drilled well (Ragab, 2013). Hence, the problems of near wellbore damage and sand production can be mitigated during water injection with this technology of drilling and may thereby improving the injectivity of water into the reservoir.

1.1 Statement of the Problem

Generally, the maximization of oil recovery by water injection through wells with perforations is restricted by injectivity problems that occur as a result of sand production and near well damage. To curb this problem, water injection should be properly handled using a trustworthy approach.

This research study seeks to apply and validate the use of radial drilling technology which uses jet energy of fluid to get as far as 100m into the reservoir to improve water injectivity and increase recovery.

1.2 Objective of the Study

The main objective of this study is to optimize water injectivity in the reservoir through Radial Drilling technology in the Niger Delta. The specific objectives in achieving the above are as follows:

i. To evaluate the performance of water injectivity in a conventional injector well.

ii. To simulate and evaluate the performance of water injectivity with the application radial drilling technology, using Eclipse simulator.
iii. Carry out a comparative analysis of water injectivity in optimizing oil production during water injection process.

1.3 Justification of Study

In today's world where the demand for energy is high, maintaining producing wells at attainable production rates is important throughout the well's life cycle. In many situations, maintaining reservoir pressure by maximizing water injection is just what is needed for production. For this reason, there is need for the water injectivity to be maintained so as to avoid shutting in of the well and losing a source of revenue.

A more robust and adaptable approach – Radial Drilling Technology can be adopted as it presents a means of maintaining water injectivity. It is used to achieve more reservoir contact thereby enhance oil recover. In mature or marginal fields, radial drilling provides fast and economic method of recovering the remaining oil. More importantly, it is a viable alternative to traditional perforation to extend beyond near wellbore damaged zones.

1.4 Scope of the Study

The model creation for improving water injectivity in the reservoir seeks to utilize an intelligent technology, radial drilling. The model will be developed based on data range gotten from the Niger Delta using eclipse and compare to a well with traditional perforations.

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CHAPTER TWO

LITERATURE REVIEW

2.1. Methods of Recovery

There are three basic stages of hydrocarbon recovery from the reservoir. They include:

i. Primary recovery
ii. Secondary recovery
iii. Tertiary recovery

2.1.1 Primary Recovery:

This is the recovery period that begins with the initial field discovery and continues until the in-situ energy sources for oil production are no longer able to sustain production at profitable rates (Muskat, 1949). The key to primary recovery is the fact that the hollow well shaft drilled to access the oil is designed to have a lower pressure than the oil that is deep in the ground. This difference in pressure can be further increased by various methods, such as pumping water into the well. This method, known as a “water drive,” succeeds by displacing the oil further into the ground, increasing its pressure.

Another popular method is the so-called “gas drive,” in which the energy of expanding underground gas is used to force oil to the surface. Eventually, oil pressure can reach a point where the oil rapidly flows upwards through the well and out of the surface, creating an oil geyser. In this stage the reservoir aids the production with its natural energy which include: the solution gas drive, gas cap drive, water drive, compaction drive and combination drive. Usually about 10%-30% of the OIIP can be extracted from the reservoir at the end of primary recovery process.

2.1.2 Secondary Recovery

As the reservoir is being produced with the natural drive, the reservoir pressure will decrease and eventually the primary recovery will become uneconomical at higher pressure decline. Then, secondary recovery method is used for further production.

In secondary recovery, another type of well-known as injector is used to inject an external fluid (was or gas or

both) into the reservoir. These injectors are located in rocks that have fluid communication with production wells. The two main types of secondary recovery techniques are:

i. Gas injection
ii. Water injection

Gas injection: the objective of gas injection has been to stop the gas cap shrinkage and increase the reservoir pressure, thereby aiding recovery (Murty, 1989). Gas injection can be presented as an immiscible displacement process where a distinct interface exists between the fluid being displaced and the displacing fluid. The injection gas could be nitrogen, hydrocarbon gas, flue gas, carbon dioxide, or any other gas mixtures. When the natural reservoir energy has been depleted through production, it becomes necessary to supplement or even substitute the natural reservoir energy with energy from an external source. This is usually accomplished by the injection of fluids, such as natural gas or water (secondary recovery). The main purpose of either a natural gas injection process (gas flooding) or a water injection process (water flooding) is to repressurized the reservoir and then to maintain the reservoir at a high pressure. The term *pressure maintenance* is sometimes used to describe a secondary recovery process.

When gas is used as the pressure maintenance agent, it is usually injected into a zone of free gas (i.e., a gas cap) to maximize recovery by gravity drainage. The injected gas is usually natural gas produced from the reservoir in question which defers the sale of that gas until the gas flooding operation is completed and the gas can be recovered. On the other hand, other gases, such as nitrogen, can be injected to maintain reservoir pressure, which allows the natural gas to be sold as it is produced.

The situation is different for heavy oil and tar sand bitumen where the reservoirs of deposits have little to no reservoir energy in the form of the pressure exerted within the reservoir by the presence of or water. Heavy oil reservoir and tar sand deposits are found in the microscopic pores of sedimentary rocks such as sandstone and limestone. Not all of the pores in a reservoir rock or deposit will contain heavy oil or bitumen—some will be filled with water or brine—the latter is water that is saturated with minerals. Seismic surveys are used to try to predict where fields may be found but the only way of making certain is by drilling.

Once found, the events leading to recovery start to unfold (Drew, 1997). Production rates from reservoirs depend on a number of factors, such as reservoir geometry (primarily formation thickness and reservoir continuity), reservoir pressure, reservoir depth, rock type and permeability, fluid saturations and properties, extent of fracturing, number of wells and their locations, and the ratio of the permeability of the formation to the viscosity of the heavy oil or bitumen and what it will take to modify the viscosity to enable recovery methods to be effective (Taber and Martin, 1983; DOE, 1996; Jayasekera and Goodyear, 1999). Operators can increase production over that which would naturally occur by such methods as fracturing the reservoir to open new channels for flow, injecting gas and water to increase the reservoir pressure, or lowering oil viscosity with heat or chemicals. These supplementary techniques are expensive, and the extent to which they are used depends on such external factors as the operator's economic condition, sales prospects, and perceptions of future prices.

The extraordinary geological variability of different reservoirs means that production profiles differ from field to field. Heavy oil reservoirs can be developed to significant levels of production and maintained for a period of time by supplementing natural drive force, while gas reservoirs normally decline more rapidly. On this basis an oil reservoir with the seemingly large reserve of a million barrels might produce only 200 to 400 barrels per day during the best production years.

The two important concepts involved in oil recovery are *mobility ratio*, M, and the *capillary number*, N_c. If the *mobility ratio* is greater than unity (i.e. $M > 1$), the displacing fluid will flow past much of the displaced fluid, displacing it inefficiently. Thus, the mobility ratio influences *displacement efficiency*, that is, the (microscopic) efficiency of oil displacement within the pores. When the mobility far exceeds unity, the displacing fluid will channel past the oil clusters. Historically, much work has been performed regarding the study of the performance behavior of gas injection. Rodriguez *et al,* (1998) presented the successful results of a simulation study of a reservoir in the Santa Barbara field located in the Northern part of Monagas state in Eastern Venezuela. The results of the simulation for a natural flowing well scenario showed a final recovery of 894mmbls of oil and 9604mmscf of gas while the simulation of a case where 1200mmscf of gas was injected yielded results of 2175mmbls of oil which was 3% of the STOIIP, over a period of 30 years. That is to say, with gas injection, 1250mmbls of oil was produced more than the natural flow scheme (Rodriguez *et al.,* 1998).

Lawrence *et al* also reported of a simulation study of gas injection process that yielded results of production up to 53% of the OOIP (Lawrence *et al.,* 2003). With secondary recovery method, a cumulative production of about 25 to 35% of the original oil in place can be made from the reservoir (Geri Karan, 2014).

2.1.3 Tertiary Recovery Method

Traditional primary and secondary methods can typically make a recovery of only about one third of the original oil in place from the reservoir. Tertiary recovery, also known as enhanced oil recovery, is applied at some point before secondary stops to be feasible if further production must be made from the reservoir.

Tertiary recovery methods comprise of techniques that reduce oil viscosity to increase oil production. It is the incremental ultimate oil that can be recovered from a petroleum reservoir over oil that can be obtained by primary and secondary recovery methods (Lake, 1989; Arnarnath, 1999). EOR processes makes use of thermal, chemical or fluid phase behavior effects to reduce the capillary forces that trap oil within the pore spaces of the rocks to enhance mobility of the oil or to alter the mobility of the displacing fluids (Borchardt and Yen, 1989).

There are three major tertiary oil recovery types which include: thermal recovery, chemical flooding and gas flooding.

Thermal recovery methods include cyclic steam injection, steam flooding, use of surfactants, etc. (Prats, 1986). It involves the process of adding heat to the reservoir to reduce the viscosity of the oil thereby increasing its mobility. Steam injection is the most used of thermally enhanced oil recovery. It is the continuous injection of steam into an injection well to effect displacement of oil into the production well.

According to the U.S department of Energy, utilizing EOR can aid the recovery of up to 75% of the original oil in place.

2.2 Water Injection

Due to many technological and economic considerations, water injection is the most used secondary recovery method and accounts for most of the oil production in the world (Alkih, 2014). Water is commonly injected into a formation for either of these purposes:

i. Pressure maintenance (secondary recovery)
ii. Water flooding (tertiary recovery)
iii. Produced water disposal

Pressure maintenance is attained by voidage replacement in the reservoir, by the injected water. On production from the reservoir, a void is created which leads to a decrease in pressure. Water injection replaces the oil that has been taken and maintains the pressure for the production to continue.

2.2.1 History of Water Injection

In the premature days of the petroleum industry, it was noticed that brine formation water was often produced alongside oil from the well and its increasing production rate would decrease oil production rate. In these days, this produced water was disposed by dumping into water bodies.

Reinjection of produced water began in the 1920s and by the 1930s, reinjection of produced water had become a common practice in the industry. It was first carried out in the Bradford oil field of Pennsylvania, US (Fettke, 1938). In the mid -1940s, the oil industry was maturing and the decline from primary production was significant and so, water injection practice grew.

In addition to the need of getting rig of produced water, some other factors made water injection logical, and they include the following:

i. Water is not expensive
ii. It is readily available

iii. It increases effectively, the reservoir pressure causing an increase in production of nearby wells.

By the 1970s, water injection was a well- known and common practice.

2.3 Water Injectivity and Performance of An Injection Well

Water injectivity can be defined as the rate of water injection over the pressure differential between the injector and the producer.

The performance of an injector can be represented as an index of injectivity. The injectivity index, represented by the symbol I, is defined as the ratio of the injection rate, Q_{inj} to the difference between the bottom hole pressure, P_{wf} and the average reservoir pressure, $P_{r,\ avg}$. (Hwang, 2014)

$$I = \frac{Q_{inj}}{p_{iwf} - p_{r,\ avg}} \qquad 2.1$$

The condition of an injection well can be monitored periodically by preparing a Hall plot on the performance of the injector (Hall, N. 1963). The Hall plot method is a technique for continuous monitoring that was developed by Howard Hall in 1963. The main concept is to plot a cumulative pressure time product against the cumulative volume of water that has been injected. The plot gives an indication of the injection behavior; a change in injectivity appears as a change in the slope of this plot. This cumulative summing reduces fluctuations in the injectivity index. In general, the slope of Hall plot is interpreted as an indicator of the average well injectivity trends.

The Hall plot can be prepared from data routinely obtained from the monitoring of the performance of the injector. These data include cumulative water injection and injection pressure versus time. The Hall method is based on the radial form of the Darcy flow equation expressed as:

$$\boldsymbol{Q_w = \frac{0.00708 k_w h(kP_{winj} - P)}{\mu_w \ln\left(\frac{re}{rw}\right)}} \qquad 2.2$$

Where Q_w is water injection rate, K_w is the effective permeability to water, h is formation thickness P_{inj} is the bottom hole injection pressure, P is the average reservoir pressure, μ_w is the water viscosity, r_e is the external radius and r_w is the wellbore radius. (Ezekwe, N. 2011)

The cumulative water injection, W_i can be expressed mathematically as:

$$\boldsymbol{W_i = \int_0^t q_w \, dt} \qquad 2.3$$

Substituting Equation 2.2 into Equation 2.3 gives:

$$\boldsymbol{\int_0^t (P_{inj} - P)dt = \left(\frac{141.2\mu_w \ln\left(\frac{re}{rw}\right)}{k_w h}\right) w_i} \qquad 2.4$$

Assuming that all terms on the right-hand side but W_i is constant, it implies that the equation can be written in this form:

$$\boldsymbol{\sum \Delta(P_{inj} - P)\Delta t = m_H w_i,} \quad \text{where } \boldsymbol{m_H = \left(\frac{141.2\mu_w \ln\left(\frac{re}{rw}\right)}{k_w h}\right)} \qquad 2.5$$

This equation implies that a plot of $\sum \Delta(P_{inj} - P)\Delta t$ against w_i would yield a straight line provided that m_H is constant. If permeability is reduced as a result of plugging and formation damage, or increased as a result of simulation, then m_H

would not be constant. Fig. 2.1 is a typical Hall plot with changes in shape due to the various injection conditions.

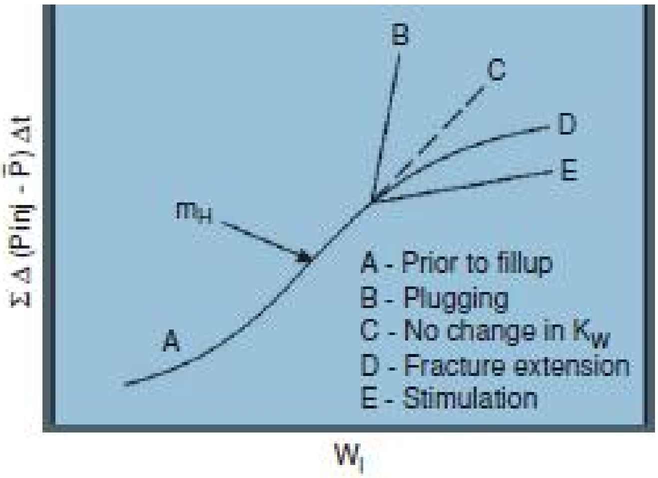


Figure 2.1: A characteristic Hall Plot (Ezekwe, 2011)

For the maximization of water injection process, it is important to determine the pressure of injection at which the formation would get fractured. One method of doing this is by using the step rate test. The step rate test consists of a series of constant-rate injections with rates increasing from low to high in a step wise fashion (Felsenthal, M. 1974; Halliburton, 2012). Fig. 2.2 is a graph of injection rate versus time.

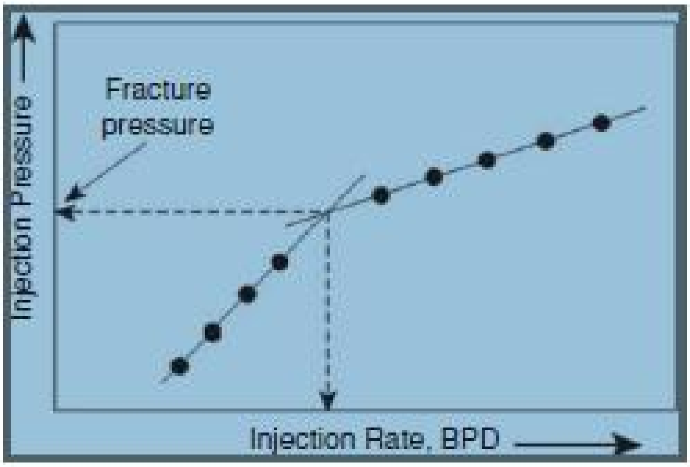


Figure 2.2: Step rate test plot (Ezekwe, 2011)

After establishing the fracture pressure, water injection is maximized by maintaining injection pressure as high as possible without exceeding the indicated fracture pressure.

2.4 Factors affecting performance of water injectors and water injectivity

The factors affecting water injectivity and the performance of water injectors can be classified as either design or operational issues. They need a careful investigation from the design stage and require verification during the operational stages. Upon any change of operational conditions, the above issues will need to be reviewed during the water injection operations to prevent rapid injectivity declines.

In a case study report on the water injection performance on two land oil fields, Sheemy *et al,* reported that their study findings indicate that well injectivity behavioral patterns can be affected by permeability of the injection zone, initial well damage, water source of the injection and operating parameters of the surface injection systems. He also mentioned that spontaneously, well injectivity improvements can occur and can be attributed to the characteristics of the injection water (Sheemy, *et al.,* 1987).

In the following sections, research on individual factors, and applications to field cases are introduced.

2.4.1 Particle Plugging Near Water Injection Wells

Suspended particles of various types and forms can be deposited on the well bore fracture faces and porous spaces in well completions. The mode of filtration of the deposited particles could internal (deep bed) or external (filter cake). External filtration results in a filter cake, typically a compressible soft filter cake on wellbores and its flow resistance of an external filter cake can be much higher than internal plugging, even though the thickness of the filter-cake deposition is thin (the order of millimetres). These two modes of filtration can lead to a severe decline in permeability near the wellbore thereby affecting injectivity (Hwang, 2014).

Barkman & Davidson (1972) showed that the half-life of injectors, which is the time required for initial injectivity to decrease by 50%, is a direct function of water quality during filter cake build-up in wellbores and perforations. Eylander (1988) presented a method to predict injectivity decline based on the core flood data and filter cake properties. This method is valuable in that it provides data about the nature of impairment (external and internal), impairment reversibility, and the depth of impairments (Hwang, 2014).

2.4.2 Fracture Propagation during Water Injection

As the bottom-hole pressure increases because of particle plugging during a water injection process, it can exceed the pressure above which the rock can crack by different modes of failure. This phenomenon can also be caused by the thermal effects of cold injection water on the *in-situ* stress in the formation. The magnitude of the stress can decrease with cold-water injection, which results in fractures being created at smaller bottom-hole pressures. Once the fracture starts to grow, the injectivity and performance of the injection well can change dramatically, because the new fluid-flow pattern will change the pressure distribution. Also, newly created fracture faces have less fluid resistance, therefore, suspended particles will preferentially plug the new fracture faces. These factors again interact with each other during long-term injection. These effects were shown by field cases reported by Paige *et al,* 1995, Hwang, 2014).

2.4.3 Sand Production

In poorly consolidated reservoirs, sand production may cause severe operational difficulties during injection and production.

Santarelli, *et al* reported a field case that the injectivity of water injectors operated by Statoil in the Norwegian Sea underwent extreme losses over short periods of time. For some wells, the injectivity was totally lost. When work over operations were carried out on the well, large amounts of sand fill that sometimes were several hundreds of meters above the top perforation was showed. A further study indicated that the injectivity decline of those water injectors was caused by a number of reasons including; failure of the reservoir rock in supporting the in situ stress when the well was shut in; sand production in front of the perforated intervals as a result of reservoir heterogeneity which led to cross flow from low permeability to high permeability areas; and sand plugging of the perforation tunnels by the produced sand that could not settle in the rat hole (Santarelli, 1998).

2.4.4 Injection Water and Formation Fluid Compatibility

In some water injection fields, fresh water can be needed for injection into the subsurface formations following some economical and logistical considerations. In cases like this, if the reservoir rocks contain interstitial clay which swells and disperses in the injected fresh water, the injectivity will decline because of permeability impairment (Guan, 2012).

Barkman, *et al* proposed an effective and inexpensive oil coating method which can prevent injectivity decline from freshwater impairment in clay containing formations. But they just suggested applying the oil-coating technique when the reservoir oil viscosity was about 5 cp. If the reservoir crude is fairly viscous, the effectiveness of this technique would decrease (Guan, 2012).

2.4.5 Injectivity Decline

Considerable work has been done to predict the injectivity decline for injection and several analytical predictive models had been developed. Most of the models developed earlier looked into internal filtration and external filtration separately, neglecting the fact that both can take place simultaneously. Many attempts in the recent times have been made to capture both processes simultaneously. Many mechanisms are involved in this process with respect to properties of suspended particles, carrying fluid and rock.

Herzig (1970) presented a comprehensive review of deep bed filtration and identified retention sites, retention forces along with the processes of clogging and de-clogging during suspended particle flow through porous media.

Barkman & Davidson (1972) proposed a measure of water quality ratio (i.e. ratio of the concentration of the suspended particles to the permeability of the filter cake formed by those particles) for an injection well and used it to predict the rate of impairment. They suggested that there are four mechanisms by which an injection well can be impaired by solids and that wellbore narrowing (EFC) is the predominant cause of impairment in injection wells.

Donaldson & Baker (1977) emphasized upon the particle size distribution. They observed that external filter-cake starts to build-up with relatively larger suspended particles and if an optimum particle size distribution is used, the particles will flow pass through the medium without getting trapped. This proposition was not appreciated by the works done later using suspended particles in the submicron ranges, as particles still got retained in the porous medium due to colloidal forces.

Gruesbeck & Collins (1982) studied abnormal decline in productivity of producing wells with particles being the naturally occurring fines (i.e., not injected but native particles). Their study focused on the flow rate variations, and they observed that there exists a critical velocity of flow above which entrainment of retained particles becomes significant. They further reported that entrainment and re-deposition of fines is restricted to the near wellbore region. This finding was later questioned as damage radius would also depend on rock structure, rock composition and size and shape of fines that may vary from reservoir to reservoir.

2.5 Radial Drilling

Horizontal drilling and new completion techniques have helped increase production in fields that may be uneconomical with traditional completions. It is known that these traditional techniques are expensive, economically unviable and may not be suitable in marginal oil/gas reservoirs. For example, the cost to drill and complete one well can range from 1.0 to 10.0 million US$. With the increase in the usage of oil and high demand, finding new resources has become paramount. Matured fields produce 60% of the world's production thereby making the extension of the production life of existing assets crucial. The desire for this has brought the new technique, radial drilling to be quite helpful in improving recovery, especially from marginal fields.

2.5.1 Definitions of Radial Drilling

Radial drilling technology is a drilling technique that makes use of hydraulic jet energy of fluids to drill lateral holes inside the reservoir (Kohar and Gogoi, 2014).

Radial drilling is a technology that is able to make a turn in a cased wellbore (vertical, slant or horizontal well) and then penetrate some distance out into the formation (Balch *et al.,* 2016; Dickinson and Dickinson, 1985; Wade, Dickinson *et al.,* 1993).

Radial drilling is a process of drilling radials of small bending diameter horizontal perforations using jets at very high pressure in different directions. The diameters of those radials is approximately 1 to 2 inches (2,54 to 5.1cm) and lengths up to 300 ft (91m). These radials can be drilled in multiple layers through same well. Fig. 2.3 is a typical example of a radial drilling operation.

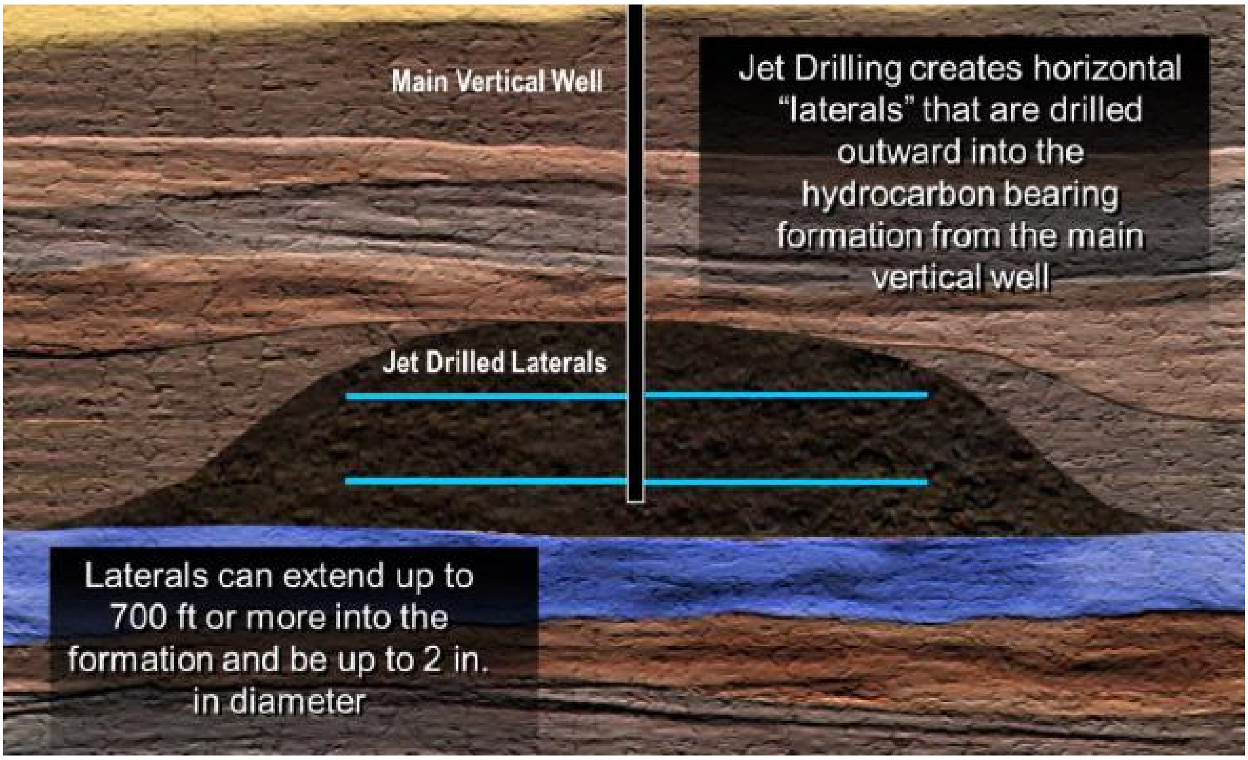


Figure 2.3: Radial drilling (Buckman Jet Drilling)

Benefit of Radial Drilling

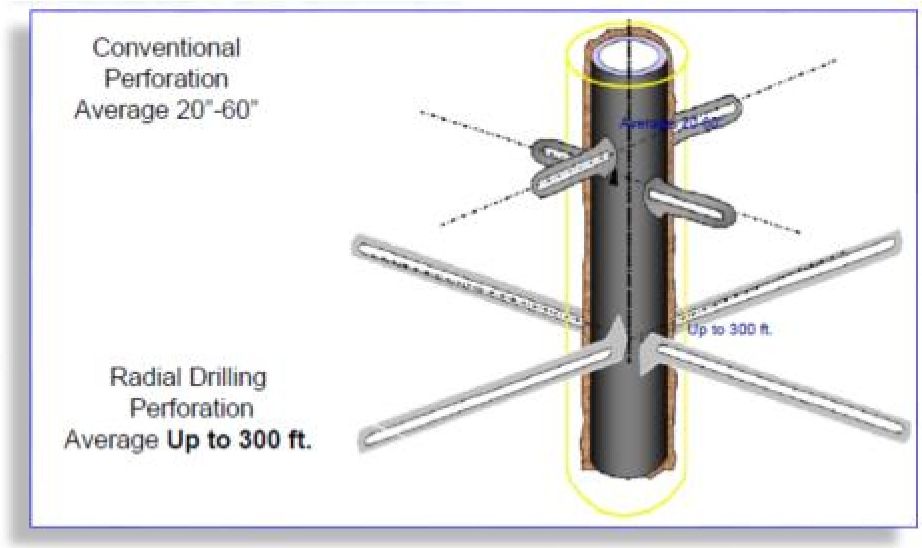


Figure 2.4: Figure showing Extended Perforation.

In reference to the research work by Ahmed (et al 2017) radial drilling is defined as an unconventional drilling technique that uses the jet energy of high velocity fluids to drill laterals with different geometries in both conventional and unconventional reservoirs. Fig. 2.4 compares the perforation length obtained using conventional method and that achieved with radial drilling.

Radial drilling technology can significantly increase productivity in many wells dependent on formation type and geology and it surpasses perforating and rival tracking. It has been tested and applied in the USA, Russia, Ukraine, Uzbekistan, Canada, China, Australia, India, Indonesia, Ecuador, Argentina, Egypt and the

Middle East with great success (Dickinson *et al.,* 1989; Li *et al.,* 2000; Stanislav Ursegor *et al.,* 2008; Abdel *et al.,* 2011).

2.5.2 History and case studies of Radial Drilling

The history of radial drilling technology can be traced back to 1989 when Dickinson *et al* introduced ultra-short radius system where multiple radial holes can be drilled from same level and also on multiple levels (Kohar *et al.,* 2014). Ultra-short radius radial system is an unconventional horizontal drilling method in that it has a buildup rate of about 100-250*/30m. The curvature alteration from vertical to horizontal turns in 30cm or 1ft. its objective was to provide an extended wellbore radius by means of multiple radials from a wellbore (Marbur, *et al.,* 2011).

Radial drilling enhancement has made enhancing production from more than 1.7 million wells that would be cost prohibitive to recover, feasible. This represents a potential untapped market of more than $50 billion. Horizontal channels up to 300 ft (91m) can be drilling from and existing wellbore using radial drilling technology with 1 to 2 inches (2.54 to 5.1cm) diameter using high-pressure fluid. In North and South America, radial drilling technology is oriented towards existing oil and gas wells at depths of 4,500ft (1372m) and shallower for productivity improvement (Cinelli and Kamel, 2013; Kamel, 2016). In 1992, water jet drilling combined with coil tubing and ultra-short radial system was started by Dickinson *et al.* Yonge *et al* developed an application of using ultra-short radial system by high-pressure jet flow in 2000, for two wells.

Elsahawl presented studies carried out to enhance production in the Belayim fields of Sinai, Petrobel – Egypt in 2001 and in 2011, Marburn *et al* presented discussions that related reservoir characteristics with drilling operations and parameters. Radial drilling technology was first applied in Belayim onshore oil field in Egypt (Kohar, *et al.,* 2014).

2.5.2.1 The Belayim Oil field

The Belayim onshore field is located in the central part of the Gulf of Suez along the coast of Sinai Peninsula and is operated by Petrobel oil company. Radial drilling pilot tests were performed on three wells. (Ahmed et al 2017)

On the first well, a static reservoir pressure of about 900 psi & PI of 2 BPD/ psi was present. Radial drilling job was performed by milling and jetting seven lateral holes drilled randomly with 164 ft lateral depth at different depths. Hydraulic jet pressure used was 7000 psi. It produces from two zones with net pay thickness of 82ft. Gross production rate showed an increase from 252 BOPD before job to 346BPD after job and net oil rate increased from 220 BPD to 289 BPD showing an increase of 37.5% for gross rate and 31.4% for net oil rate. The average rate remained for nearly one year after which it declined but decline rate was still above the pre-job rate (Kohar, & Gogoi, 2014).

The second well produced from three zones having a rock porosity of 20% and heterogeneous permeability. The static reservoir pressure was 1990 psi and productivity index of 1 BPD/ Psi and net pay thickness of 133ft. Radial drilling job were performed to get 6 lateral holes at two depths. Holes were drilled based on geological maps and fault orientations. Gross production rate increased from

472 bpd to 818BPD while net oil rate increased from 465BPD to 686BPD. But Static well pressure decreased due to fluid level decrease with PI still remaining same. Production performance declined in less than a year after the radial drilling job and decline rate went below pre job rate. Maybe this was due to heterogeneous nature of the pay zones (Kohar, & Gogoi, 2014).

The third well was produced from only one zone with static reservoir pressure of 970psi with PI of 2BPD/ Psi and porosity of 20% and heterogeneous permeability. Pay zone thickness was 87 ft. Four lateral holes were drilled at two depths in that zone with radial drilling technique. Production performance showed a little increase for very less period of time and then declined at rates mostly below pre job rates. (Kohar, & Gogoi, 2014)

2.5.2.2 The Donelson West Field, USA

Cinelli and Kamel (2013) presented the case study of a radial drilling work performed on the Donelson West Field, which contained 1200 acres reservoir of limestone and formation thickness between 6 and 10ft. Its permeability was between 1 and 10md and the field possessed a porosity between 15 and 20%. The cumulative production from 13 wells in 1968 was about 83000 bbl of oil. Afterwards, production declined quickly and in 1973, the cumulative production was about15, 000bbl. Between the years of 2000 and 2009, the average production was about 1000 bbl. annually (Kamel, 2017).

Due to its declining history despite its high potential, a development plan was adopted in 2010 to stimulate the old wells and drill new ones. Eight old wells were reentered where laterals were jetted with radial jet drilling. In addition, two new wells were also drilled and were also jetted with radial jet drilling. After laterals were finished all the wells were hydraulically treated with equal quantities of acid and nitrogen. Afterwards, production started.

The results obtained was that seven old wells and the two new wells showed significantly improved production. The last well of the old ones did not show any production at all as it was drilled in the west of the field where the formation was normally very thin. A summary of the field production before and after the treatment showed that monthly production bounced from 197bbl with an average production of 157bbl, before treatment, to 1100bbl with an average production of 938bbl, right after treatment.

In conclusion, despite of losing one well, the results showed a significant effect of the treatment which confirms radial jet drilling as a viable alternative technique for production enhancement in oil fields (Cinelli and Camel 2013).

2.5.3 Radial Drilling Tools

Several techniques cutter to energized fluid containing abrasive materials can be used to drill holes in casing and cement. The jetting nozzle size is normally between ½ -in and ¾-in (1.27 to 1.9 cm) in diameter with a length of 1.0-in (2.5 cm) and it contains a number of forward orifices that allows fluid to widen the lateral and push the nozzle forward (Dickinson *et al.,* 1992; Cinelli and Kamel, 2013). The hardware used are bottom hole assemble that consists of casing cutter, small diameter, bit, mud motor, hydraulic piston along with auxiliary tools of tubing end connector, anchor, orienter, steering tool, controller. A coiled tubing unit conveys the drilling process from the surface (Kohar and Gogoi, 2014). Fig 2.5 shows the radial drilling downhole assembly.

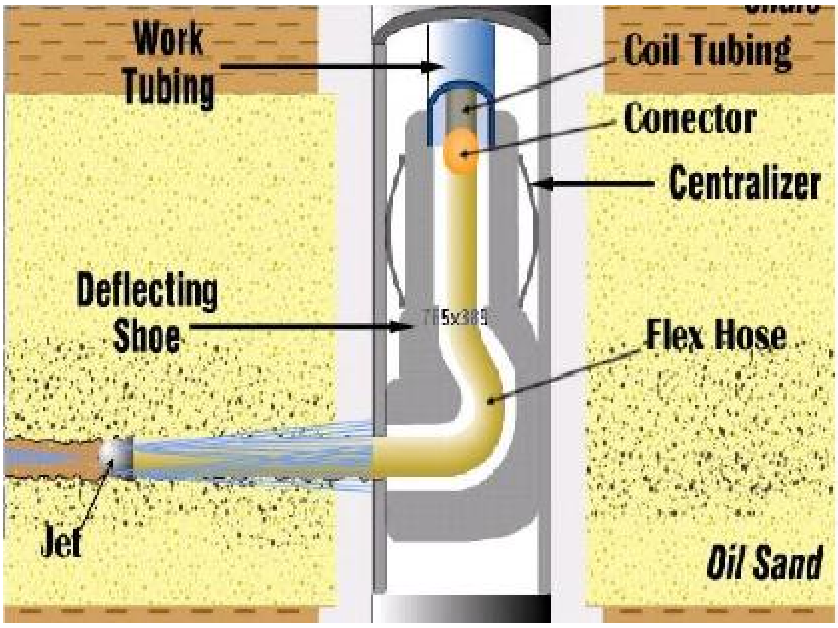


Figure 2.5: Radial drilling downhole equipment

2.5.4. Radial Drilling Fluids

The fluid plays important indirect roles like; store ant transfer energy required to accelerate abrasive particles, protect the abrasive particles and focuses impacts within a small spot flush debris and abrasive particles away from the working zone, and ensure that fresh surface material is always exposed. It also provides lubrication between the particle and the formation, reduces frictional heating, and provides a convention-cooling medium where heat generated during deformation is extracted immediately from the formation (Al-Marahleh, 2015).

Cinelli and Kamel (2013) discussed about the radial drilling fluids in details. In radial drilling process, different fluids can be used and the candidate fluid depends on both formation rock and fluids properties. The most common fluid is water as its advantages over other fluids are obvious. In cases, where water cannot be used like water-sensitive formations, diesel is used instead to avoid swelling problems. It also enhances penetration rate due to its solvent properties mostly paraffinic crude oils. Hydrochloric acids are best for carbonate formations because it reacts and dissolves carbonate formations.

2.5.5 Radial Drilling Process

The process starts by removing the production equipment from the well, see Fig. 2.6 – Fig. 2.12. Radial drilling drills small-size laterals using a coiled tubing unit and is a cost-effective alternative. It eliminates the need for the conventional bit and mud system. It circulates high pressurized fluid through forward and backward nozzles connected to a high-pressure hose. The energized fluid leaving the forward nozzles is used to erode and drill the formation while the fluid leaving the backward nozzles is used to push the nozzle forward and to widen the laterals drilled (Abdel-Ghany *et al.,* 2011; Cinelli and Kamel, 2013).

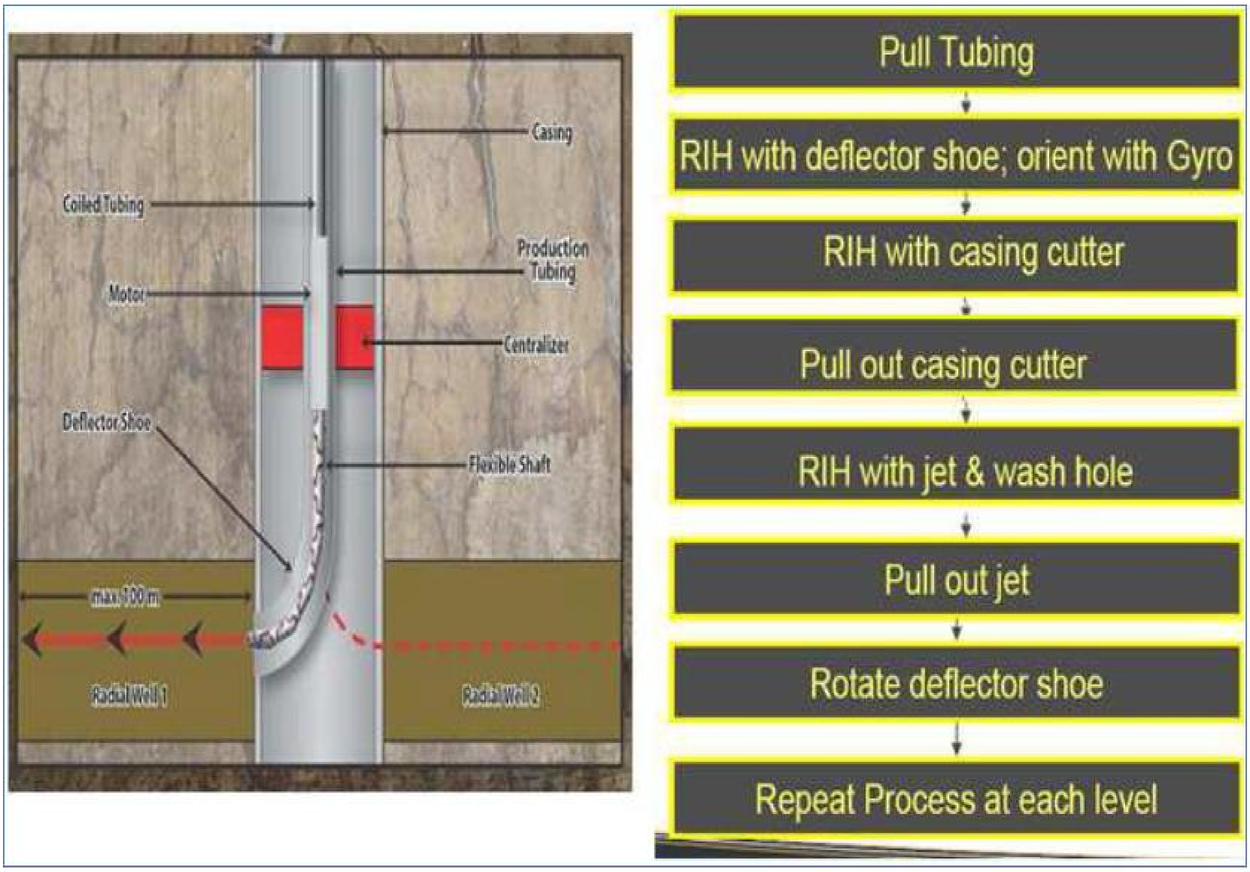
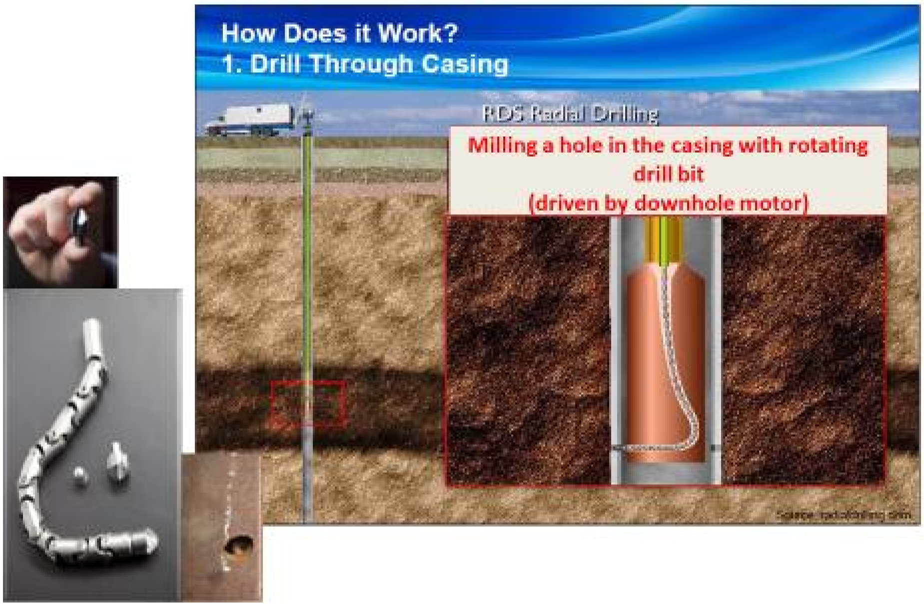


Figure 2.6: Radial Drilling Process

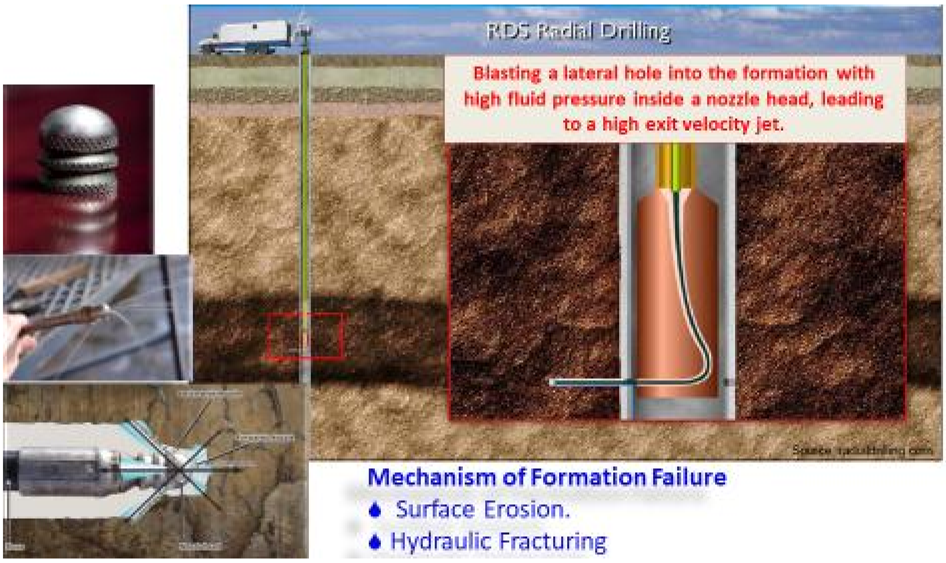


How Does it Work?
1. Drill Through Casing

RDS Radial Drilling

Milling a hole in the casing with rotating drill bit
(driven by downhole motor)

Figure 2.7: Radial Drilling Process through casing



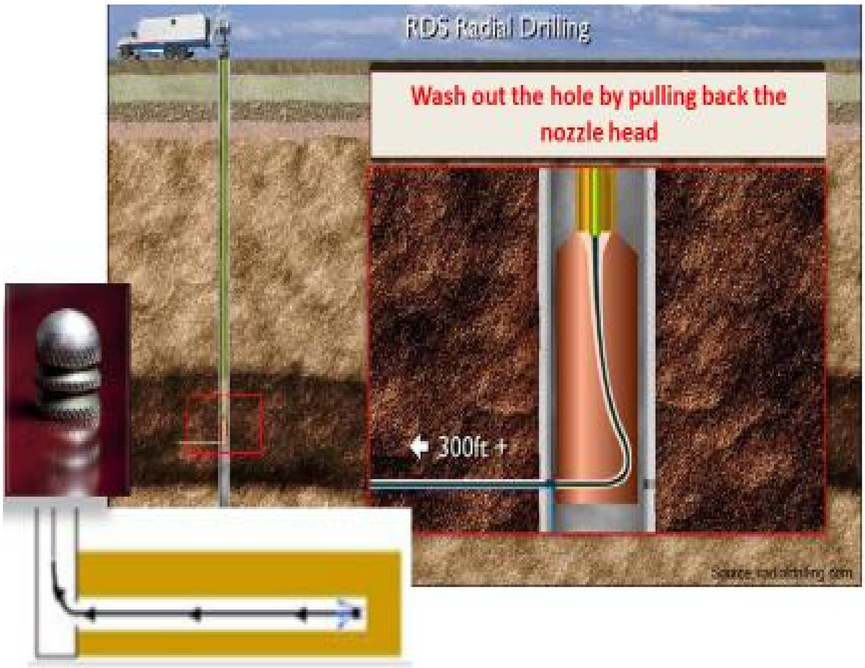
RDS Radial Drilling

Blasting a lateral hole into the formation with high fluid pressure inside a nozzle head, leading to a high exit velocity jet.

Mechanism of Formation Failure

- Surface Erosion.
- Hydraulic Fracturing

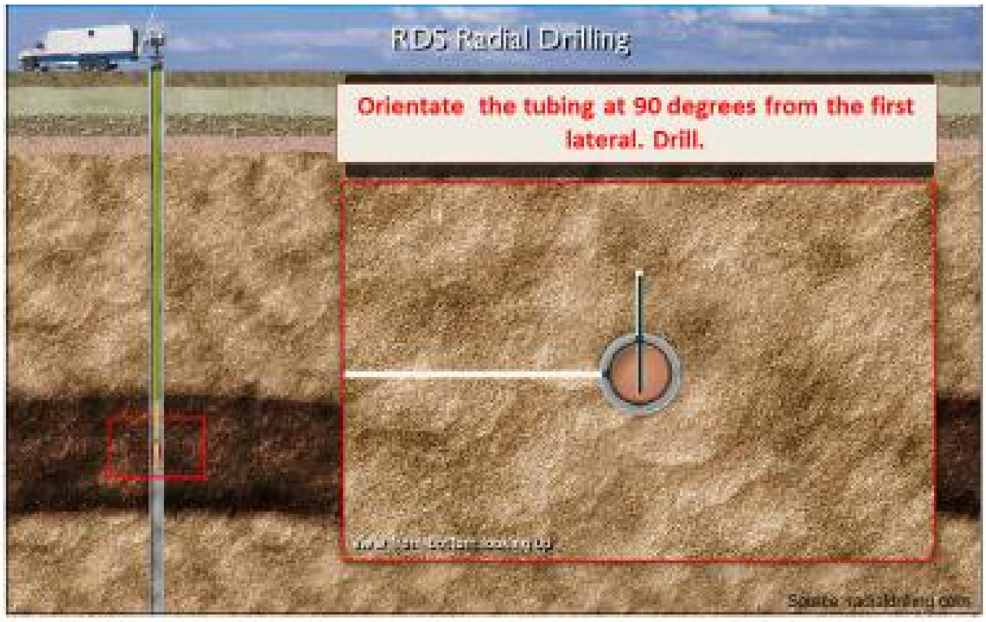
Figure 2.8: Switch to jet Assembly



RDS Radial Drilling

Wash out the hole by pulling back the nozzle head

Figure 2.9: RDS Radial Drilling (Jet the Lateral)

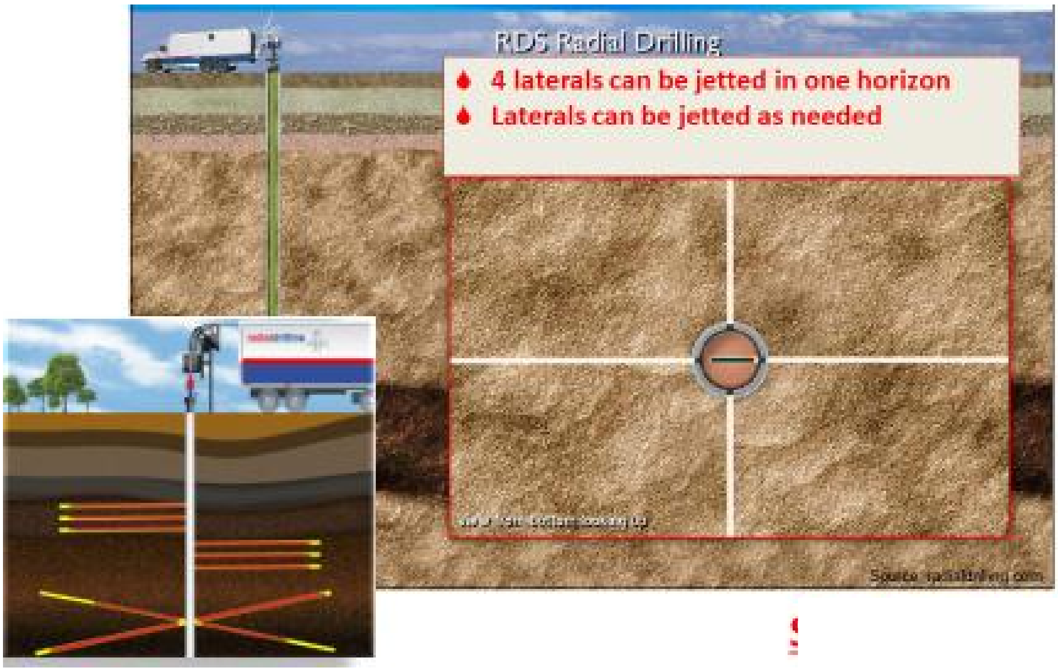


RDS Radial Drilling

Orientate the tubing at 90 degrees from the first lateral. Drill.

Source: radialdrilling.com

Figure 2.10: RDS Radial Drilling (Rotate to Next Hole)

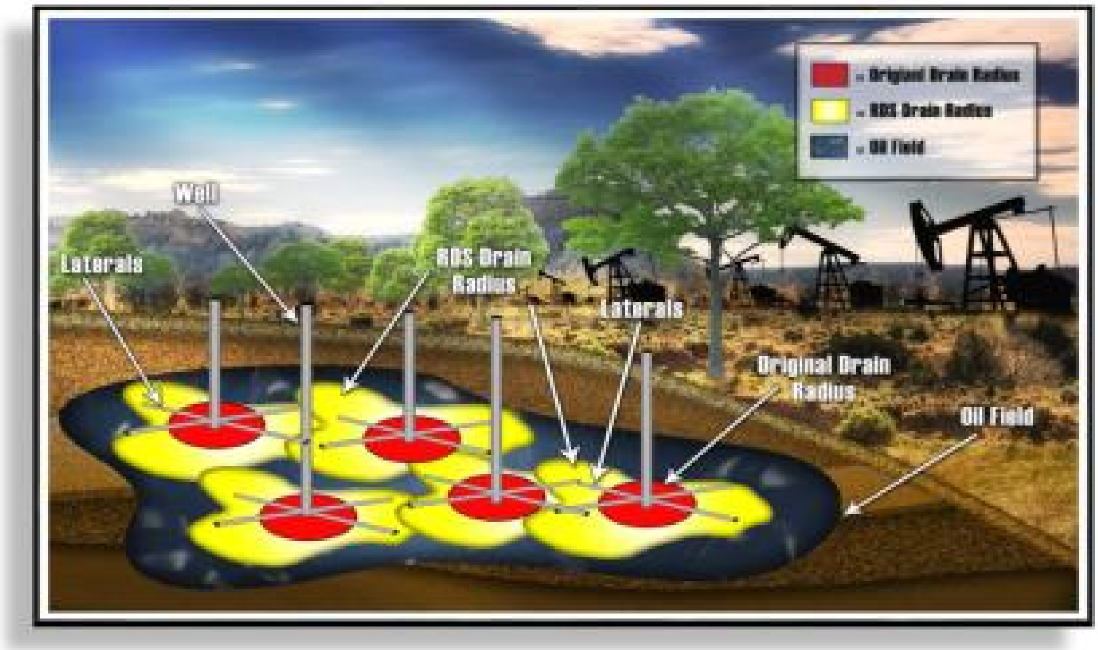


RDS Radial Drilling

- 4 laterals can be jetted in one horizon
- Laterals can be jetted as needed

Source: radialdrilling.com

Figure 2.11: RDS Radial Drilling (Repeat Drilling)



- Access residual oil trapped between existing wells in a mature field

Figure 2.12: Extended Drainage Area

In the cased holes completion, lower a cutter to open a hole through both the casing and cement; while in open-hole completion, there is no need for a cutter. A deflector shoe is lowered into the well using coiled tubing unit to reach the target and oriented using gyro. The system starts circulating fluid under high pressure through the high-pressure hose and then exits the nozzle at very high speed to erode and drill laterals, push nozzles into the laterals and widen the drilled laterals. Once a lateral is drilled, pressure is decreased and the hose is removed. The process can be repeated as often as required to drill more laterals (Zhonghou *et al*., 1999; Gensheng *et al*., 2010; Marburn *et al*., 2011; Cinelli and Kamel, 2013).

2.5.6 Applications of Radial Drilling Technology

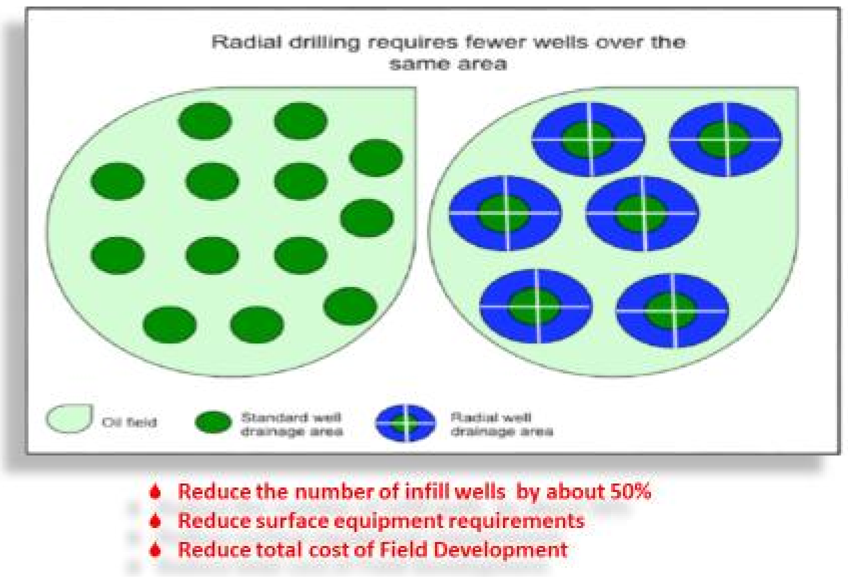
In the oil and gas industry, radial drilling can be used to increase the drainage surface area and enhance oil production. In drilling, torque and thrust required for drilling can be reduced due to the high-pressure of the radial drilling system, therefore increasing reliability, drilling rate of penetration and lateral reach which eventually results in the reduction in the drilling cost. The main application of radial drilling is to provide fast and economical methods that can be used to recover hydrocarbons. Ragab, 2013 stated that radial drilling is a good alternative for traditional perforation to go beyond near wellbore damaged zone and an alternative for layered formations when close to water contact.

The radial drilling technology can be applied in various areas in the oil industry, among which includes:

i. Water disposal and re-injection.

ii. Improve water injection.
iii. Improve vertical cleaning.
iv. Reduce water coning.
v. Well completions.
vi. Well stimulations.
vii. New wellbores instead of standard completion methods.

2.5.7 Advantages of Radial Drilling Technology: Fig 2.13 shows a field development using radial wells and standard wells.



- Reduce the number of infill wells by about 50%
- Reduce surface equipment requirements
- Reduce total cost of Field Development

Figure 2.13: Reduced infill requirement

Radial drilling technology is economical, because it can serve as a cost-effective method which can be used to complete vertical wells to make them perform like an open-hole horizontal completion. Based on what has been performed on some fields worldwide, radial drilling technology have some economical and technical benefits like (Dickinson and Dickinson, 1985; Bruni *et al.*, 2007):

i. Radial drilling penetration exceeds conventional perforation penetration and can reach far beyond the damaged area of the wellbore.
ii. It can reach beyond the damaged area of the wellbore. It can penetrate up to 300 feet in up to 16 different directions.
iii. It does not require mud pit as this can cause damage to the environment.
iv. It does not require additional stimulation.
v. There is no need for pulling the production tubing, laterals can be jetted through tubing.
vi. There is no need for large expensive rotary rigs.
vii. The process is fast, average operation duration is two days per well, it can be used to drill up to eight laterals in only two days, so there is no big loss in the production.
viii. Logging expense is no required.
ix. There is no need to change wellbore configurations.
x. There is no need to circulate the mud back to the surface because no milling casing is required.

2.5.8 Limitations of Radial Drilling Technology

Radial drilling technology to date have been in marginal and mature fields with low productivity and shallow depths. Presently, radial drilling can only be applied in vertical or near vertical wells. Its application in deviated and horizontal wells is still under investigation. There are some limitations and challenges when applying the radial drilling technology. Among these limitations include (Abdel-Ghany *et al*., 2011; Elliott, 2011):

i. Penetration difficulty under porosity of 3 to 4%.
ii. 4000 to 9000ft (1220 to 2740m) maximum working depth.
iii. Bottom hole temperature should not exceed 248°F (120°C).
iv. Maximum wellbore inclination of 30° and no more than 15° at the zone target depth/ zone of interest.
v. Maximum tensile strength of 100,000psi (7×10^8 Pa).
vi. Laterals can prematurely end due to fractures, faults or other reservoir heterogeneities.
vii. Directional control of the lateral is also very difficult.
viii. Standard logging tools will likely not fit into the laterals.
ix. Re-entering the lateral after it has been drilled could be tricky.

2.6 Location and Study of the Geology Area

The geology of the tertiary section of the Niger Delta is divided into three formations, representing prograding depositional facies distinguished mainly on the basis of sand-shale ratio (Short and Stauble, 1965; Doust and Omatshola, 1990; Kulke, 1995). They are namely Benin Formation, the Paralic Agbada Formation and Prodelta marine Akata Formation. They range in age from Paleocene to Recent. The Benin Formation is a continental latest Eocene to Recent deposit of alluvial and upper coastal plain sands. It predominantly consists of freshwater baring massive continental sands and gravels deposited in an upper plain deltaic environment. The Agbada Formation is made up of paralic siliciclastics, which underlines the Benin Formation. It consists of fluviomarine sands, siltstones, and shales. The sandy parts constitute the main hydrocarbon reservoirs. The grain size of these reservoir ranges from very coarse to fine. The Akata Formation is the basal unit of the Tertiary Niger Delta complex. It is of marine origin and compound of thick shale sequences (potential source rock), turbidities sand (potential reservoirs) in deep water and minor amount of clay silt. Beginning in the Paleocene and through the Recent, the Akata Formation formed during low stands, when terrestrial organic matter and clays were transported to deep-sea water areas characterized by low energy conditions and oxygen deficiency (Staches, 1995). It is the major source rock in the Niger Delta.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Materials

During the execution of this project work, the software that was used is Eclipse 100. Eclipse 100 is a dynamic simulation tool designed for the purpose of modeling reservoir flow regime and for generating of different important reservoir parameters. It is a fully implicit, three-phase, three-dimensional, a general purpose black oil simulator with gas condensate options. Well specifications and connections were modelled in order to accurately analyze the effect of radials in the injector well setup on the injectivity and consequently on production history. The materials utilized to carry out this study are broadly explained below.

3.1.1 Eclipse 100 Software:

The dynamic simulation study was carried out using the ECLIPSE 100 dynamic reservoir simulator to model the benefits radial drilling completion in a vertical injector well placed in a heterogeneous reservoir. Modeling of Radials in ECLIPSE was achieved using the Multi-Segment Well model. The facility is specially designed for horizontal and multi-lateral wells but can also be implemented on very special cases for vertical well modelling such as ICDs, Radials, AICVs and ICVs. It provides a detailed description of fluid flow in the well bore. The detailed description of the fluid flowing conditions within the well is obtained by dividing the well bore into a number of 1-dimensional segments with each segment having its own set of independent variables to describe the fluid conditions. The annulus space is presented as segments and connected to the grid cells which correspond to the reservoir. With this model, injected water flows from surface towards annulus and then from annulus to the radials segment and finally it flows into the reservoir.

3.1.2 Microsoft Excel 2016:

The excel spreadsheet package from Microsoft was used to analyze the data sets from the Eclipse database. Plots were established to compare the relative parameters required to measure and evaluate the propensity of the several completion cases studied. Also several plots used to analyze the methods and inputs of this study were established using the package.

3.2 Method

In this study, data from a reservoir in Niger data field was used to carry out simulation to deepen the understanding of the effect of applying radial drilling in water injectivity improvement. The study aimed at exploring the impacts of radial drilling technique as a remedy for declining water injectivity and optimizing water acceptability or contact with the reservoir in a consequential objective of making uniform contact with the in-situ oil in the reservoir for an efficient water flooding operation.

Three different methods were used to calculate the increase in productivity due to improved water injectivity resulting from adding radials to a well. The methodology applied in this project involves detailed study on a Niger delta reservoir. The approach consists of two distinct phases which is:

i. A full numerical model (industry standard tool Eclipse) which is used to carry out the analysis through detailed modelling and simulation of water injectivity and its effect on field oil production while using radial drilling as compared to the conventional perforations (and fracturing) commonly used in the industry.
ii. Evaluating the recovery factors also known as field efficiency as well as the displacement efficiency of the water flooding operation when applying the radial drilling technique for water injectivity optimization as compared to the conventional perforations.

Evaluating the water injectivity index of the base case without radials and the proposed case involving the implementation of radials in the injector well.

3.2.1 Reservoir Field Location

The reservoir field was discovered in 2000, the field is located in ultra-deep water of Nigeria. It is situated on OML 130 approximately 200 kilometres (124 mi) from Port-Harcourt (Fig. 3.1), with water depths range from 1,100 to 1,700 metres (3,600 to 5,600 feet).

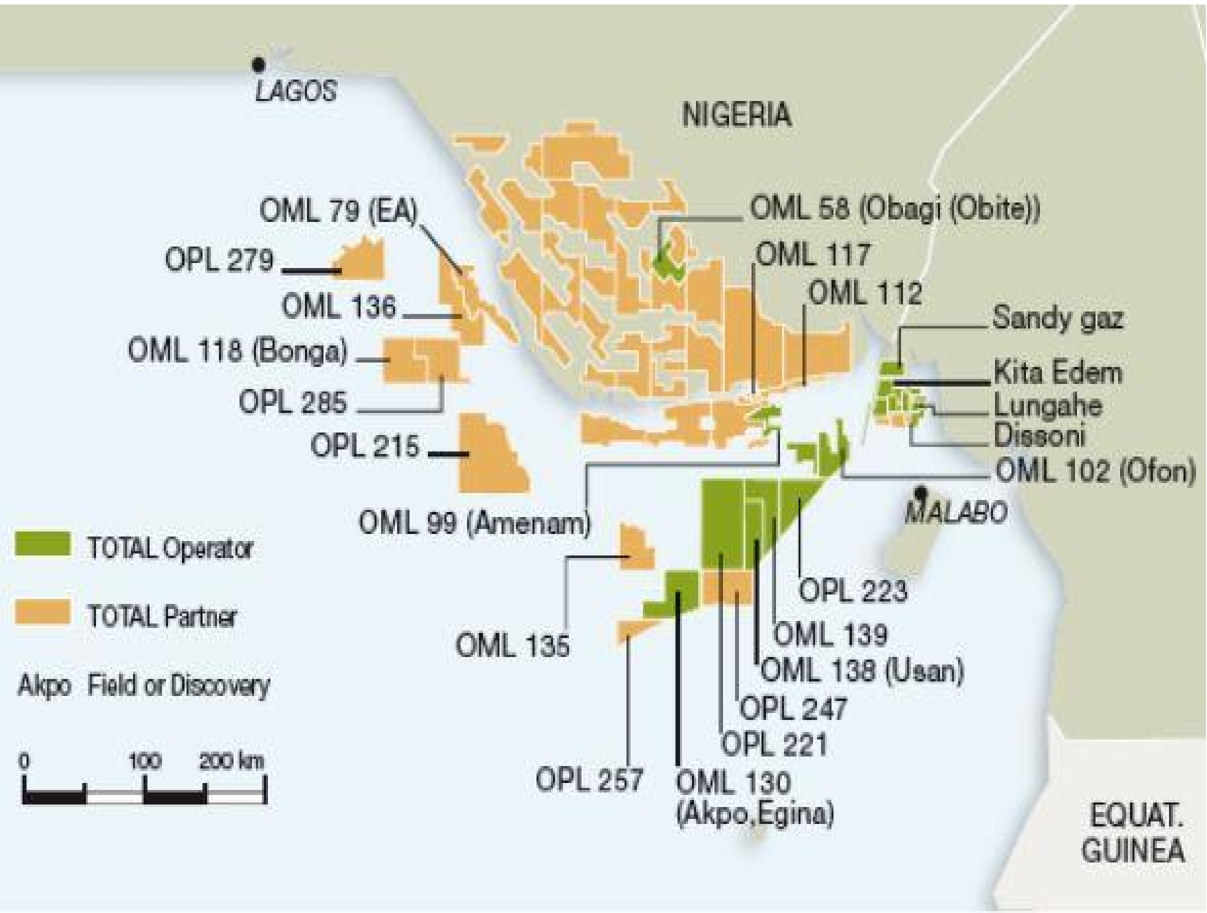


Figure 3.1: Map of the field (http://energy-cg.com/OPEC/Nigeria) .

3.2.2 Reservoir Model Descriptions

A simulation study was carried out, using ECLIPSE black oil model to deepen the understanding of water injectivity through radials to improve oil recovery mechanism. The structure of the model is a simple 3D model with uniform average properties populated across the grid. The 3D section of reservoir being modelled has dimensions 2500' x 2500' x 150', and it is divided into three layers of equal thickness. The number of cells in the x and y directions are 10 and 10 respectively.

The reservoir rock and fluid properties used in the model is presented in table 3.1.

Table 3.1: Reservoir Rock and Fluid Properties (Source: Niger delta Offshore Field)

S/N	Reservoir Properties	Value	Unit
1	Reservoir depth	8000	Ft
2	Oil density	49	lb/ft^3
3*	Water density	63	lb/ft^3
4	Gas density	0.000413	lb/ft^3
5	Oil viscosity	5	Cp
6	Oil formation volume factor	1.25	rb/stb
7	Permeability	1250	Md
8	Oil column thickness	150	Ft
9	Well bore radius	0.5	Ft
10	Porosity	25	%
11	Water saturation	20	%
12	Initial reservoir pressure	6000	Psia
13	Bubble point pressure	3416	Psia
14	Reservoir temperature	172	^oF
15	API	50.4^o	^{o} API
16	Formation compressibility	0.000003	1/psi
17	Water compressibility	0.000003	1/psi

The simplistic reservoir model used in the simulation was built using a reservoir data in Niger Delta as stated in table 1. The simulation model is shown in figure 3.2.

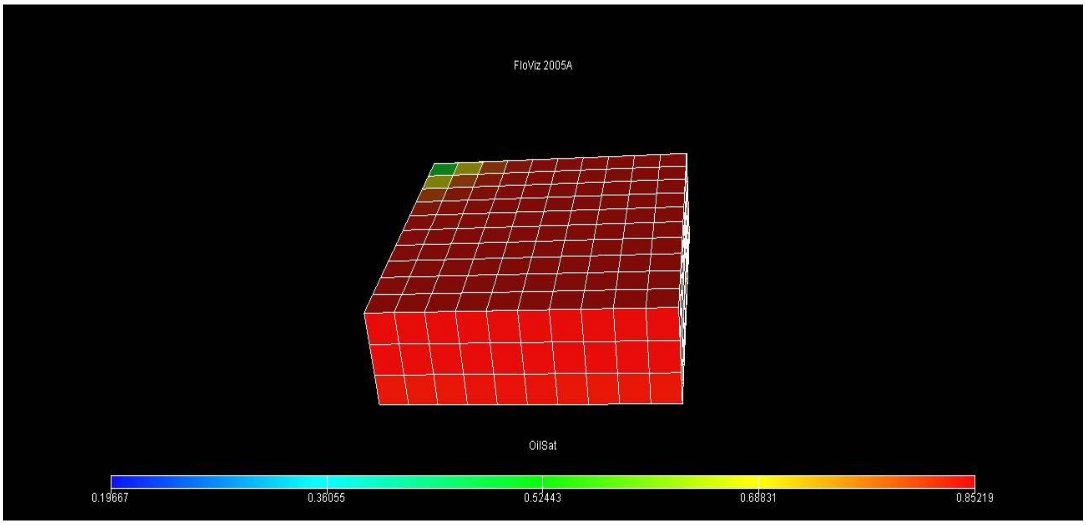


Figure 3.2: 3D view of the reservoir Model without production & injection well

3.2.3 Well Description

The well model built in this case studies are loosely patterned after the reservoir properties of a Niger Delta field formation. The reservoir is modelled using 10*10*3 with a total of 300 active cells for the well pattern. The well pattern used in the simulation is direct line drive. The injection and production well are fully completed penetrating the three layers of the reservoir.

3.2.4 The Injection Well with Radial Drilling Completion

The completed well with radial drilling was implemented on the water injector well at the third grid section, initially, injector wells are completed with perforations to bypass the skin or invaded zone thereby consequentially providing better communication with the reservoir. The radial drilling implementation was done by increasing the milling (perforated) length as well as the milling diameter. In Table 3.2, the descriptions for the well completed with radials and completed without radials are given. The figure below (Fig. 3.4 and Fig. 3.5) displays an illustration of the geometry of the water injector well completed with 2 and 4 radials. The well was completed with 2 and 4 radials for several case studies with different radial lengths. The angle between the radials is 180°for the cases completed with 2 radials and 90° for that completed with 4 radials. Six cases were evaluated along with the base case which involved no radials, the cases involved the length of the radials of 25 meters which is approximately 82feet for the cases with 2 and 4 radials each, 50 meters (approx. 164feets) and radial length of 100 meters (approximately 338 feet) for the cases with 2 and 4 radials each.

Table 3.2: Table showing the different cases of simulations

	BASE CASE (perfs)	**CASE 1**	**CASE 2**	**CASE 3**	**CA**
Number of Radials	None	2	2	2	
Length of radials	None (perf length = 20m)	25 meters/82ft	50 meters/164ft	100 meters/338ft	25 met

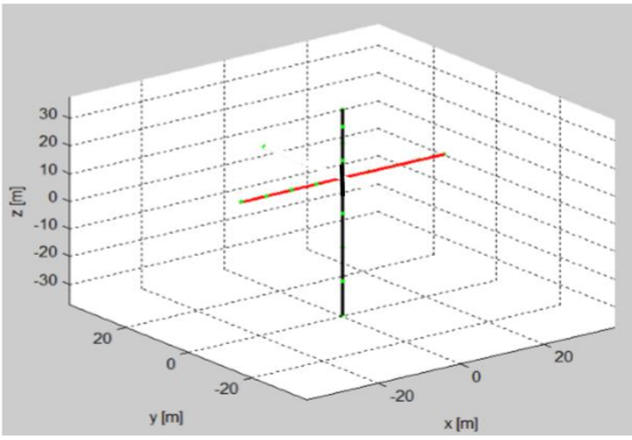


Figure 3.3: Injector well with 2 traverse radials (180°)

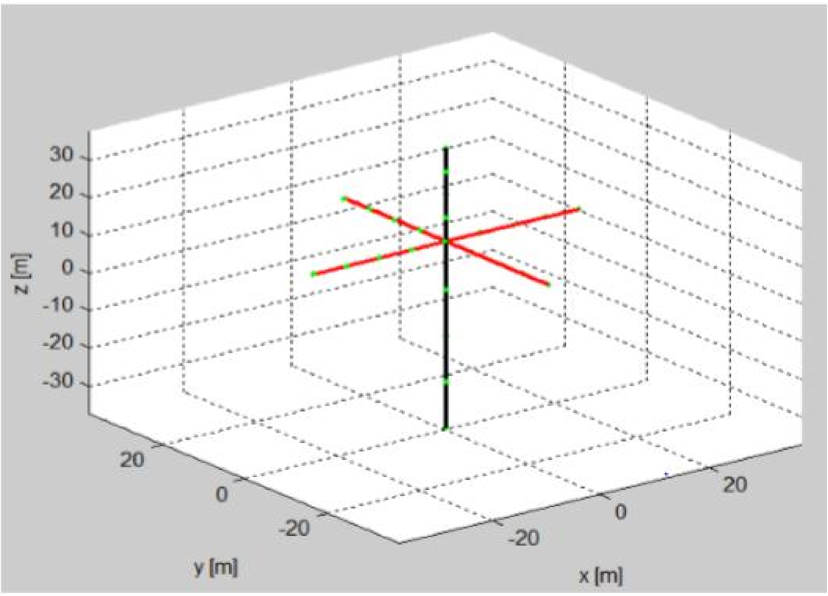


Figure 3.4: Injector well with 4 traverse radials (90°)

In the Eclipse dynamic simulation, the salinity of the injected water was set to optimum level to mimic flooding water to create a hydrophilic rock scenario so that more oil will be recovered from the reservoir. The properties of the injected water are presented in the table below.

Table 3.3: Injected water PVT and flooding properties

S/N	**Properties**	**Value**	**Unit**
1	Water viscosity	0.8	Cp
2	Water formation volume factor	1.02	rb/stb
3	Water density	63	lb/ft^3
4	Injection rate	11000	stb/day
5	Injection pressure	6000	Psia
6	Injection well radius	0.5	Ft
7	Water compressibility	0.000003	1/psi

3.2.5 Assumptions guiding the model & simulation activity

i. There is no free gas in the production well

ii. The flooding pattern is a 2 spot direct line drive pattern i.e. one injector and one producer

iii. The fluids involved in the flooding process are incompressible fluids

iv. The reservoir is homogenous and anisotropic

v. Areal and vertical sweep efficiency is unity (i.e. =1)

3.2.6 Water Injectivity and Injectivity Index

Whereas productivity index is the ability of a well to produce hydrocarbons, injectivity index, I, in B/D/psi, is a measure of the ability of a well to accept fluids mathematically represented by equ. 3.1

$$\boldsymbol{I = \frac{q_{sc}}{P_{iwf} - P_e}} \qquad 3.1$$

where $q_{sc}$is the flow rate in B/D at surface conditions, $P_{iwf}$is the flowing bottom hole pressure in psi, and P_e is the external pressure in psi. Some literatures express injectivity in terms of $\frac{q_{sc}}{P_{iwf}}$ so that when injectivity is given, there is need to understand what base pressure was intended. By dividing I by reservoir thickness, a specific injectivity index (specific to one well) can be obtained in B/D/psi/ft. In addition to expressing injectivity in terms of fluid injection rate in B/D. Values of injectivity depend on properties of the reservoir rock, well spacing, injection water quality, fluid-rock interactions, and pressure drop in the reservoir. Typical values of injectivity are in the range of 8–15 B/D/net ft or $0.75 - 1.0$

B/D/net ac-ft. In water flooding operations, water injection may begin into a reservoir produced by solution-gas-drive in which a mobile gas saturation exists, or injection may begin prior to the development of a mobile gas saturation. In the latter case, the system can be considered filled with liquid.

In this study, the injectivity for all cases would be calculated using the formula provided above, the flowing bottom whole pressure, P_{iwf} is the quantifying factor that enables lucid understanding on which of the cases provides the best medium for optimum or improved water injectivity.

3.2.7 Sweep Efficiency

The sweep efficiencies are factors used to quantify the effectiveness of the injection pattern used. It is a means required for intensive evaluation of the flooding pattern or technique used. The sweep efficiencies include displacement sweep efficiencies, areal sweep efficiencies and vertical sweep efficiencies. The areal and vertical sweep efficiencies for the scope of this study is assumed to be unity (i.e. =1). Therefore, the displacement efficiencies for the cases to be modelled and analyzed would be evaluated.

As defined previously, displacement efficiency E_D is the fraction of movable oil that has been recovered from the swept zone at any given time. The overall recovery also known as recovery factor (R_f) is a product of displacement efficiency (E_D), invasion or vertical sweep efficiency (E_v) and the pattern or areal sweep efficiency (E_A).

$$\boldsymbol{R_f = E_D \, x \, E_A \, x \, E_v} \qquad 3.2$$

Where R_f = overall recovery (fraction of initial oil in place recovered) E_D = displacement efficiency or volume of oil displaced divided by total oil volume (fraction) E_v = vertical or invasion efficiency (fraction of vertical reservoir section contacted by injection fluid) E_A = pattern efficiency or pattern swept by total pattern area.

The Recovery factor,

$$\boldsymbol{R_f = N_p/N_s} \qquad 3.3$$

Where N_p the cumulative amount of oil is produced and N_s is amount of oil originally in place. Substituting the value of R_f in equation, 16 into equation 15,

$$\boldsymbol{N_p = N_s\,(E_D\ x\ E_A\ x\ E_v)} \qquad 3.4$$

From the assumptions made for this study; areal and vertical sweep are assumed to be unity when Ea. and Ev is one, therefore the above equation is reduced to;

$$\boldsymbol{N_p = N_s\ x\ E_D} \qquad 3.5$$

Thus, the displacement efficiency is expressed as:

$$\boldsymbol{E_D = \frac{N_p}{N_s}} \qquad 3.6$$

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Results

Here, in comparison with the research work on water injectivity simulation with radial drilling by Ahmed H. Kamel (et al 2017, March) , Kohar, J & Gogoi, S. (2014, Nov.) and Elliott, S. (et al 2011) the results for water-injection modelling and simulation for an injection well completion without radials and six other cases with 2 and 4 radials, 25 meters long, 2 and 4 radials, 50 meters long and another completed with 2 and 4 radials, 100 meters long using the eclipse dynamic simulation tool were compared in order to determine which injection method offers the best water injectivity, displacement sweep efficiency, recovery efficiency and field oil production total. Also, results on sensitivity analysis carried out to determine the field water cut and the pressure maintenance value (pressure trend due to water injection) and also evaluate the factors that promote or relegate early gas or water breakthrough due to the water injection operation using the completion methods as stated above.

The simulation models for each case are shown in the figures below:

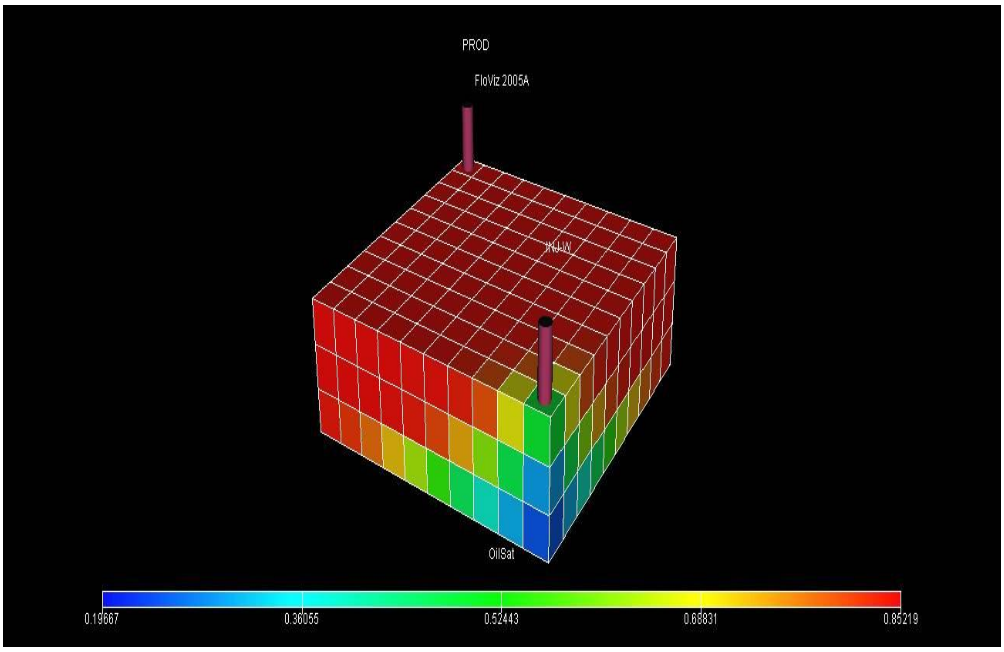


Figure 4.1: 3D view of the Reservoir Model at the period of water flood for base case

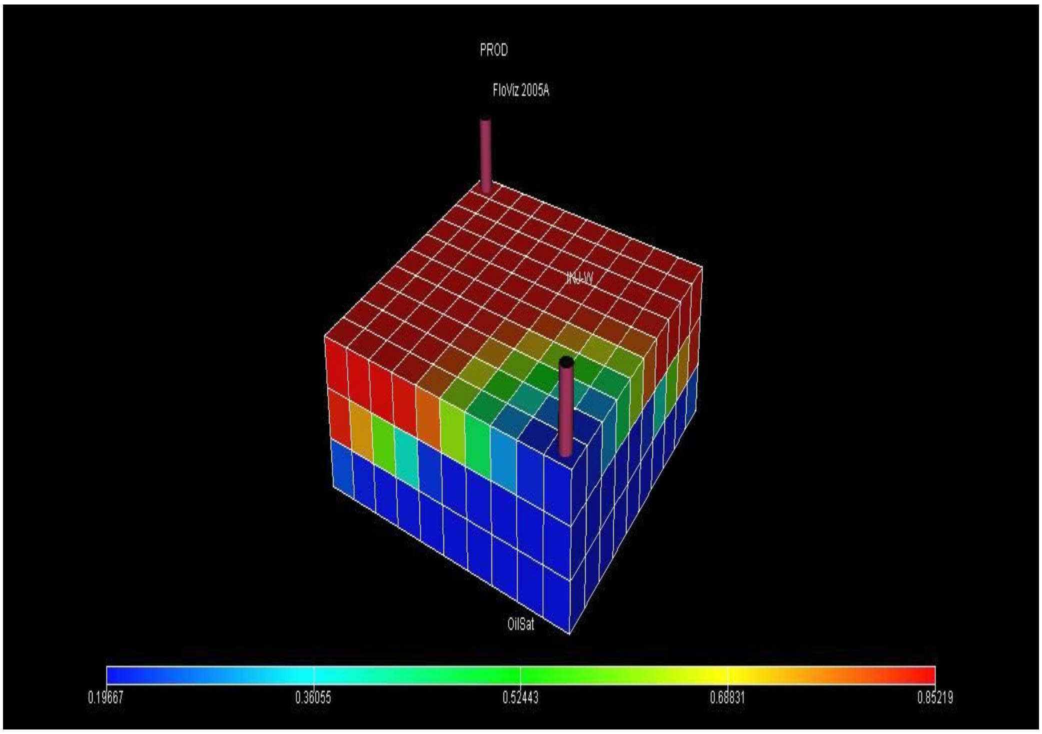


Figure 4.2: 3D view of the reservoir Model at the period of water flood for case 2 and 5 (2 and 4radials, 50m long)

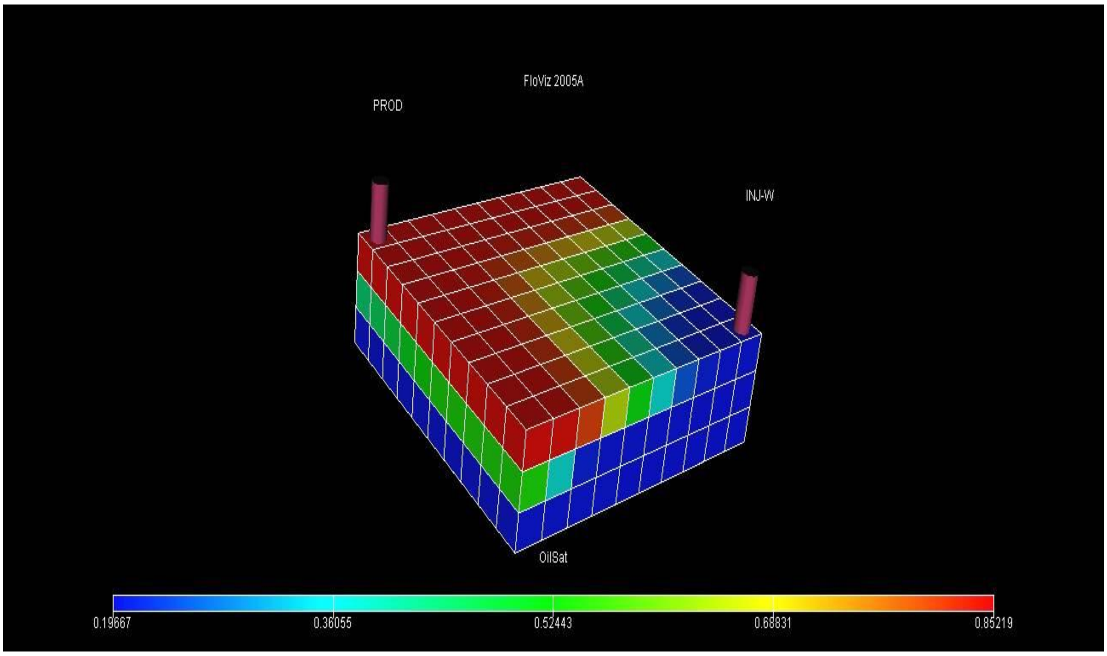


Figure 4.3: 3D view of the reservoir Model at the period of water flood for case 3 and 6 (2 and 4radials, 100m long)

The results obtained from the numerical simulation study are listed in the figures below.

4.1.1 Field Oil Efficiency/Recovery Factor & Cumulative Oil Production

The result of field oil production total (cumulative oil production) is shown in Fig. 4.5, it shows the total oil produced when the pressure maintenance method used through water injection consists of case scenarios for a water injection well completed with no radials, 2 radials 25m long, 2 radials 50m long, 2 radials 100m long, 4 radials 25m long, 4 radials 50m long and 4 radials with 100m long. The result for the field oil recovery efficiency (FOE) for No radials water injection case, 2 radials 25m long, 2 radials 50m long, 2 radials 100m long, and 4radials, 25 meters long, 4 radials 50m long, 4radials, 100meters long water injection cases are calculated below for a water injection period of 3400days. The trend displaying the recovery factor from a period of 0 to 4200 days is shown in Fig 4.6.

From the simulation case the reservoir studied has original oil in place value, N_s of 19285714 STB.

$$\text{FOE} = \frac{FOPT}{OOIP} \; i.e. R_f = \frac{N_p}{N_s} \qquad 4.1$$

$N_s \; (i.e. OOIP), stb$ = 19285714 STB

1. For No radials water injection case at 3400 injection days,

$$\text{FOE} = \frac{10000000}{19285714}$$

FOE = 0.513

FOE = 51%.

2. For 2 radials, 25 meters long water injection case at 3400 injection days,

$$\text{FOE} = \frac{5300000}{19285714}$$

FOE = 0.275

FOE = 28%.

3. For 2 radials, 50 meters long water injection case at 3400 injection days,

$$\text{FOE} = \frac{6300000}{19285714}$$

FOE = 0.327

FOE = 33%.

4. For 2 radials, 100 meters long water injection case at 3400 injection days,

FOE = $\frac{10200000}{19285714}$

FOE = 0.529

FOE = 53%.

5. For 4 radials, 25 meters long water injection case at 3400 injection days,

FOE = $\frac{9600000}{19285714}$

FOE = 0.497

FOE = 50%.

6. For 4 radials, 50 meters long water injection case at 3400 injection days,

FOE = $\frac{11900000}{19285714}$

FOE = 0.617

FOE = 62%.

7. For 4 radials, 100 meters long water injection case at 3400 injection days,

$$\text{FOE} = \frac{12450000}{19285714}$$

FOE = 0.645

FOE = 65%.

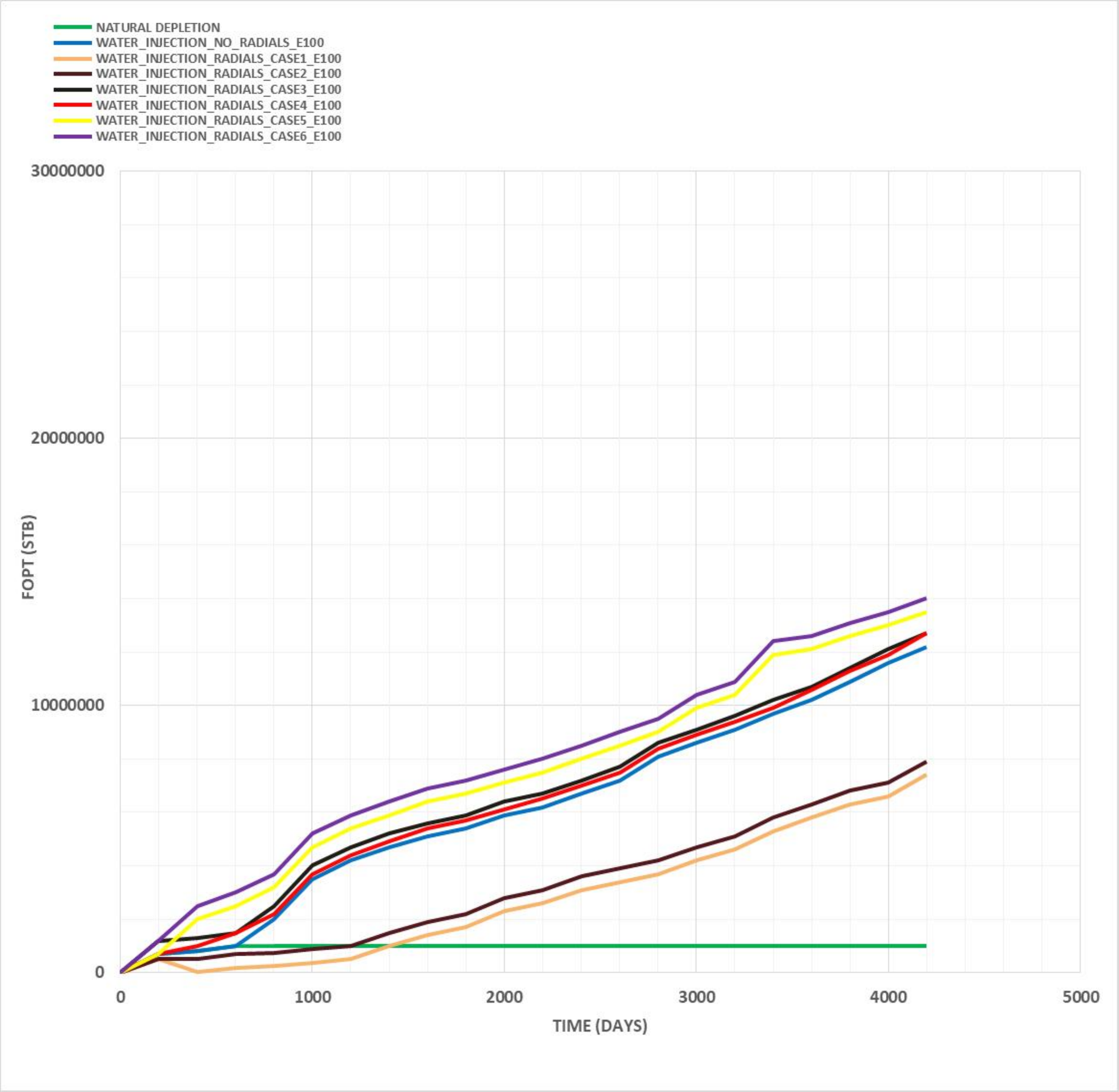


Figure 4.4: Plot of Field Oil Production Total (Np) against time for all cases

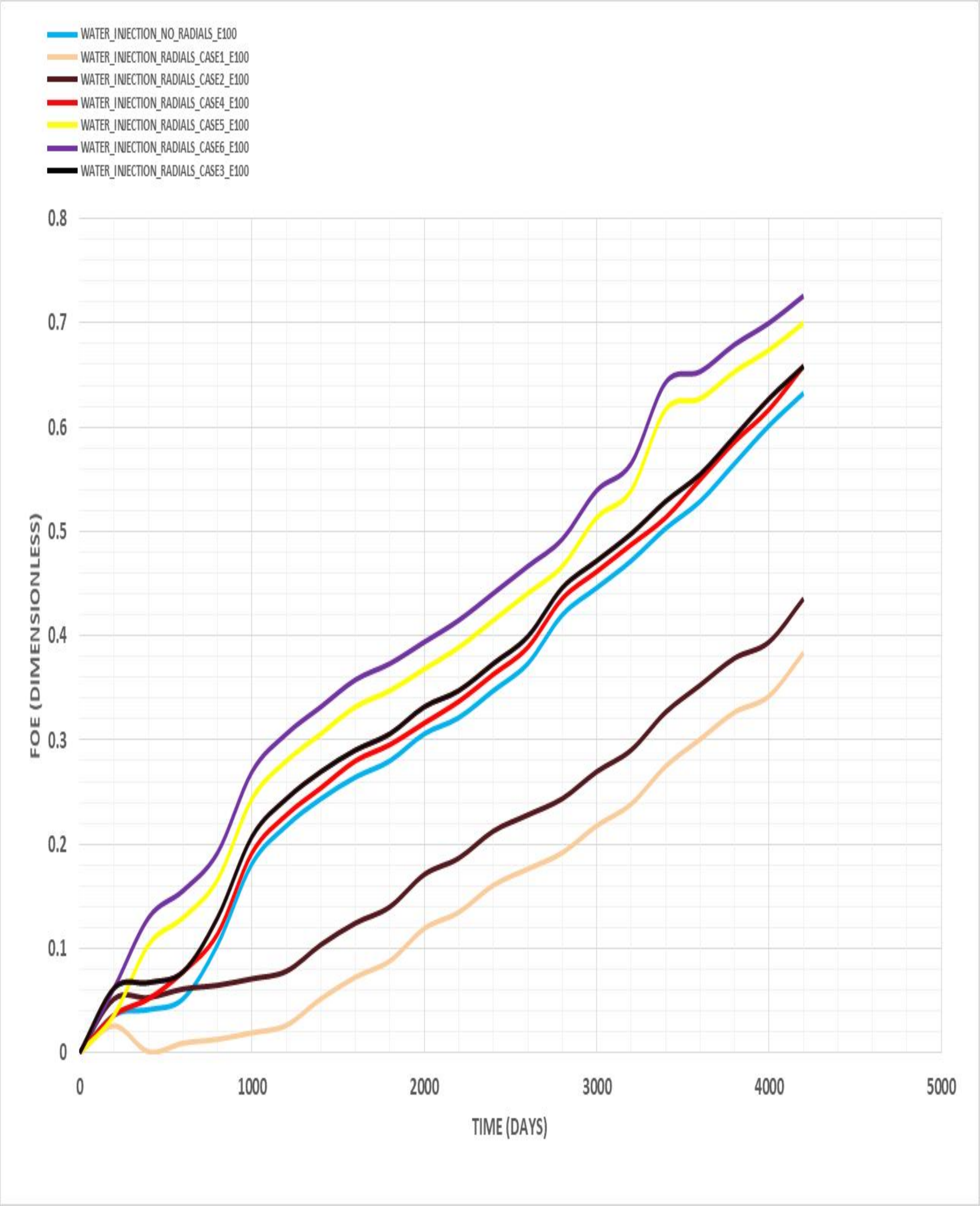


Figure 4.5: Plot of FOE (Field Oil Efficiency or Recovery factor) against time for all cases.

4.1.2 Field Water Cut & Field Water Production Total

The results for the field water cut and the field water production total from the simulation carried out is displayed in Fig. 4.7 and 4.8 .

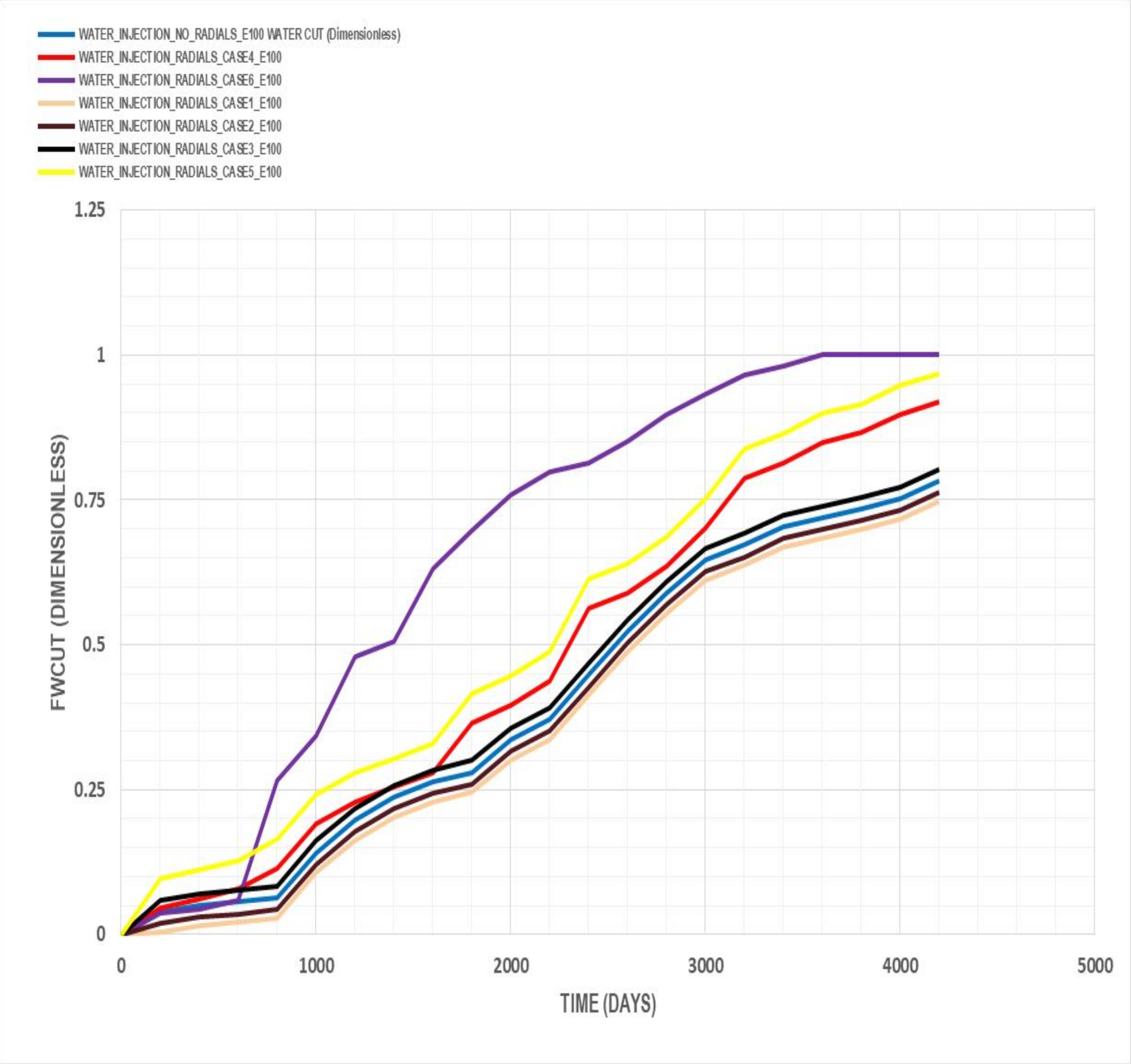


Figure 4.6: Plot of FWCUT (Field water cut) against time for all cases

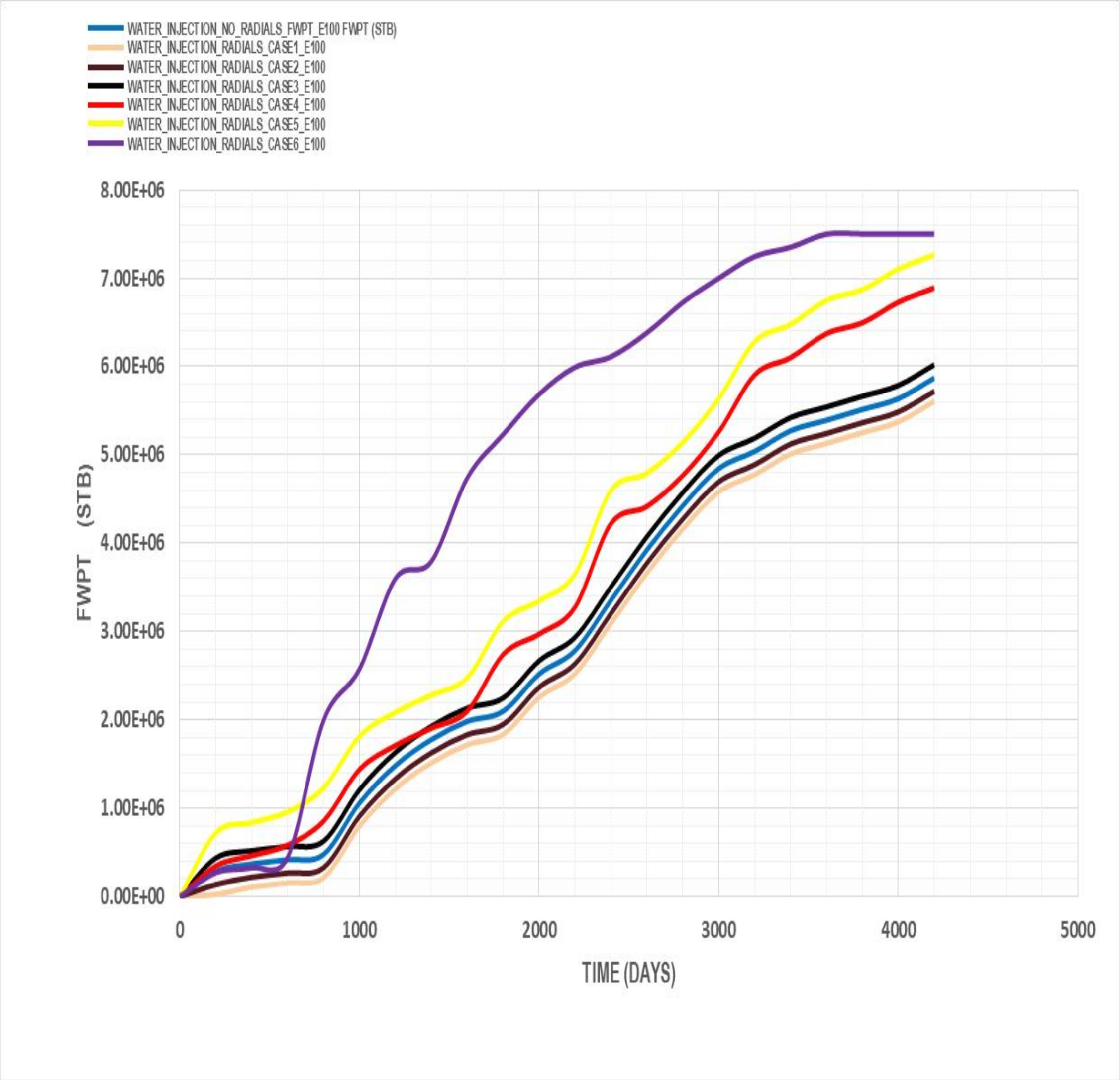


Figure 4.7: Plot of FWPT (Field water production total) against time all cases

It is used to quantify and further evaluate the suitability of using radials to improve water injectivity, promote residual oil saturation depletion and consequently promote cumulative oil production. The simulation result for field pressure after water injection is shown in Figure 4.9. The pressure is used to calculate the water injectivity index, I for the three-water injector well completion case to deduce which has more water injectivity and potential to sustain reservoir pressure consequently leading to improve oil production.

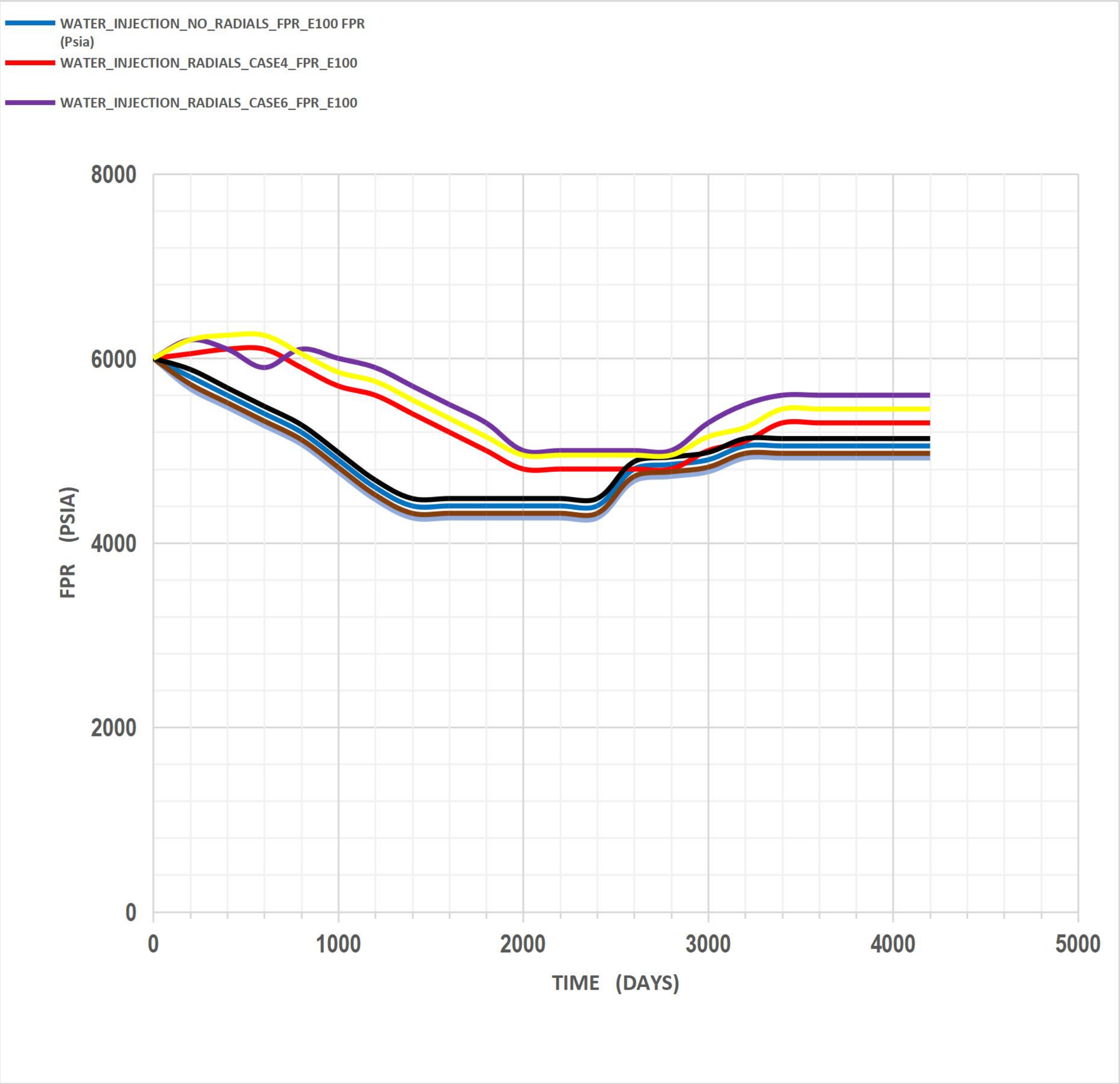


Figure 4.8: Plot of FPR (Field pressure – base pressure) against time for all cases

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$ 4.2

Where q_{sc} is 11000 stb/day

P_{iwf} = 6000psi

To find the water injectivity index for the three cases, pressure values from Fig 4.9 at 4000 days is used.

1. For No radials water injection case at 4000 injection days, P_e = 5050 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 5050}$$

I = 11.6 STB/D/Psi

2. For 2 radials, 25 meters long water injection case at 4000 injection days, P_e = 4920 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 4920}$$

I = 10.2 STB/D/Psi

3. For 2 radials, 50 meters long water injection case at 4000 injection days, P_e = 4970 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 4970}$$

I = 10.7 STB/D/Psi

4. For 2 radials, 100 meters long water injection case at 4000 injection days, P_e = 5130 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 5130}$$

I = 12.6 STB/D/Psi

5. For 4 radials, 25 meters long water injection case at 4000 injection days, P_e = 5300 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 5300}$$

I = 15.7 STB/D/Psi

6. For 4radials, 50 meters long water injection case at 4000 injection days, P_e = 5450 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 5450}$$

I = 20.0 STB/D/Psi

7. For 4 radials, 100 meters long water injection case at 4000 injection days, P_e = 5600 psia

Water Injectivity Index, $I = \frac{q_{sc}}{P_{iwf} - P_e}$

$$I = \frac{11000}{6000 - 5600}$$

I = 27.5 STB/D/Psi

The plot below shows the water injectivity index trend for the three cases studied.

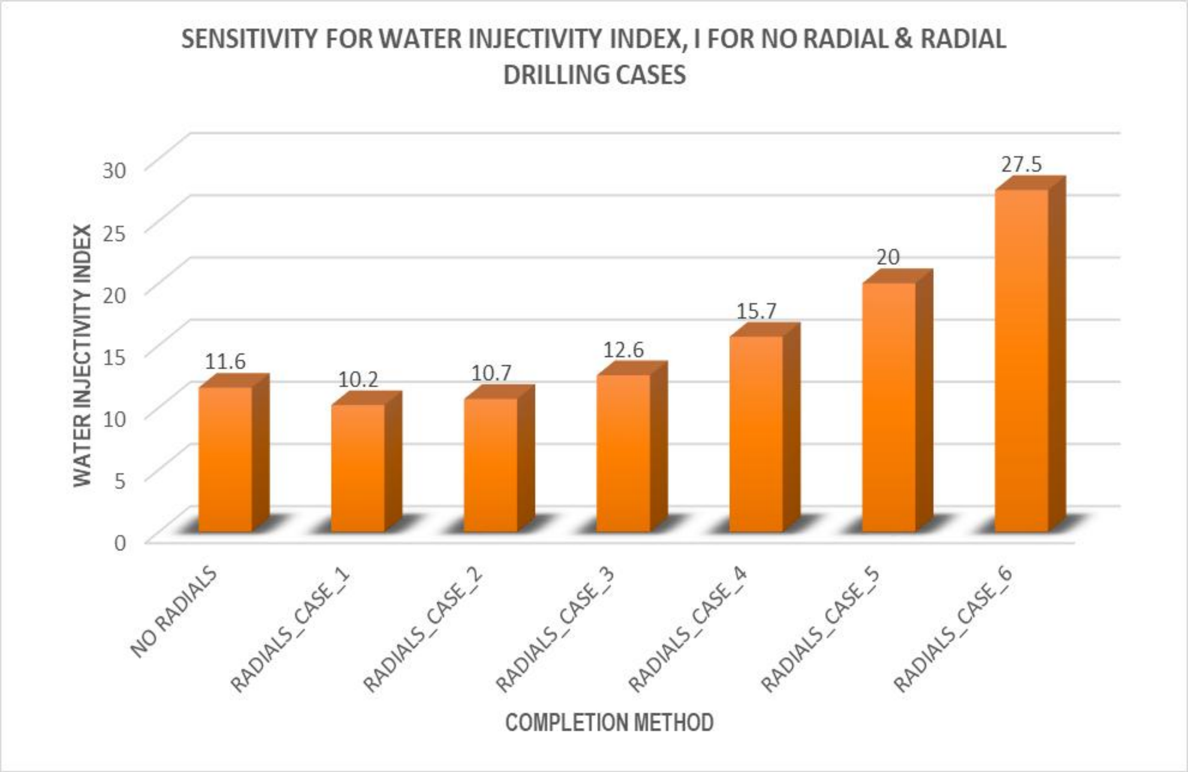


Figure 4.9: Plot of completion type (water injector) against water injectivity index

4.1.4 Displacement Sweep Efficiency

The displacement sweep efficiency for the three cases were measured using the formula below,

$$R_f = E_D \, x \, E_A \, x \, E_v \qquad 4.3$$

$R_f \, is \, the \, recovery \, factor \, also \, known \, as \, the \, total \, field \, oil \, efficiency$

$E_D \, is \, the \, displacement \, sweep \, efficiency$

$E_A \, is \, the \, areal \, sweep \, efficiency$

$E_v \, is \, the \, vertical \, sweep \, efficiency$

The vertical and areal sweep efficiency for this study was assumed to be unity (i.e. 1) or 100%, therefore, the displacement sweep efficiency is proportional and equal to the recovery factor. As calculated above, the result for the field oil efficiency (FOE) for No radials water injection case is 51%, 2 and 4 radials, 25 meters long water injection case is 28% and 50% respectively, 2 and 4 radials, 50 meters long injection case is 33% and 62% respectively and that of 2 and 4radials, 100meters long water injection case is 53% and 65% respectively for a water injection period of 3400days. Therefore, the displacement sweep efficiencies are 0.51, 0.28, 0.33, 0.53, 0.50, 0.62 and 0.65 respectively for the base case and six radial cases at injection time of 3400days and at areal and vertical sweep efficiencies considered to be unity. The Fig. Fig 4.7 shows a plot displaying the displacement sweep efficiencies for the base case and 6 radial cases.

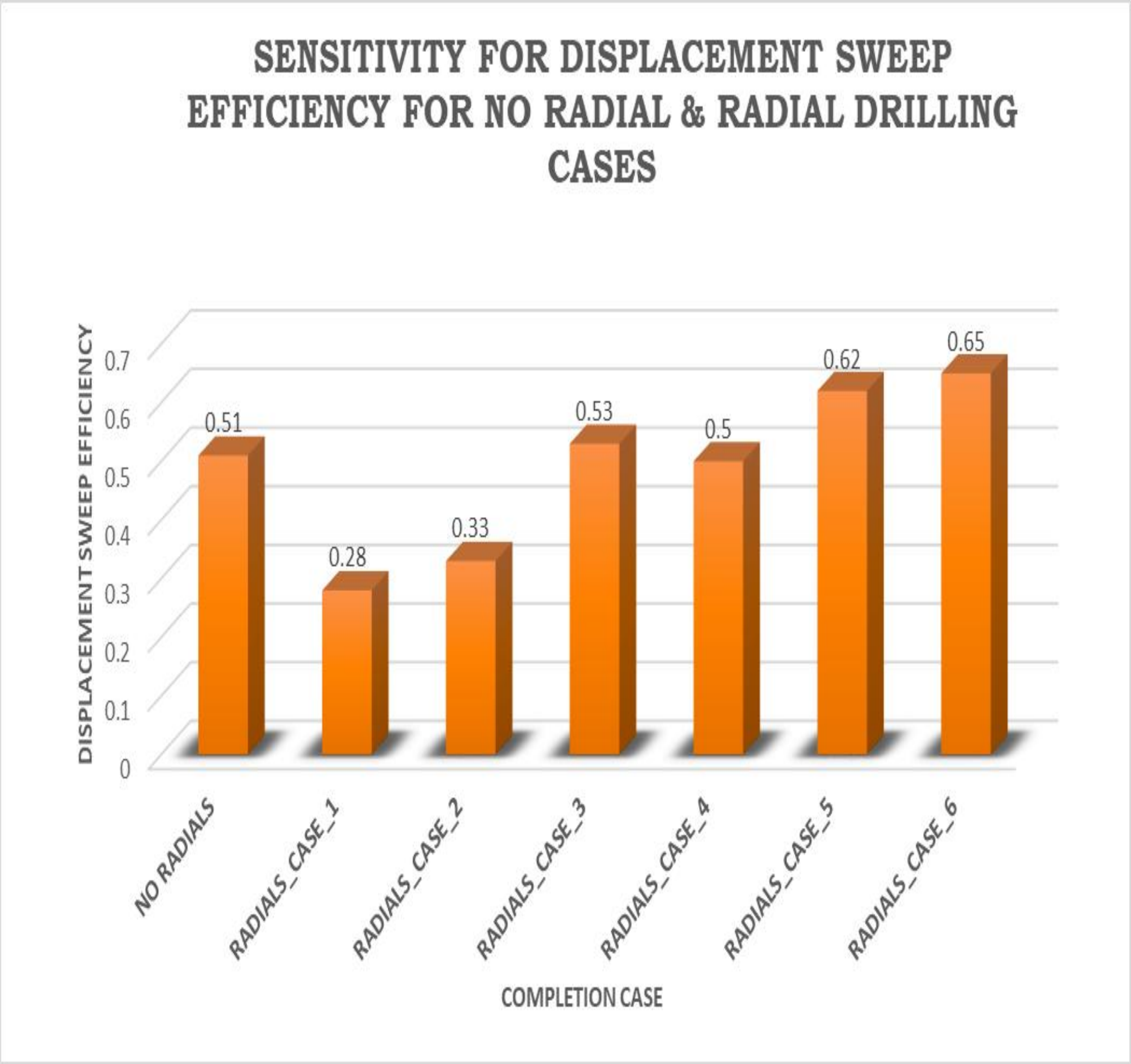


Figure 4.10: Plot of completion type (water injector) against displacement sweep efficiency

Table 2: Table of Results

CASES	**FIELD OIL EFFICIENCY (%)**	**INJECTIVITY INDEX (STB/D/PSI)**
Base case	51	11.6
Case 1	28	10.2
Case 2	33	10.7
Case 3	53	12.6
Case 4	60	15.7
Case 5	62	20.0
Case 6	65	27.5

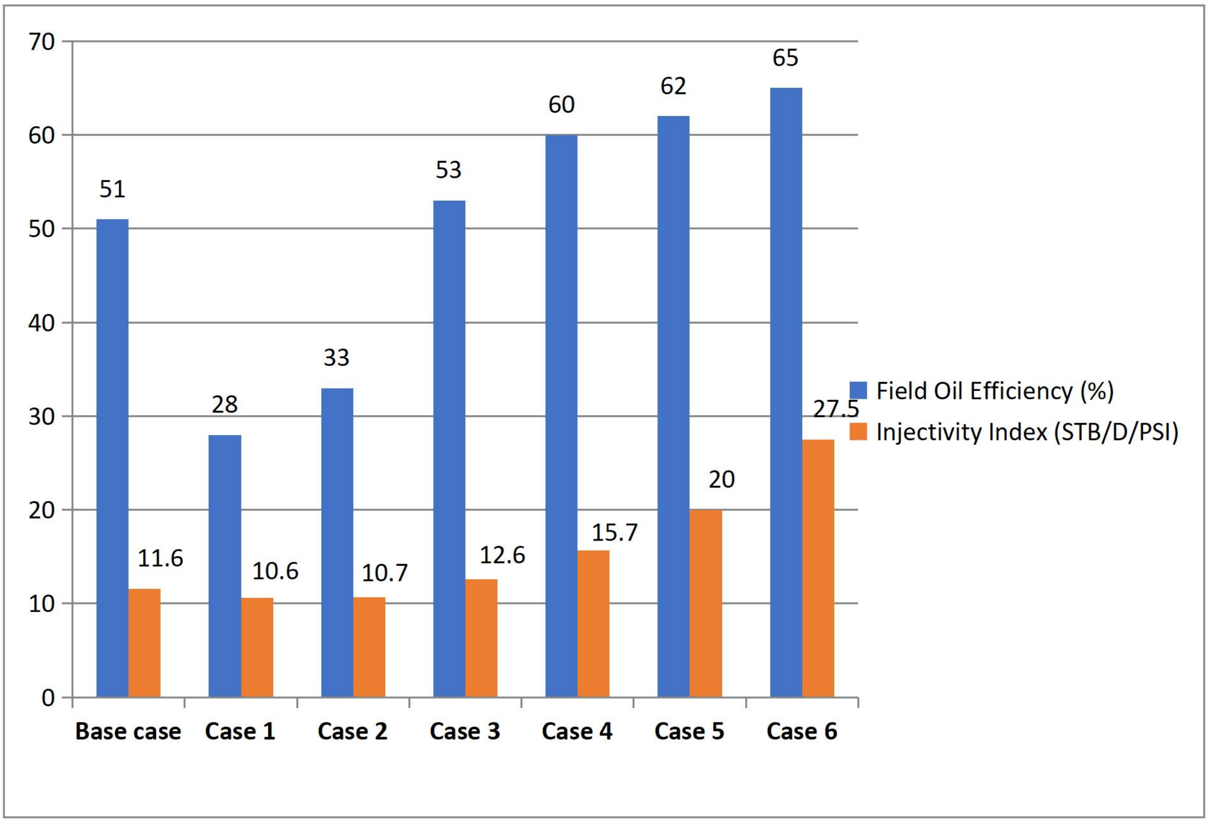


Figure 4.11: plot of field oil efficiency and injectivity index for each case

4.2 Discussion of Results

The result obtained after numerical simulation studies will be discussed under water injectivity index, oil recovery efficiency, oil production total, water cut, water production total, oil production respectively.

Fig. 4.5 and 4.6; indicate that injecting water into an injection well completed with radials would recover more residual oil than that completed with no radials otherwise conventional perforations. The establishment of radials was modelled and compared with primary recovery (natural depletion) cases as well as water injection scheme using perforations. The study shows that from the recovery factor deduced as seen in Fig 4.6. The water injector well completed with radials would have a recovery of 28-65% of the original oil in place. Radials completed with longer radial lengths recovered more oil. It was noted that a lower number of radial laterals didn't prove more efficient than the case carried out with perforations only. The cases of 2 radials, 25meters and 50 meters long didn't show a better trend than the perforation case with 28% and 33% recovery factor as compared to the 51% from the peroration case. This shows that lower amount of radials with shorter lengths would not improve the water injectivity of the water injector except if the lengths of the radials are increased or number of radials deployed in the water injector well. From the results given, only cases of 2 radials, 100 meters long, with RF=53%, 4 radials, 50 meters long with RF=62% and 4 radials, 100 meters long with RF=65% performed better than the base case with RF=51% where perforations was the completion method deployed to improve the water injectivity. Needless to say, the case where 4 radials with 25 meters long laterals produced an RF=50% which is almost equal to the values gotten from the base case. The simulation carried out elaborated on the fact that radials incorporated in water injectors will cause the injectivity of the water to be optimized so as to contact more oil and deliver the oil to the production interval. From studies carried out in recent times, it is thought that adding radials to an injector well is likened to increasing the well bore diameter of the injector well which is a conventional technique popular in the industry for stimulating wells, reducing near wellbore damage, and improving injectivity consequently leading to optimized productivity.

Fig. 4.7 and 4.8; indicates that water produced along with oil (water cut) increases with the use of longer radial laterals; the shorter the radial laterals, the lesser it is for water encroachment into the production interval would occur and hence low water cut, but these cases with shorter radial laterals produce rather small oil recovery values. Although longer radial lengths have proven from the simulation study to recover more oil, however, it also shows and allows increase water production and more water cut that shorter radials and cases with no radials as well. This can be seen at simulation period of 2000 days in Figure 4.7; the perforation completion case produced 35% water, the radial completion case for case1, case2, case3, case4, case5 and case 6 produced water cut values of 30%, 32%, 36%, 40%, 47% and 75% after 200days showing that water cut values increases with increasing number of radials as well as longer radial lengths.

Fig. 4.9 indicates that injecting water in an injector completed with radials will maintain the reservoir pressure at a longer time than that without radials. This in turn gives a more uniform residual oil recovery as a result of improved water injectivity and efficient contact of flooding fluid (water) and fluid to be flooded (oil).

Figure 4.10 indicated that the water injectivity index which is the factor used in this study to quantify the effectiveness of radials on water injectivity performance is higher for injectors completed with radials and lower for those with no radial drilling completion. The radial completion case for case1, case2, case3, case4, case5 and case 6 recorded water injectivity index of 11.6, 10.2, 10.7, 12.6, 15.7, 20.0 and 27.5 STB/D/Psi respectively. The displacement sweep efficiencies which are proportional to the recovery factor as estimated in this study due to assumptions that areal and vertical sweep efficiency is equal to 1 showed significant and increased values for injectors completed with radials. As seen in Figure 4.11, the displacement sweep efficiencies for radial completions case1, case2, case3, case4, case5 and case 6 recorded displacement sweep efficiencies of 0.28, 0.33, 0.53, 0.50, 0.62 and 0.65 while that with no radials at all (perforations) produced a displacement sweep efficiency of 0.51. The modelling and simulation of water injectivity using radial drilling has indicated intense potentials in the incorporation of radial drilling with completion of water injector wells to improve injectivity of flooding fluid, contact and sweep efficiencies as well as oil productivity and general reservoir performance.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The work in this project focused on evaluating a substitute technique to improving water injectivity in tight/damaged formation/reservoir by modelling, simulation and optimization of water injectivity through radial drilling technology in the Niger delta and to investigate whether this technology is compatible with the Niger delta petroleum system as well as efficient in improving field and reservoir performance particularly during improved and enhanced oil recovery operations. This section summarizes the most important observations from this work as follows.

i. The theoretical injectivity improvements as a result of well stimulation by radials in homogeneous reservoirs are very promising. Especially for completions with more radial laterals across 360 degrees and radials with longer lateral length, a considerable increase in injectivity or productivity can be achieved (for example a 20 and 27.5 STB/D/Psi injectivity for 4 radials and 50meters long radials and 4 radials and 100meters long respectively as compared to 11.6 STB/D/Psi injectivity for completions without radials and 10.7 and 12.6 STB/D/Psi injectivity for 2, 50m-radials and 2, 100m-radials in a vertical well). Maximum achieved injectivity increase is around 133% for 4 radials of 100 m long for a vertical well.

ii. From the analysis of the effect of radials on oil production, it was found that the inclusion of radial drilling technology into the water injector well completion increased oil productivity and consequently increased the total oil production. On the other hand, the radials appear to be very suitable for water injection schemes aimed as optimizing the residual oil recovery, it is observed that the longer the radial laterals the better the contact and the higher the volume of oil recovered

iii. Although the addition of radial drilling technology may be limited by high volume of water produced at the production well along with the oil causing problems of separation and oil treatment, it is imperative to notice the improved displacement sweep efficiency that would be encountered by the use of radial drilling technology. From the study, the inclusion of radial drilling technology would increase the displacement sweep efficiency within a range of 0.28 – 0.53 for 2 radials and 0.50 - 0.65 for 4 radials. This range is completely dependent on the size in terms of length of the radial laterals used.

5.2. Recommendations

The following recommendations have been made and are directed to the petroleum industry in general.

1. The radial drilling technology for water injectivity improvement is proven to be very effective and economical.

2. The implementation of radial drilling is still at its novel stage; EOR experts should consider its development, global acceptance and adoption in most EOR practices.

3. Radial drilling technology is a cheap innovation, and it would solve injector well stimulation problems and prove as a useful alternative to hole reaming, acidization, hydraulic fracturing and other sophisticated measures used to improve injectivity and improve injector well performance.

4. Researchers are encouraged to do more research on water injectivity simulation and modelling where areal and vertical sweep efficiencies can be deduced and also its application on horizontal/deviated wells.

5.2.1 Further Research Areas

1. Further research can be carried out to ascertain the effects of extending the radials beyond the simulated length (100m) to be able to recover more oil without damaging the wellbore.

2. Evaluation and testing of jet nozzle penetration mechanism in order to identify the best nozzle configuration.

5.3 Contribution to Knowledge

1. Many mature formations and reservoirs around the world still have as much as 30-45% of the original oil or gas in place after primary recovery. By successfully applying Radial Drilling as part of a secondary recovery plan, as much as an additional 20-30% of the oil/gas could easily be recovered.

2. Most of the simulation work done on Radial drilling was carried out on carbonate sandstone formation. From this research work it shows that if this oil

recovery technique is applied in the shaly / unconsolidated sandstone formation of the Niger Delta more oil will be recovered.

Nomenclature

A	Reservoir area
B_o	Formation volume factor of oil
B_g	Formation volume factor of gas
B_t	Two-phase formation volume factor
B_W	Formation volume factor of water
c_o	Reservoir oil compressibility
c_t	Reservoir rock compressibility
c_w	Reservoir water compressibility
G_i	Cumulative gas injected
h	Formation thickness
k	Permeability
m	Ratio of initial gas cap size to initial oil zone size
N	Initial oil in place
N_p	Oil produced
q	Production rate
r	Radius
R_p	Cumulative produced gas–oil ratio (scf/stb)
R_s	Solution gas oil ratio (scf/stb)
S_o	Oil saturation
S_{or}	Residual oil saturation
S_w	Water saturation
T	Temperature
W_e	Cumulative water influx, rb
W_i	Cumulative water injected, stb
W_p	Cumulative water produced, stb
ΔP	Pressure drop, psi

ϕ	Porosity
C_w	Conductivity of brine.

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