بسم الله الرحمن الرحيم

Sudan University of Science and Technology

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Optimization of Water Injection Wells Locations

(Case Study- Aradiba D Formation Fula North Field, Sudan)

أمثلة مواقع آبار الحفر المائي - دراسة حالة تكوين عرديب - حقل

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الاستهلال

قال تعالى:

بسم الله الرحمن الرحيم

{اقْرَأْ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ} (1) {خَلَقَ الْإِنسَانَ مِنْ عَلَقٍ} (2){اقْرَأْ وَرَبُّكَ الْأَكْرَمُ}(3){الَّذِي عَلَّمَ بِالْقَلَمِ} (4){عَلَّمَ الْإِنسَانَ مَا لَمْ يَعْلَمْ} (5)

صدق الله العظيم

سورة العلق

Dedication

To my loved parent ....

To my loved wife Dr.Fathiah............................

To my loved son Hammad.......................................

To my brothers and sisters...............................

To my teachers ....

To my colleagues...........................

ACKNOWLEDGEMENTS

I would like to thank everyone who helped me to reach this stage, I would like to express my sincere gratitude and appreciation to Dr. Elradi Abass, for his patience and continued support throughout my research. I would also like to thank Eng. Mohaned Mahjoub, for his support; Finally, I would like to express my gratitude and appreciation to all my colleagues in Sudan University of Science and Technology.

ABSTRACT

Lack of sufficient natural drive in most reservoirs has led to the practice of supplementing the natural reservoir energy by introducing some form of artificial drive, the most basic method being the injection of gas or water. This technique known as pressure maintenance or reservoir stimulation. Water flooding called secondary recovery because the process yields a second batch of oil production after a field is depleted by primary production. The main purpose of either a natural gas or a water injection process is to repressurize the reservoir and then to maintain the reservoir at a high pressure.

Water flooding is the most commonly used secondary oil recovery method for both conventional and heavy oil reservoirs because of its relative simplicity, availability of water, and cost-effectiveness .

Aradeiba-D formation pressure was rapidly decreased after it was put in production; so needed pressure support by water injection, in order to repressurize the reservoir , maximize oil production and increase oil recovery.

The resaults of asimulation study for the base case shwed that if Aadeiba-D formation production by existing system the presure will decrese rapidly and then more oil will remain in the formation ,therfore low recovery factor will get accordinaly .

Drilling new production wells in the potential area to recover more oil will increase little cumulative oil productin but also it still have a low recovery factor due to low pressure support.

The study showed that drill new wells for injecting in differentt loctions or convert selected wells with low production rate or hight water cut to injection wells as suggested scenarios it will provide reasonable resaults for presure maintenance therefore increasing the cumulative oil production.

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تجريد

عدم توفر الطاقة الطبيعية الكافية في معظم المكامن يقود لاستخدام بعض التطبيقات على المكمن لزيادة الانتاج باستخدام الطرق الاصطناعية ,في كثير من الحالات يتم حقن الماء والغاز فيما يعرف بعملية صيانة الضغط او تحسين انتاج المكمن . عملية الغمر المائي تسمى بطريقة الاستخلاص الثانوية لانها تطبق بعد المرحلة الاولية للانتاج . ان الهدف الاساسي من عملية حقن الماء او الغاز هودعم ضغط المكمن خلال فترة الانتاج.

تعتبر عملية الغمر المائي شائعة الاستخدام وواسعة الانتشار في عمليات الاستخلاص الثانوي في مكامن النفط وذلك لسهولة استخدامها وتوفرها وجدواها الاقتصادية.

انخفاض الضغط بصورة سريعة في طبقة عرديبة مع بداية الانتاج جعل من الضروري اجراء عمليات صيانة لتدعيم ضغط المكمن بغرض زيادة الانتاج الكلي للمكن وزيادة معامل الاستخلاص فيه .

من الدراسة اتضح انه في حالة استمرار الانتاج دون اجراء اي عمليات تحسين للمكن سيزداد انخاض الضغط بصورة اكبر مما يؤدي الى ضعف الانتاج الكلي والحصول على معامل استخلاص ضعيف.

ان حفر ابار انتاج جديدة في طبقة عرديبة يزيد الانتاج الكلي قليلا الا ان معامل الاسخلاص سيظل منخفضا نسبة لانخفاض ضغط المكمن.

اوضحت الدراسة ان عملية تحويل بعض الابار المنتجة ذات الانتاجية المنخفضة او ذات الانتاج العالي من الماء الي ابار حقن مائي تحقق نتايج جيدة بالنسبة لتدعيم ضغط المكمن وزيادة الانتاج الكلي للزيت ومعامل الاستخلاص.

كذلك اوضحت الدراسة ان عملية حفر ابار حقن في مواقع مختارة لانماط الغمر المختلفة اعطت نتائج جيدة بالنسبة لدعم ضغط المكمن وزيادة الانتاج الكلي للزيت ومعامل الاستخلاص.

Nomenclature and Abbreviations

M= mobility ratio

a= distance between like wells (injection or production) in a row, ft

d= distance between adjacent rows of injection and production wells, ft

RF = overall recovery factor

E_D = displacement efficiency

E_A = areal sweep efficiency

E_V = vertical sweep efficiency

A_S= the swept area ft^2

A_T = the total area ft^2

λ_o,λ_w and λ_g = mobility of oil, water and gas, respectively

k_o, k_w and k_g = effective permeability to oil, water and gas, respectively, md

k_{ro}, k_{rw} and k_{rg} = relative permeability to oil, water and gas, respectively

k = absolute permeability, md

bbl = reservoir barel.

W_{inj}= Cumulative water injected, bbl

S_{wi} = initial water saturation%

K_h = horizontal permeability, md

K_V=vertical permeability, md

i_w = water injection rate, bbl/d

h = formation thickness, ft

μ_w = water viscosity at reservoir conditions, cp.

r = radius of the external boundary, ft

r_w = well radius, ft

μ_o= oil viscosity at reservoir conditions, cp

r_e= outer radius of the oil bank, ft.

cp= centy poise.

EOR= enhanced oil recovery.

SOR = secondary oil recovry

OOIP = orignal oil in place, bbl.

API = American petroeum inistitute.

BHP = Bottom hole pressure, psi.

FN = Fula north.

OWC = Oil water contact, ft.

SCAL = spectial core analyses

ROPT= region oil prodution total, bbl.

RWPT = region water prodution total, bbl.

ROE = region recovery factor, %.

RPR = region average pressure, psi.

GNPOC = Greater Nile Petroleum Operating Company.

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Chapter One

Introduction

Chapter One
Introduction

1-1 Introduction

Petroleum reservoir is accumulations of oil and gas in underground traps that are formed by structural and /or stratigraphic features. A reservoir is the portion of the trap that contains the oil and/or gas in a hydraulically connected system. Many reservoirs are hydraulically connected to water-bearing rocks or aquifers that provide a source of natural energy to aid in hydrocarbon recovery. Oil and gas may be recovered by: fluid expansion, fluid displacement, gravity drainage, and or capillary expulsion. In the case of a reservoir with no aquifer (which is referred to as volumetric reservoir), hydrocarbon recovery occurs primary by fluid expansion, which, in case of oil, may be aided by gravity drainage. If there is water influx or encroachment from the aquifer, recovery occurs mainly by the fluid displacement mechanism which may be aided by gravity drainage or capillary expulsion. In many instances, recovery of hydrocarbon occurs by more than one mechanism .When the natural reservoir energy has been depleted, it becomes necessary to augment the natural energy with an external source. This is usually accomplished by the injection of fluids, either a natural gas or water. The use of this injection scheme is called a secondary recovery operation. When water injection is the secondary recovery process, the process is referred to as water flooding. The main purpose of either a natural gas or a water injection process is to repressurize the reservoir and then to maintain the reservoir at a high pressure. Hence, the term pressure maintenance is sometimes used to describe a secondary recovery process. Tertiary Recovery (EOR) enables to recover more oil than would be obtained by the conventional recovery method depending on the reservoir and the method of EOR process applied.

1-2 Problem statement:

Fula North Field is located in the southern part of Fula sub-basin of Block 6 of Sudan. It contributes the highest production potential in block 6. There are three producing formation of Fula North field which are Bentiu and Aradeiba formation (Heavy oil) and Abu Gabra formation

(Light oil). Aradeiba formation is associated with weak edge water aquifer and its pressure rapidly decreased after it was put in production so it needed pressure support by water injection, in order to maximize oil production and increase oil recovery (Petro-Energy, 2011).

1-3 Objectives

The main objectives of this research are:

1-3-1 To predict the parameters of Aradieba-D formation under water flooding process using Eclipse simulator. These parameters are: Cumulative oil production, cumulative water production, and recovery factor and formation pressure.

1-3-2 To select the optimum flooding pattern for Aradieba-D formation by comparing its parameters with different pattern of injection wells locations using Eclipse simulator.

1-4 Research Outline:

Chapter One: Introduction to the study, research objectives and problem statement. Chapter Two this chapter includes many previous study and theoretical background of water flooding. Chapter Three consist of materials and methods include the available data of the Aradeiba D formation, methodology, model information, history matching and simulation. Chapter Four showed the simulation study results and its discussion which are FPR, FOPT, ROE and FWPT. Chapter Five contains the conclusion and recommendation of the simulation study.

Chapter Two

Theoretical Background and Literature Review

Chapter Two
Theoretical Background and Literature Review

2-1 Primary Recovery

The recovery of oil by any of the natural drive mechanisms is called primary recovery. The term refers to the production of hydrocarbons from a reservoir without the use of any process (such as fluid injection) to supplement the natural energy of the reservoir.

Muskat (1907) defines primary recovery as the production period "beginning with the initial field discovery and continuing until the original energy sources for oil expulsion are no longer alone able to sustain profitable producing rates.

There are basically six driving mechanisms that provide the natural energy necessary for oil recovery:

I. Rock and liquid expansion drive
II. Depletion drive
III. Gas cap drive
IV. Water drive
V. Gravity drainage drive
VI. Combination drive

2-1-1Rock and Liquid Expansion

When an oil reservoir initially exists at a pressure higher than its bubble point pressure, the reservoir is called an under saturated oil reservoir. At pressures above the bubble-point pressure, crude oil, connate water, and rock are the only materials present. As the reservoir pressure declines, the rock and fluids expand due to their individual compressibilities. The reservoir rock compressibility is the result of two factors: Expansion of the individual rock grains and formation compaction. Both of the above two factors are the results of a decrease of fluid pressure within the pore spaces, and both tend to reduce the pore volume through the reduction of the porosity.

As the expansion of the fluids and reduction in the pore volume occur with decreasing reservoir pressure, the crude oil and water will be forced out of the pore space to the wellbore. Because liquids and rocks are only slightly compressible, the reservoir will experience a rapid pressure decline. The oil reservoir under this driving mechanism is characterized by a constant gas-oil ratio that is equal to the gas solubility at the bubble point pressure.

This driving mechanism is considered the least efficient driving force and usually results in the recovery of only a small percentage of the total oil in place.

2-1-2 The Depletion Drive Mechanism

This driving form may also be referred to by the following various terms: Solution gas drive, dissolved gas drive or internal gas drive.

In this type of reservoir, the principal source of energy is a result of gas liberation from the crude oil and the subsequent expansion of the solution gas as the reservoir pressure is reduced. As pressure falls below the bubble-point pressure, gas bubbles are liberated within the microscopic pore spaces. These bubbles expand and force the crude oil out of the pore space as shown conceptually in Figure (2-1).

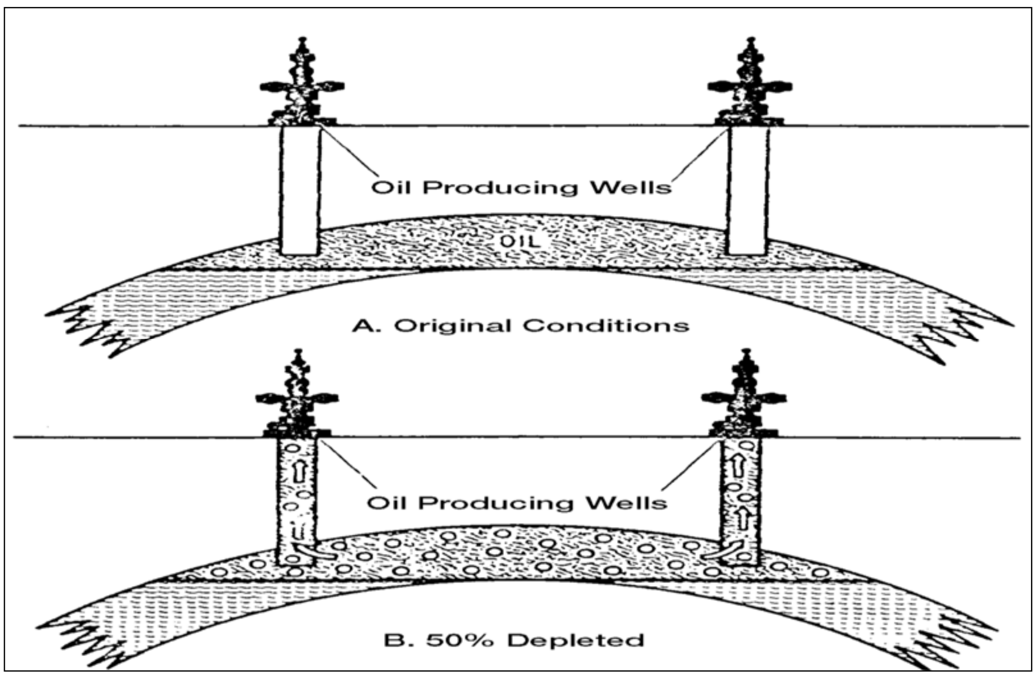

Figure 2-1. Solution (Depletion) Gas Drive Reservoir. (After Clark, N. J., 1969).

2-1-3 Gas Cap Drive

Gas-cap-drive reservoirs can be identified by the presence of a gas cap with little or no water drive as shown in Figure (2-2).

Due to the ability of the gas cap to expand, these reservoirs are characterized by a slow decline in the reservoir pressure. The natural energy available to produce the crude oil comes from the following two sources:

I. Expansion of the gas-cap gas

II. Expansion of the solution gas as it is liberated

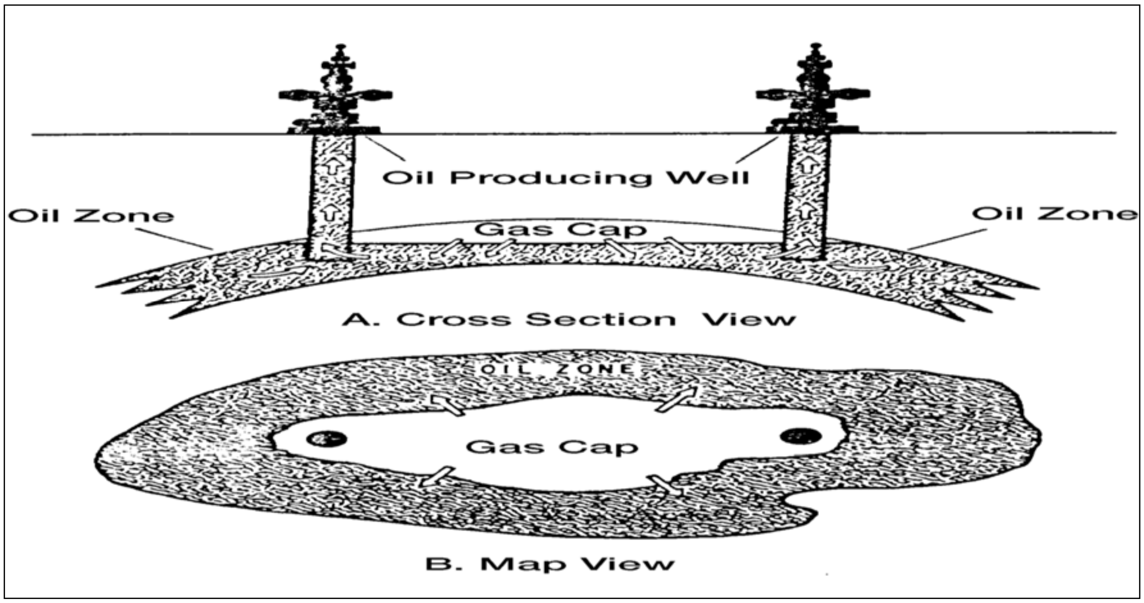

Figure 2-2. Gas-Cap-Drive Reservoir. (**After Clark, N. J., 1969.)**

2-1-4 The Water-Drive Mechanism

Many reservoirs are bounded on a portion or all of their peripheries by water bearing rocks called aquifers. The aquifers may be so large compared to the reservoir they adjoin as to appear infinite for all practical purposes, and they may range down to those so small as to be negligible in their effects on the reservoir performance. The aquifer itself may be entirely bounded by impermeable rock so that the reservoir and aquifer together form a closed (volumetric) unit. On the other hand, the reservoir may be outcropped at one or more places where it may be replenished by surface water. Water drives are also classified as edge water or bottom water drives, depending on the nature and location of the water encroachment into the reservoir. Bottom water occurs directly beneath the oil and edge water occurs off the flanks of the structure at the edge of the oil.

2-1-5 The Gravity-Drainage Drive Mechanism

Gravitational forces can be a major factor in oil recovery if the reservoir has sufficient vertical relief and vertical permeability. The effectiveness of gravitational forces will be limited by the rate at which fluids are withdrawn from the reservoir. If the rate of withdrawal is appreciably greater than the rate of fluid segregation, then the effects of gravitational forces will be minimized in order to take maximum advantage of the gravity-drainage-producing mechanism, wells should be located as structurally low as possible. This will result in maximum conservation of the reservoir gas. Factors that affect ultimate recovery from gravity-drainage reservoirs are:

I. Permeability in the direction of dip
II. Dip of the reservoir
III. Reservoir producing rates
IV. Oil viscosity
V. Relative permeability characteristics

2-1-6 The Combination-Drive Mechanism

The driving mechanism most commonly encountered is one in which both water and free gas are available in some degree to displace the oil toward the producing wells.

Two combinations of driving forces can be present in combination drive reservoirs. These are (1) depletion drive and a weak water drive and; (2) depletion drive with a small gas cap and a weak water drive. Then, of course, gravity segregation can play an important role in any of the aforementioned drives. Combination-drive reservoirs can be recognized by the occurrence of a combination of some of the following factors:

I. Relatively rapid pressure decline. Water encroachment and/or external gas-cap expansion are insufficient to maintain reservoir pressures.
II. Water encroaching slowly into the lower part of the reservoir. Structurally low producing wells will exhibit slowly increasing water producing rates.
III. If a small gas cap is present the structurally high wells will exhibit continually increasing gas-oil ratios, provided the gas cap is expanding. It is possible that the gas cap will shrink due to production of excess free gas, in which case the structurally high wells will exhibit a decreasing gas-oil ratio. This condition should be avoided whenever possible, as large volumes of oil can be lost as a result of a shrinking gas cap.

IV. A substantial percentage of the total oil recovery may be due to the depletion-drive mechanism. The gas-oil ratio of structurally low wells will also continue to increase due to evolution of solution gas throughout the reservoir, as pressure is reduced.

V. Ultimate recovery from combination-drive reservoirs is usually greater than recovery from depletion-drive reservoirs but less than recovery from water-drive or gas-cap-drive reservoirs. Actual recovery will depend upon the degree to which it is possible to reduce the magnitude of recovery by depletion drive. In most combination-drive reservoirs, it will be economically feasible to institute some type of pressure maintenance operation, either gas injection, water injection, or both gas and water injection, depending upon the availability of the fluids.

2-2 Secondary Recovery

Lack of sufficient natural drive in most reservoirs has led to the practice of supplementing the natural reservoir energy by introducing some form of artificial drive, the most basic method being the injection of gas or water. This technique known as Pressure Maintenance or Reservoir Stimulation, Water flooding, called secondary recovery because the process yields a second batch of oil after a field is depleted by primary production (GNPOC, 2005).

The practice of water flooding apparently began accidentally as early as 1890, when operators realized that water entering the productive formation was stimulating production. The practice of water flooding expanded rapidly after 1921. The earlier slow growth of water flooding was due to several factors. The oil demand was less and impact of water flooding on oil production was immense (GNPOC, 2005).

However, after 1921 demand of oil picked up and interest for water flooding grew many folds Separate wells are used for this injection water flooding is now the principal SOR method and it expected to produce between 20% to 40% of the OOIP, Gas injection developed about the same time as the Water flooding and was a competing process in some reservoirs (GNPOC, 2005).

2-2-1Water Flooding

Water flooding is the most commonly used secondary oil recovery method for both conventional and heavy oil reservoirs because of its relative simplicity, availability of water, and cost-effectiveness. In the case of heavy oil, water is combined with “thermal energy injection” either as hot water or steam, but this is usually treated as a tertiary oil recovery method. Like primary recovery, the efficiency of water flooding is determined by intrinsic factors, such as hydrocarbon properties, microscopic oil displacement efficiency, rock/fluid properties, and reservoir heterogeneities. Water flooding, called secondary recovery because the process yields a second batch of oil after a field is depleted by primary production. (P. Zitha et al.**).**

Water injection process may be designed to dispose of brine water, conduct a pressure maintenance project to maintain the reservoir pressure when expansion of an aquifer or gas cap is insufficient to maintain pressure or implement a water drive or water flood of oil after primary recovery (Williamc.Lyons, 1996).

2-2-1-1 Development of Water Flooding

The discovery of crude oil by Edwin L. Drake at Titusville, PA, on Aug. 27, 1859, marked the beginning of the petroleum era. Although the first oil well produced about 10 B/D [1.6 m3/d], within 2 years other wells were drilled that flowed thousands of barrels per day , Production rates from these shallow Pennsylvania reservoirs declined rapidly as reservoir energy was depleted. Recovery was a small percentage of the amount of oil estimated to be initially in place. As early as 1880, Carll raised the possibility that oil recovery might be increased by the injection of water into the reservoir to displace oil to producing wells. The practice of waterflooding apparently began accidentally. The experience in the Bradford field, PA, is typical. Many wells were abandoned in the Bradford field following the flush production period of the 1880's. Some were abandoned by pulling casing without plugging, while in other wells the casing was left in the wells, where it corroded. In both cases, fresh water from shallower horizons apparently entered the producing interval. Water injection began, perhaps as early as 1890, when operators realized that water entering the productive formation was stimulating production. By 1907, the practice of water injection had an appreciable impact on oil production from the Bradford field. The first flooding pattern, termed a circle flood, consisted of injecting water into a well until surrounding producing wells watered out. The wateredout production wells were converted to injection to create an expanding circular waterfront. Many operators were against the injection of water into the sand.

A Pennsylvania law requiring plugging of abandoned wells and dry holes to prevent water from entering oil and gas sands was construed as prohibiting waterflooding, so waterflooding was done secretly. In 1921, the Pennsylvania legislature legalized the injection of water into the Bradford sands.

The practice of water injection expanded rapidly after 1921. The circle-flood method was replaced by a line flood, in which two rows of producing wells were staggered on both sides of an equally spaced row or line of water intake wells. By 1928, the line flood was replaced by a new method termed the five-spot because of the resemblence of the pattern to the five spots on dice. Waterflooding was quite successful in the Bradford field.Water-injection operations were reported in Oklahoma in 1931, in Kansas in 1935, and in Texas in 1936.

The slow growth of water injection was caused by several factors. In the early days, waterflooding was understood poorly. Gas injection developed about the same time as waterflooding and was a competing process in some reservoirs. Major discoveries of crude oil in the U.S. in the 1920's and 1930's led to proration in several states. The capability to produce oil was much greater than market demand. Consequently, primary depletion of many reservoirs was controlled by market demand.

In the intervening years, major oil discoveries were made throughout the world. Shut-in production capacity exceeded demand. Large supplies of low-cost imported oil also prolonged the primary life of reservoirs, delaying implementation of water injection, Interest in waterflooding developed in the late 1940's and early 1950's as reservoirs approached economic limits and operators sought to increase reserves. By 1955waterflooding was estimated to contribute more than 750,000 B/D [119 200 m3 /d] out of a total production rate of 6.6 million B/D [106 m3/d} in the U.S. Waterflooding is practiced extensively throughout the world. In the U.S. as much as half of the current oil production is thought to be the result of water injection (Forrest F. Craig Jr., 1993, The Reservoir Engineering Aspect of Water Flooding, SPE Monograph, Vol. 3).

2-2-1-2 Important of Water Flooding

Once the primary energy of the reservoir tends to deplete it becomes necessary to maintain the pressure inside the reservoir to achieve optimum production and maximise ultimate recovery. In such condition the pressure maintenance can be done by injecting water into the reservoir which is compatible to the formation water present in the reservoir through several water injection wells. In this process, the primary objective is to fill the voidage created by the produced oil fractions thus avoiding the reservoir pressure to decrease with the increased production, displacing fluid is injected in the oil zone through the surrounding water injection wells creating an edge water drive flooding oil towards the production well. For better efficiency, the pressure of the reservoir should be such that no secondary gas cap is formed.

2-2-1-3 Disadvantages of Water Injection

I. Reaction of injected water with the formation water can cause formation damage.

II. Corrosion of surface and sub-surface equipment.

2-2-1-4 Water Flooding Candidate Reservoir Conditions

Thomas, Mahoney, and Winter (1989) pointed out that in determining the suitability of a candidate reservoir for waterflooding, the following reservoir characteristics must be considered: Reservoir geometry, fluid properties, reservoir depth, lithology and rock properties, fluid saturations, reservoir uniformity and pay continuity and Primary reservoir driving mechanisms.

I. Reservoir Geometry

The areal geometry of the reservoir will influence the location of wells and, if offshore, will influence the location and number of platforms required.

II. Fluid Properties

The physical properties of the reservoir fluids have pronounced effects on the suitability of a given reservoir for further development by waterflooding. The viscosity of the crude oil is considered the most important fluid property that affects the degree of success of a waterflooding project. The oil viscosity has the important effect of determining the mobility ratio that, in turn, controls the sweep efficiency.

III. Reservoir Depth

Reservoir depth has an important influence on both the technical and economic aspects of a secondary or tertiary recovery project. Maximum injection pressure will increase with depth. The costs of lifting oil from very deep wells will limit the maximum economic water–oil ratios that can be tolerated, thereby reducing the ultimate recovery factor and increasing the total project operating costs. On the other hand, a shallow reservoir imposes a restraint on the injection pressure that can be used, because this must be less than fracture pressure. In waterflood operations, there is a critical pressure (approximately 1 psi/ft of depth) that, if exceeded, permits the injecting water to expand openings along fractures or to create fractures. This results in the channeling of the injected water or the bypassing of large portions of the reservoir matrix. Consequently, an operational pressure gradient of 0.75 psi/ft of depth normally is allowed to provide a sufficient margin of safety to prevent pressure parting.

IV. Lithology and Rock Properties

Reservoir lithology and rock properties that affect flood ability and success are: porosity, permeability, clay content and net thickness

In some complex reservoir systems, only a small portion of the total porosity, such as fracture porosity, will have sufficient permeability to be effective in water-injection operations. In these cases, a water-injection program will have only a minor impact on the matrix porosity, which might be crystalline, granular, or vugular in nature. Although evidence suggests that the clay minerals present in some sands may clog the pores by swelling and deflocculating when waterflooding is used, no exact data are available as to the extent to which this may occur. Tight (low-permeability) reservoirs or reservoirs with thin net thickness possess water-injection problems in terms of the desired water injection rate or pressure.

V. Fluid Saturations

A high oil saturation that provides a sufficient supply of recoverable oil is the primary criterion for successful flooding operations. Note that higher oil saturation at the beginning of flood operations increases the oil mobility that, in turn, gives higher recovery efficiency.

VI. Reservoir Uniformity and Pay Continuity

If the formation contains astratum of limited thickness with a very high permeability, rapid channeling and bypassing will develop. Unless this zone can be located and shut off, the producing water–oil ratios will soon become too high for the flooding operation to be considered profitable. The lower depletion pressure that may exist in the highly permeable zones will also aggravate the water-channeling tendency due to the high permeability variations. Moreover, these thief zones will contain less residual oil than the other layers, and their flooding will lead to relatively lower oil recoveries than other layers.Areal continuity of the pay zone is also a prerequisite for a successful waterflooding project. Isolated lenses may be effectively depleted by a single well completion, but a flood mechanism requires that both the injector and producer be present in the lens. Breaks in pay continuity and reservoir anisotropy caused by depositional conditions, fractures, or faulting need to be identified and described before determining the proper well spanning and the suitable flood pattern orientation.

VII. Primary Reservoir Driving Mechanisms

The primary drive mechanism and anticipated ultimate oil recovery should be considered when reviewing possible waterflood prospects:

Water-Drive Reservoirs

That are classified as strong water-drive reservoirs are not usually considered to be good candidates for waterflooding because of the natural ongoing water influx. However, in some instances a natural water drive could be supplemented by water injection in order to:

1. Support a higher withdrawal rate
2. Better distribute the water volume to different areas of the field to achieve more uniform areal coverage
3. Better balance voidage and influx volumes.

Gas-Cap Reservoirs

Are not normally good waterflood prospects because the primary mechanism may be quite efficient without water injection. Smaller gas-cap drives may be considered as waterflood prospects, but the existence of the gas cap will require greater care to prevent migration of displaced oil into the gas cap. This migration would result in a loss of recoverable oil due to the establishment of residual oil saturation in pore volume, which previously had none. If a gas cap is repressured with water, a substantial volume may be required for this purpose, thereby lengthening the project life and requiring a higher volume of water. However, the presence of a gas cap does not always mean that an effective gas-cap drive is functioning. If the vertical communication between the gas cap and the oil zone is considered poor due to low vertical permeability, a waterflood may be appropriate in this case.

Analysis of past performance, together with reservoir geology studies, can provide insight as to the degree of effective communication. Natural permeability barriers can often restrict the migration of fluids to the gas cap. It may also be possible to use selective plugging of input wells to restrict the loss of injection fluid to the gas cap.

Solution Gas-Drive Mechanisms

Generally are considered the best candidates for waterfloods. Because the primary recovery will usually be low, the potential exists for substantial additional recovery by water injection.

Volumetric Under Saturated Oil Reservoirs

These reservoirs will offer an opportunity for greatly increasing recoverable reserves if other conditions are favorable.

2-2-1-5 Optimum Time to Water Flooding

Many calculations are used as procedure to determine time to water flooding:

I. Anticipated oil recovery
II. Fluid production rates
III. Monetary investment
IV. Availability and quality of the water supply
V. Costs of water treatment and pumping equipment
VI. Costs of maintenance and operation of the water installation facilities
VII. Costs of drilling new injection wells or converting existing production wells into injectors

These calculations should be performed for several assumed times and the net income for each case determined. The scenario that maximizes the profit and perhaps meets the operator's desirable goal is selected.

2-2-1-6 Water Flooding Design

Water flooding is similar to water injection including selection parameters of the displacing fluid, the only difference being the displacing phenomenon.

The design of a waterflood involves both technical and economic considerations; Economic analyses are based on estimates of waterflood performance. These estimates may be rough or sophisticated depending on the requirements of a particular project and the philosophy of the operator. Technical analysis of a waterflood produces estimates of the volumes of fluids and rates. Those estimates are used also for sizing equipment and fluid-handling systems; design includes arrangements for proper disposal of produced water.

2-2-1-7 Water Flooding Design Steps

I. Evaluation of the reservoir, including primary production performance.
II. Selection of potential flooding plans.
III. Estimation of injection and production rates.
IV. Projection of oil recovery over the anticipated life of the project for each flooding plan.
V. Identification of variables that may cause uncertainty in the technical analysis.

2-2-1-8 Selection of Water Flooding Pattern

One of the first steps in designing a waterflooding project is flood pattern selection. The objective is to select the proper pattern that will provide the injection fluid with the maximum possible contact with the crude oil system. This selection can be achieved by:

I. Converting existing production wells into injectors or
II. Drilling infill injection wells.

2-2-1-9 Water Flood Patterns Selection Criteria

I. Reservoir heterogeneity and directional permeability
II. Direction of formation fractures
III. Availability of the injection fluid (gas or water)
IV. Desired and anticipated flood life
V. Maximum oil recovery
VI. Well spacing, productivity, and infectivity.

2-2-1-10 Water Flood Pattern Methodology

I. Irregular injection patterns
II. Peripheral injection patterns
III. Regular injection patterns
IV. Crestal and basal injection patterns

Irregular Injection Patterns

Willhite (1986) points out that surface or subsurface topology and/or the use of slant-hole drilling techniques may result in production or injection wells that are not uniformly located. In these situations, the region affected by the injection well could be different for every injection well. Some small reservoirs are developed for primary production with a limited number of wells and when the economics are marginal, perhaps only few production wells are converted into injectors in a nonuniform pattern. Faulting and localized variations in porosity or permeability may also lead to irregular patterns.

Peripheral Injection Patterns

In peripheral flooding, the injection wells are located at the external boundary of the reservoir and the oil is displaced toward the interior of the reservoir, as shown in Figure (2-3).

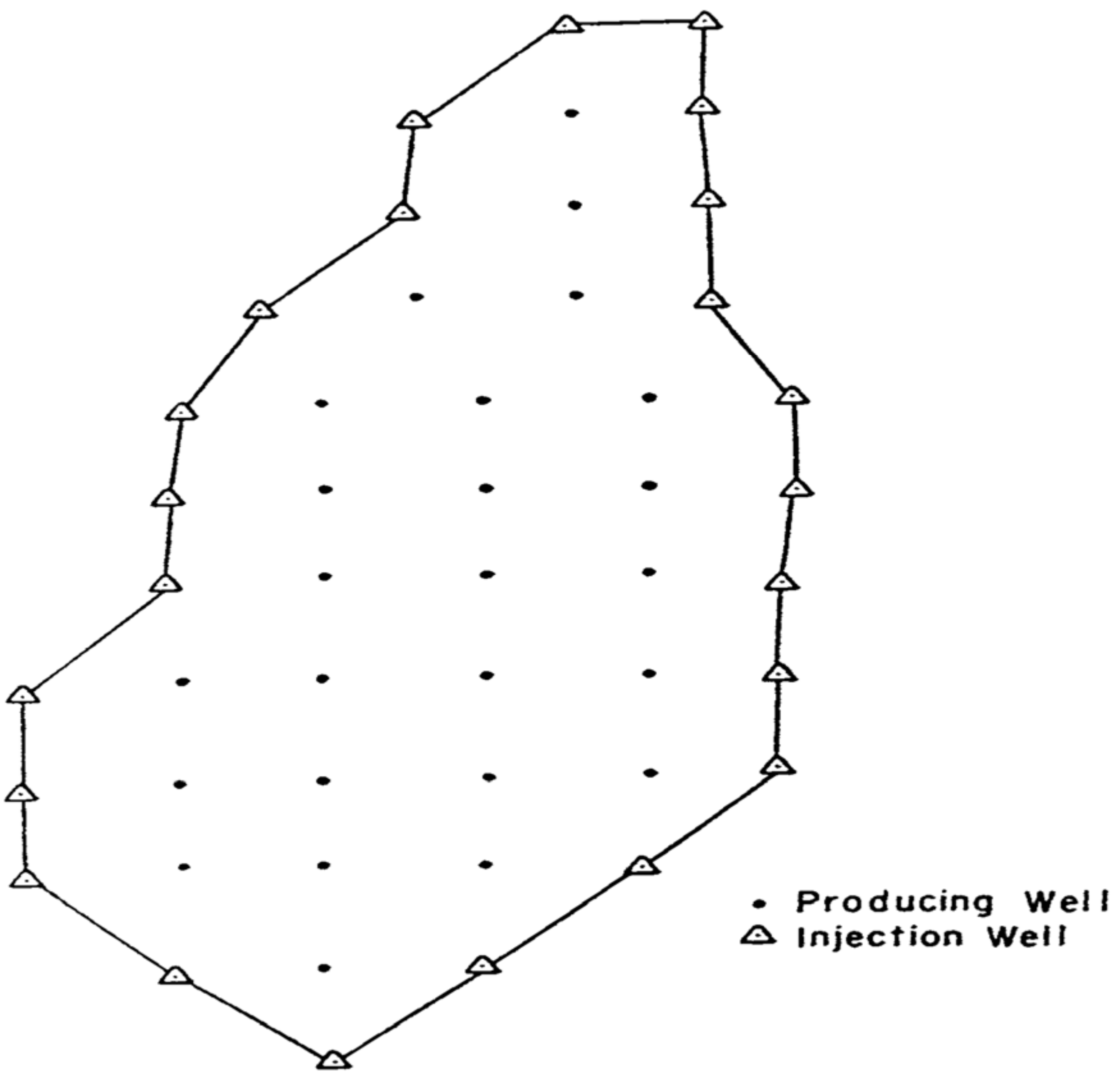

Figure 2-3 Typical Peripheral Waterflood. (After Cole, F., 1969.)

Regular Injection Patterns

I. Direct Line Drive

The lines of injection and production are directly opposed to each other. The pattern is characterized by two parameters: a = distance between wells of the same type, and d = distance between lines of injectors and producers.

II. Staggered Line Drive

The wells are in lines as in the direct line, but the injectors and producers are no longer directly opposed but laterally displaced by a distance of a/2.

III. Five Spot

This is a special case of the staggered line drive in which the distance between all like wells is constant, i.e., a = 2d. Any four injection wells thus form a square with a production well at the center.

IV. Seven Spot.

The injection wells are located at the corner of a hexagon with a production well at its center.

V. Nine Spot.

This pattern is similar to that of the five spot but with an extra injection well drilled at the middle of each side of the square. The pattern essentially contains eight injectors surrounding one producer.

The patterns termed inverted have only one injection well per pattern. This is the difference between normal and inverted well arrangements. Note that the four-spot and inverted seven-spot patterns are identical. Figure 2-4 show the different regular injection flood patterns.

Crestal and Basal Injection Patterns

In crestal injection, as the name implies, the injection is through wells located at the top of the structure. Gas injection projects typically use a crestal injection pattern. In basal injection, the fluid is injected at the bottom of the structure.

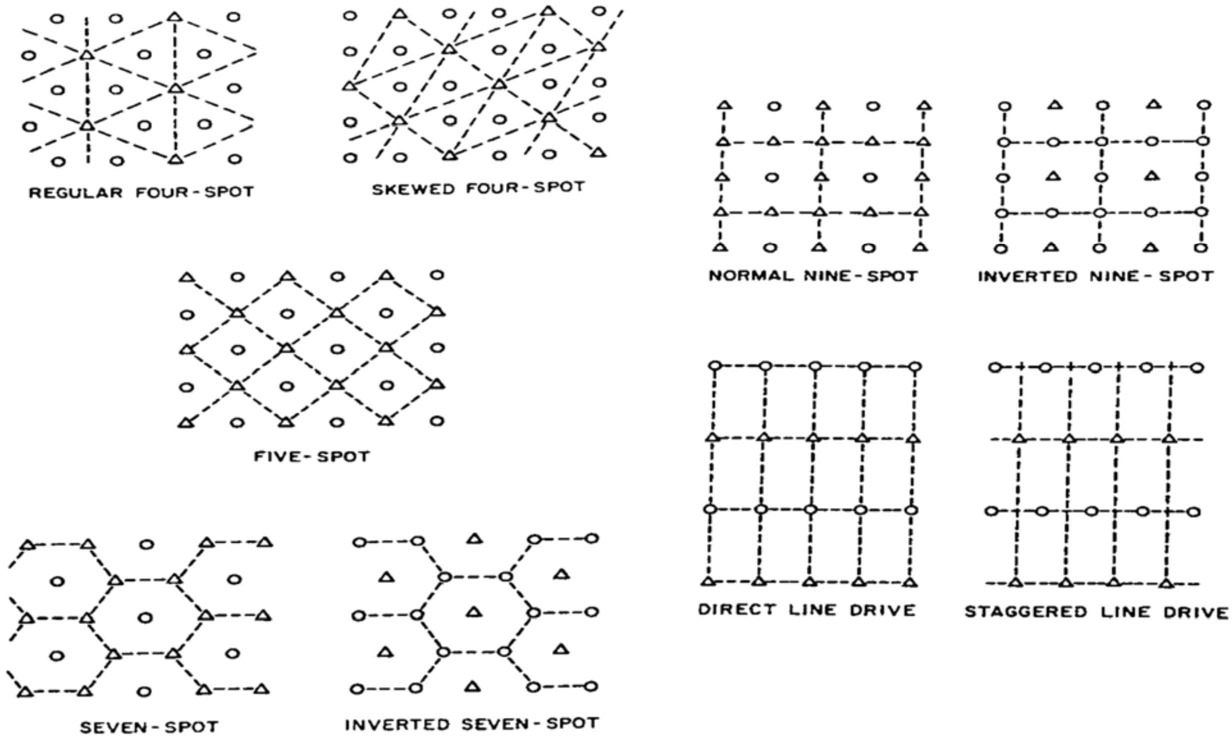

Figure 2-4 Flooding Patterns (Craig, F.F. Jr. 1971)

2-2-1-11 Overall Recovery Efficiency of Water Flooding

The overall recovery factor (efficiency) RF of the water flooding or any secondary or tertiary oil recovery method is the product of a combination of three individual efficiency factors displacement efficiency, areal sweep efficiency and vertical sweep efficiency as given by the following generalized expression:

$$RF = E_D E_A\ E_V \qquad (2\text{-}1)$$

Where RF = overall recovery factor

E_D = displacement efficiency

E_A = areal sweep efficiency

E_V = vertical sweep efficiency

Displacement Efficiency of Water Flooding

The fraction of movable oil that has been displaced from the swept zone at any given time or pore volume injected. Because an immiscible gas injection or waterflood will always leave behind some residual oil, ED will always be less than 1.0.

Vertical Sweep Efficiency

The fraction of the vertical section of the pay zone that is contacted by injected fluids. The vertical sweep efficiency is primarily a function of:

I. Vertical heterogeneity
II. Degree of gravity segregation
III. Fluid mobilities
IV. Total volume injection

Areal Sweep Efficiency

The fractional area of the pattern that is swept by the displacing fluid mathematically expression as:

$$E_A = \frac{A_S}{A_T} \qquad (2\text{-}2)$$

Where:

E_A = areal sweep efficiency
A_S= the swept area ft^2
A_T = the total areaft^2

It increases steadily with injection from zero at the start of the flood until breakthrough occurs, after which E_A continues to increase at a slower rate. The areal sweep efficiency depends basically on the following three main factors:

I. Mobility ratio M
II. Flood pattern
III. Cumulative water injected W_{inj}

2-2-1-12 Mobility and Mobility Ratio

The mobility of any fluid defined as the ratio of the effective permeability of the fluid to the fluid viscosity:

$$\lambda_o = \frac{k_o}{\mu_o} = \frac{kk_{ro}}{\mu_o} \qquad (2\text{-}3)$$

$$\lambda_w = \frac{k_w}{\mu_w} = \frac{kk_{rw}}{\mu_w} \quad \text{(2-4)}$$

$$\lambda_g = \frac{k_g}{\mu_g} = \frac{kk_{rg}}{\mu_g} \quad \text{(2-5)}$$

Where:

λ_o,λ_w and λ_g = mobility of oil, water and gas, respectively

k_o, k_w and k_g = effective permeability to oil, water and gas, respectively, md

k_{ro}, k_{rw} and k_{rg} = relative permeability to oil, water and gas, respectively

μ_o , μ_w *and* μ_g = viscosity of oil, water and gas, respectively, cp

k = absolute permeability, md

The mobility ratio M is defined as the mobility of the displacing fluid to the mobility of the displaced fluid and mathematically:

$$M = \frac{\lambda_{displacing}}{\lambda_{displaced}} \quad \text{(2-6)}$$

For waterflooding then:

$$M = \frac{\lambda_w}{\lambda_o} \quad \text{(2-7)}$$

Substituting for λ_o and λ_w :

$$M = \frac{k_{rw}}{k_{ro}}\frac{\mu_o}{\mu_w} \quad \text{(2-8)}$$

2-2-1-13 Relative Permeability

Define as the ratio of the effective permeability for a particular fluid to a reference or base permeability of the rock and it is characteristics are a direct measure of the ability of the porous system to conduct on fluid when one or more fluids are present. These flow properties are the composite effect of pore geometry, wettability, fluid distribution, and saturation history .mathematical expression:

$K_{ri=}\frac{K_i}{K}$ ……………………………………………………………………………...… (2-9)

Where:

$K_{ri=}$ Relative permeability of the fluid i.

K_i= effective permeability of the fluid i, md

K = base permeability of the rock or absolute permeability, md

2-2-2Gas Injection

Historically, both natural gas and air have been used in gas injection projects, and in some cases nitrogen and flue gases have been injected. Many of the early gas injected projects used air to immiscibly displace crude oil from reservoirs. The injection of hydrocarbon gas may result in a miscible or immiscible process depending on the composition of the injected gas and crude oil displaced reservoir pressure, and reservoir temperature. Hydrocarbon miscible injection is considered as an enhanced recovery process. Although the ultimate oil recovery from immiscible gas injection projects will normally be lower than for water flooding, gas injection may be the only alternative for secondary recovery under certain circumstances .if permeability is very low, the rate of water injection may be so low that gas injection is preferred. In reservoir with swelling clays, gas injection may be preferable. In steeply dipping reservoirs, gas that is injected up dip can very efficiently displace crude oil by a gravity drainage mechanism; this technique is very effective in low permeability formations such as fractured shales. In thick formations with little dip, injected gas (because of its lower density) will tend to override and result in vertical segregation if the vertical permeability is more than about 200 md. In thin formations especially if primary oil production has been by solution gas drive, gas may be injected into a number of wells in the reservoir on a well pattern basis; this dispersed gas injection operation attempts to bank the oil in a frontal displacement mechanism. In addition to the external gas injection into reservoirs with dip as just described (which may be into a primary or secondary gas cap), a variation called attic oil recovery involves injection of gas into a lower structural position. If there is sufficient vertical permeability, the injected gas will migrate upward to create a secondary gas cap that can displace the oil downward where it is recovered in wells that are already drilled Williamc (Lyons, 1996).

2-3 Tertiary (Enhanced Oil) Recovery

Enhanced oil recovery (EOR) is an engineering activity concerned with increasing the recovery of hydrocarbons from various types of petroleum reservoirs and it is generally refers to oil recovery over and above that obtained through the natural energy of the reservoir (Erle C.Donaldson, 1989). According to American Petroleum Institute estimates of original oil in place and ultimate recovery, approximately two-thirds of the oil discovered will remain in an average reservoir after primary and secondary production .The EOR processes can be divided into four major categories:

Chemical, thermal, miscible and other.

2-4 Literature Review

Many studies were directed to evaluate and develop the water flooding include relations between sweep efficiency and reservoir or fluid characterization parameters, breakthrough. Some these studies listed below.

Pitts, Gerald N., Crawford, Paul B. (1971):

This study describes the possible effect of heterogeneous media on the areal sweep efficiencies for different pattern distributions. The direct streamline method was applied to three well known reservoir patterns: five-spot, direct-line drive (square) and staggered line drive patterns. Each pattern was simulated with three different permeability ranges. The ranges were (a) 100 to 50 md, (b) 100 to 1.0 md and (c) 100 to 0. 1 md. These distributions were used along with a random process to distribute the permeabilities throughout a 20 x 20 matrix yielding a 400 block system.

It was found that areal sweeps for very heterogeneous five-spot patterns were reduced to nearly 25 percent or about one-third of the sweep expected in homogeneous media.

The heterogeneous staggered line drive pattern gave surprisingly low areal sweeps, the average areal sweep for the (100 to 50) md range was 76 percent, 65 percent for the (100 to 1.0) md range, and 26 percent sweep for the (100 to 0.1) md range. The two smaller permeability ranges resulted in a larger areal sweep for the staggered line-drive than the five-spot or direct-line drive patterns. However, for the wide permeability range of (100 to 0. 1), about the same areal sweep was obtained for the staggered-line drive and the five-spot patterns, but both gave smaller sweeps than the direct-line drive square pattern.

Brigham, William E., Kovscek, Anthony R., Wang, Yuandong (1998):

In this particular research it was found that for unit mobility ratio, unfavorable mobility ratios and some favorable mobility ratios (M >□0.3) in a staggered line-drive pattern has higher areal sweep efficiency than a five-spot pattern. However, for very favorable mobility ratios (M <□0.3), a five-spot pattern has better sweep efficiency than a common staggered-line-drive. The reason for this behavior was the change of streamline and pressure distributions with mobility ratios. For very favorable mobility ratios, the displacing front is near an isobar and intersects the pattern boundary at 90 degrees. That causes the fronts at times near breakthrough to become radial around the producer for a five-spot pattern. This displacing front shape is due to the symmetry of the five-spot pattern. Also, noticed more numerical dispersion in results for unfavorable mobility ratio cases ($M > 1$).

For a staggered line drive, the displacing front is also perpendicular to the border of the pattern. However, because the pattern is not symmetric, sweepout at breakthrough is not complete. So theoretically it seems that only in the limit of very large d/a will the areal sweep efficiency approach 1.

R. E. COLLINS and L.H.SIMONS (2000):

The purpose of study is to present a mathematical method for calculating the reservoir volume swept by a pilot flood. The method is applicable to any well pattern and can be used for field-wide floods as well as pilot floods. However, certain simplifying assumptions made about the nature of the reservoir and its contained fluids.

The effects of anisotropic permeability are included in the analysis.

Used four examples for two wells and five examples for five wells spots calculated The position of the front at various times and some of the stream-lines the flood was balanced; that is, the injection and production rates were equal.

After calculated the areal sweep at breakthrough for various cases by using the orientation of permeability axes and the value of K_x/K_Y the recoverable oil per unit area of reservoir obtained mathematically.

RUSLAN GULIYEV (2008):

This research studied the effect of mobility ratios on five-spot and staggered waterflood patterns behavior for areal (2D) displacement in a reservoir that is homogeneous and isotropic containing no initial gas saturation. Simulation was performed using Eclipse 100 simulator.

A simulation study has been performed with the main objective of determining the areal sweep efficiency at breakthrough for waterflood staggered line drive as a function of the Craig mobility ratio for a range of aspect ratios. The two-dimensional simulation model represents 1/8 of a 40-acre pattern unit with a reservoir thickness of 20 ft.

Simulation runs using a number of Cartesian grid models were made to determine the optimum grid model. The Cartesian models tested were 20x10x1, 40x20x1, 60x30x1 and 200x100x1. The simulation results of areal sweep efficiency versus mobility ratio were compared against available experimental data for 5-spot pattern and staggered line drive with aspect ratio of 1. The simulation model that gave the most satisfactory match with experimental data was the 60x30x1 model and therefore was selected for detailed study.

Finally, made simulation runs and determined areal sweep efficiencies at breakthrough for other grid block dimensions and staggered line drive patterns with various aspect ratios.

Although this evaluation study looking for the optimum water injection wells location for the candidate reservoir(Aradeiba D formation) like the previous studies but use the reservoir parameters (RPR ,ROPT, ROE and RWPT) while the other studies focus on other parameters such mobility ratio ,breakthrough, areal sweep efficiency and etc.

Chapter Three

Materials and Methods

Chapter Three
Materials and Methods

3-1 Geological and Engineering Data

This section demonstrates the Aradeiba D formation (Fula north field) data including geological background, reservoir characteristics and production history.

3-1-1 Background of Aradeiba D Formation

Aradeiba formation deposited in meandering river environment with weak stratified-edge water aquifer its pressure is rapidly decreased after put in production so that need pressure support by water injection in order to re-pressurize the reservoir and maximize oil production and increase oil recovery (Petro-Energy, 2011).

3-1-2 Aradeiba-D Formation Pressure Decline

The bellow figure (figure 3-1) showed the Aradieba-D formation pressure decline:

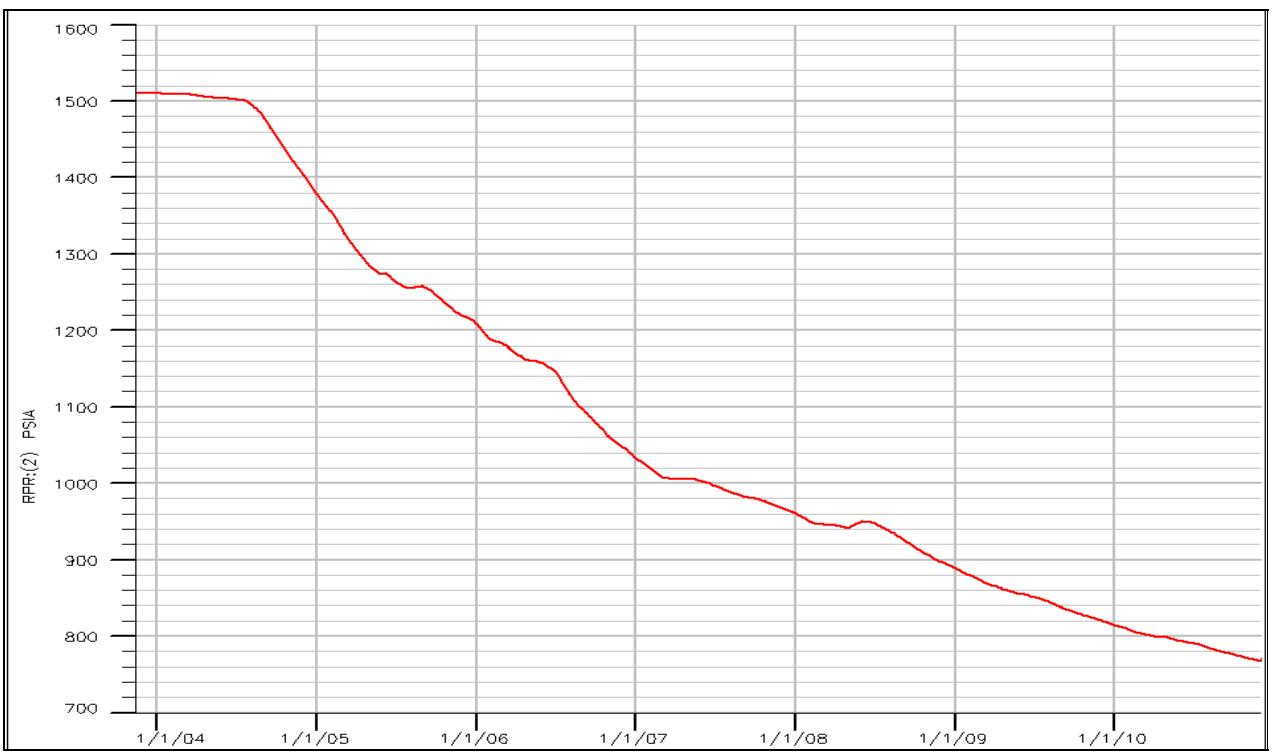

Figure 3-1 Aradeiba-D Pressure Declines (Petro-Energy, 2011).

3-1-3 Remaining Oil Analysis for Aradeiba Formation

After 7 years production there is still a lot of oil remaining in the reservoir formation. It can be found from table (3-1) that the most oil remains in Aradeiba-D with only 2.66% and 2.45% in Aradeiba-F of OOIP produced as there are only limited wells (less than 20) producing from that zone (Petro-Energy, 2011).

Table 3-1 The Remaining Oil Distribution In Each Layer (Petro-Energy, 2011).

Zone	Initial Oil (His. Model) (MMbbl)	Remain Oil (MMbbl)	Production (MMbbl)	Recovery (%)
Arad.C	1.25	1.25	0.00	0.00
Arad.D	73.38	71.43	1.95	2.66
Arad.E	9.64	9.64	0.0	0.00
Arad.F	4.9	4.78	0.12	2.45

3-1-4 Aradeiba-D Formation Production Performance

The bellow figure (figure 3-2) showed the Aradieba-D formation production performance:

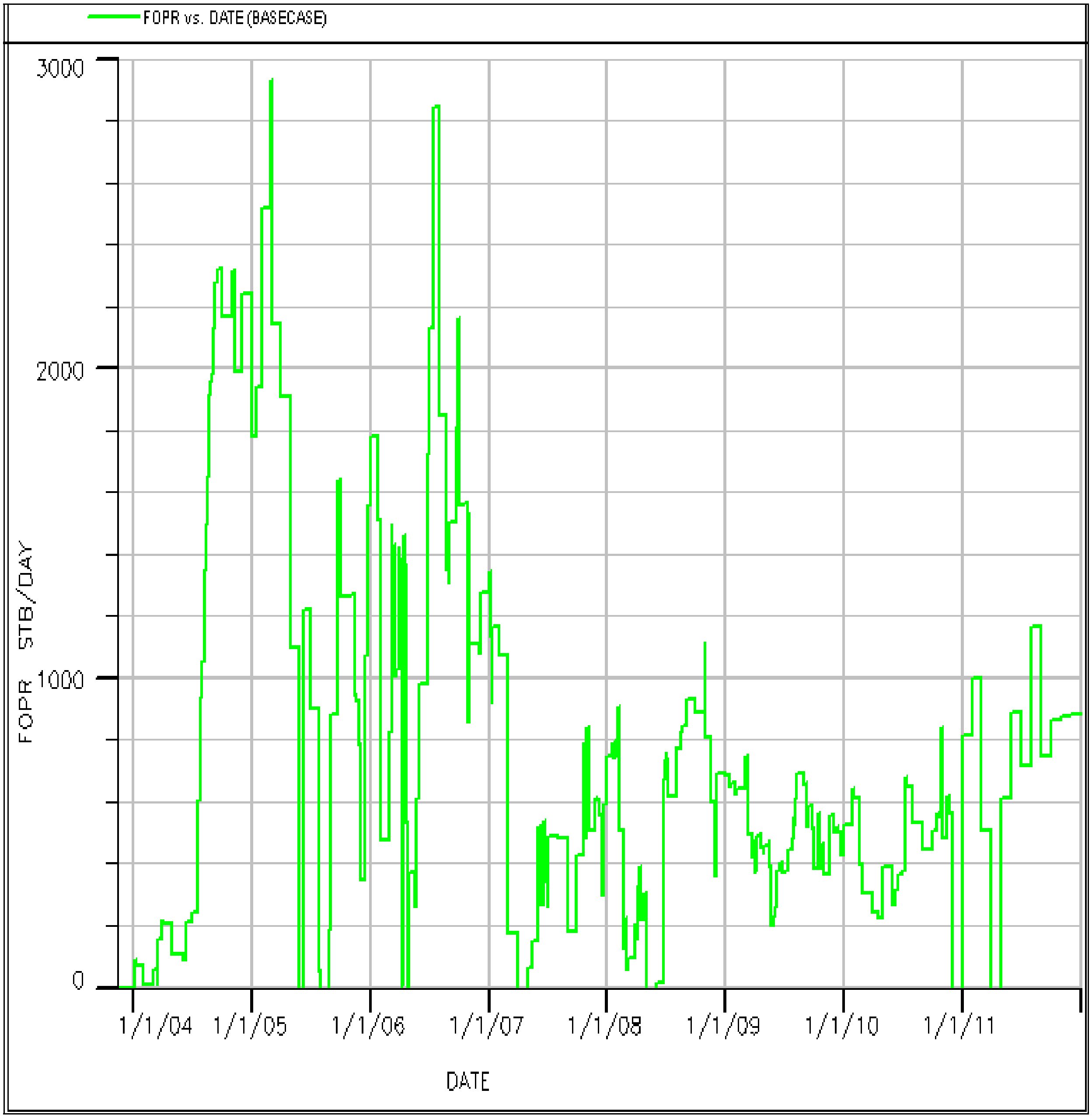

Figure 3-2 Aradeiba-D Production Performance (Petro-Energy, 2011).

3-1-5 Pseudo Relative Permeability Curve for Aradieba-D Formation

The bellow figure (3-3) and table (3-2) showed the pseudo relative permeability for the wells (FN-12 & FN-13) which located in Aradeiba-D formation:

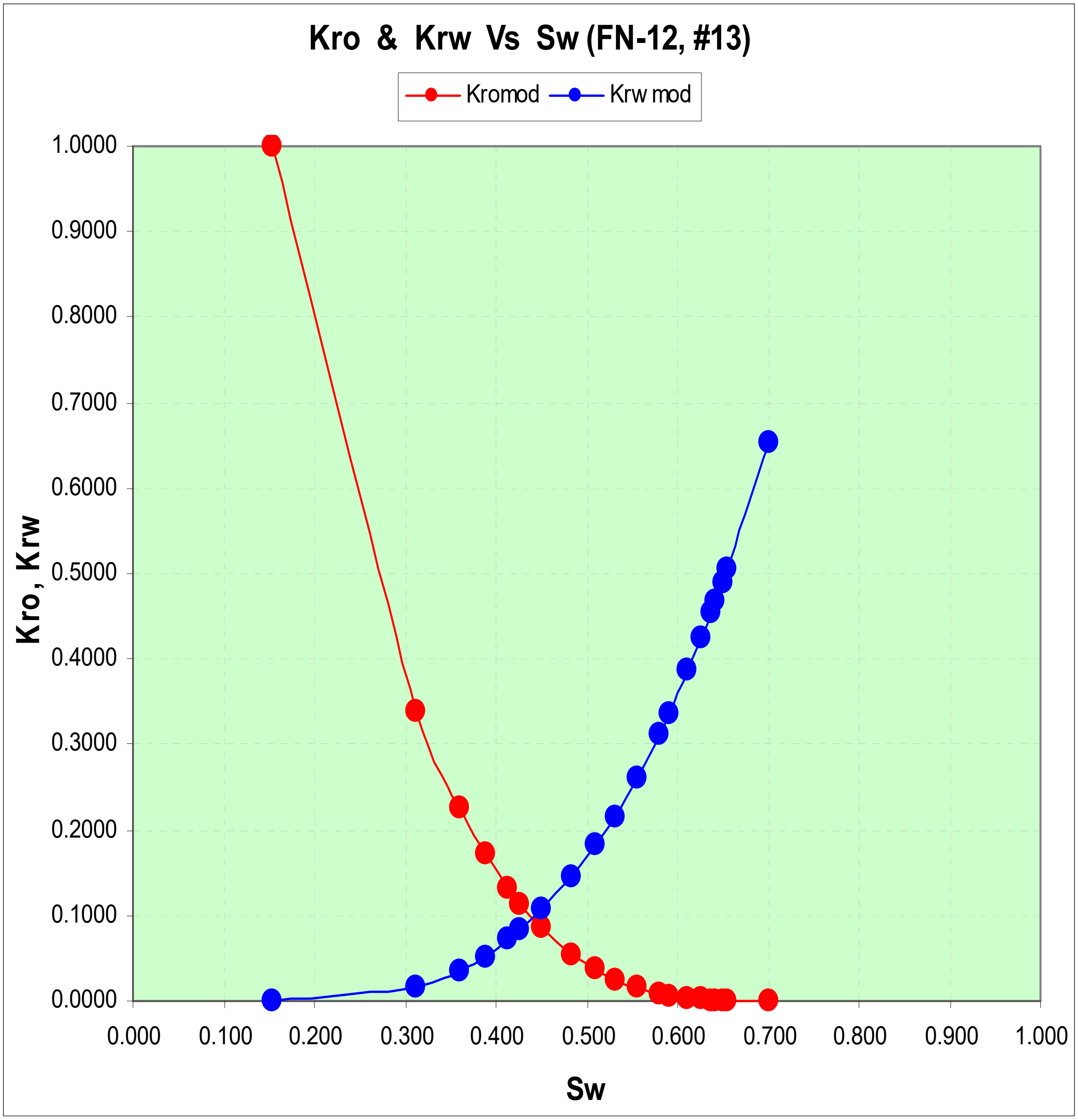

Figure 3-3 Pseudo Relative Permeability Curve (Aradeiba-D) (Petro-Energy, 2011).

Table 3-2 Pseudo Relative Permeability for Aradeiba-D Formation (Petro-Energy, 2011).

Sw	Kro	Krw	Pc(psi)	Sw	Kro	Krw	Pc(psi)
0.153	1.0000	0.0000	37.93	0.555	0.0157	0.2601	1.46
0.313	0.3387	0.0165	10.37	0.580	0.0087	0.3115	1.19
0.360	0.2259	0.0357	7.09	0.591	0.0064	0.3362	1.09
0.388	0.1726	0.0522	5.65	0.612	0.0033	0.3867	0.92
0.414	0.1315	0.0715	4.58	0.627	0.0018	0.4258	0.81
0.427	0.1137	0.0826	4.12	0.637	0.0012	0.4532	0.75
0.451	0.0852	0.1062	3.39	0.642	0.0009	0.4673	0.72
0.484	0.0546	0.1454	2.59	0.650	0.0006	0.4900	0.68
0.510	0.0366	0.1824	2.10	0.655	0.0004	0.5055	0.65
0.531	0.0253	0.2164	1.77	0.700	0.0000	0.6535	0.45

3-2 Modeling and Simulation

3-2-1 Reservoir Modeling

In this the reservoir simulation models have been built up based on the upscaled static models and basic reservoir engineering study results. The grid size of X and Y direction is around 100 meters and is about 50 meters in Z direction. The units of simulation are divided into Arad.C, Arad.D, Arad.E1, Arad.E2, Arad.F, BentiuB1a, B1b, B1c, B1d, B1e, B2 and B3. The total number of the model's cells is 502656. The model's S_{wi} is provided by geo-model inclining OWC (Petro-Energy, 2011). The number of sublayer in each zone and the initialization results (OOIP matching) for the reservoir simulation model are listed in the table (3-3)

Table 3-3 Parameters of Geo-Model and OOIP Matching (Petro-Energy, 2011).

Block	Zone	Subgrid	UpScaled Grid (MMB)	Ini.Model (MMB)	Difference (%)
FN	Ara.C	1	1.24	1.25	0.81
	Ara.D	4	73.21	74.48	1.73
	Ara.E	1	6.57	9.64	46.73
	Ara.F	1	4.47	4.96	10.96
	B1	9	114.35	118.07	3.25
	B1b	9	77.82	78.53	0.91
	B1c	9	100.92	99.98	-0.93
	B1d	6	7.95	7.39	-7.04
	B1e	1	0	0.00	
	B2	1	0	0.00	
	B3	2	8.13	9.09	11.81
	Subtotal	44	394.66	403.39	2.21

3-2-2 History Matching

Reasonable history matching has been achieved for Fula North field through validating the geological model, core data and fluid properties that were input into the model. To achieve the reasonable history matching, adjustments of cell permeability, transmissibility, value of K_V/K_h, volume of aquifer, the shape of the relative permeability curves and etc. were conducted to reflect the individual well behavior and field production performance. In addition, adjustments were also made to the productivity index of some wells to achieve the actual oil and liquid production rate. Both of well-wise and field-wise reasonable history matching was obtained (Petro-Energy, 2011).The details of the history matching shall be discussed below. The well fluid production rate is used for input data; simulated oil production rates of all the production wells, the field production rate and water cut are matched reasonably good. The history match plots of the field oil production rate, cumulative oil production, water cut and bottom hole pressure (BHP) for both Bentiu and Aradeiba are shown in figure (3-4).

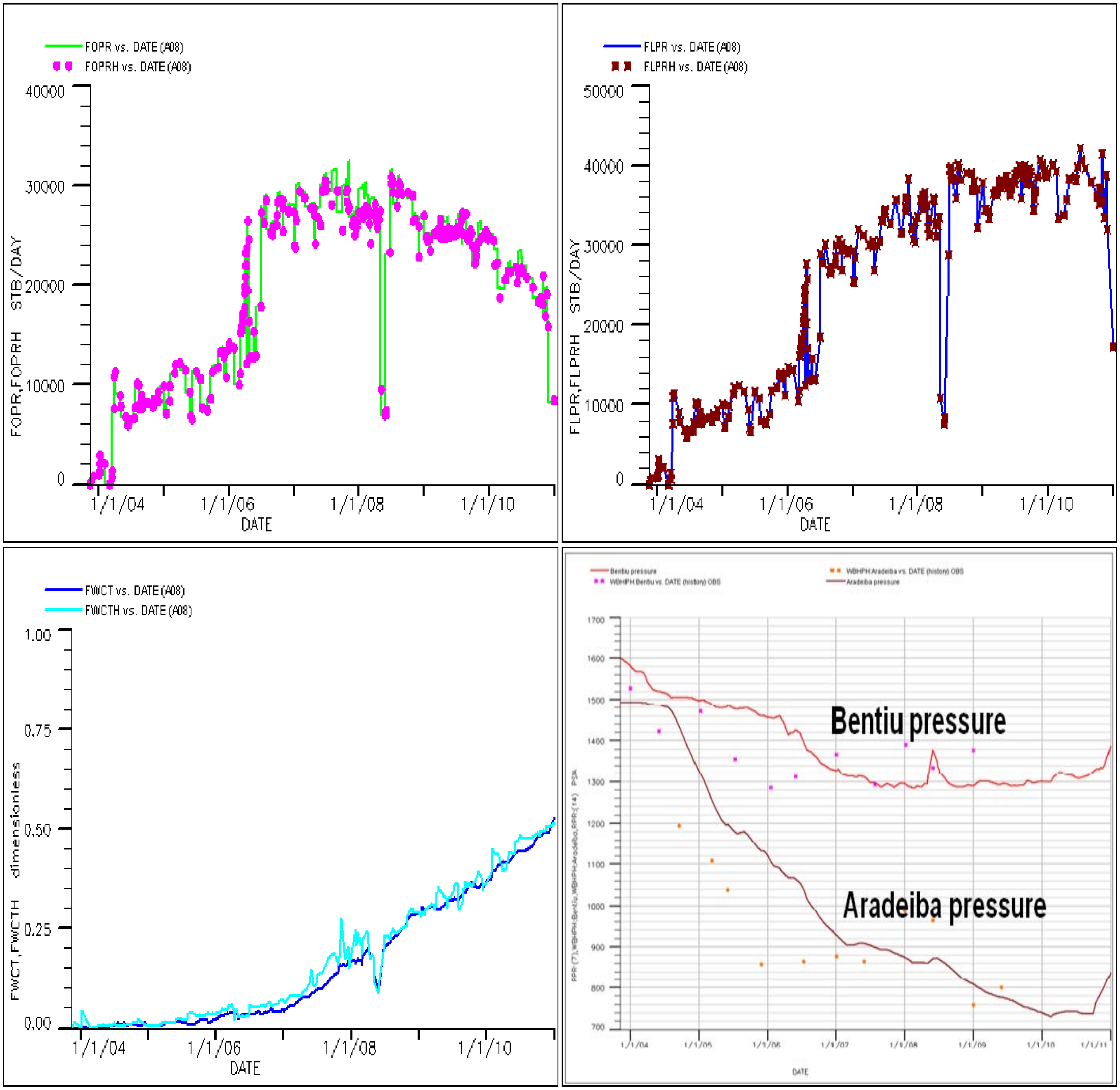

Figure 3-4 The History Match Plots of the FN Field (Petro-Energy, 2011).

More than 80% of the wells have got good match, and the model is considered good enough to predict future performances. The typical wells of FN-1 and FN-10 history match plots of oil production rate, water cut and BHP of individual well are shown as Figure (3-5) and Figure (3-6).

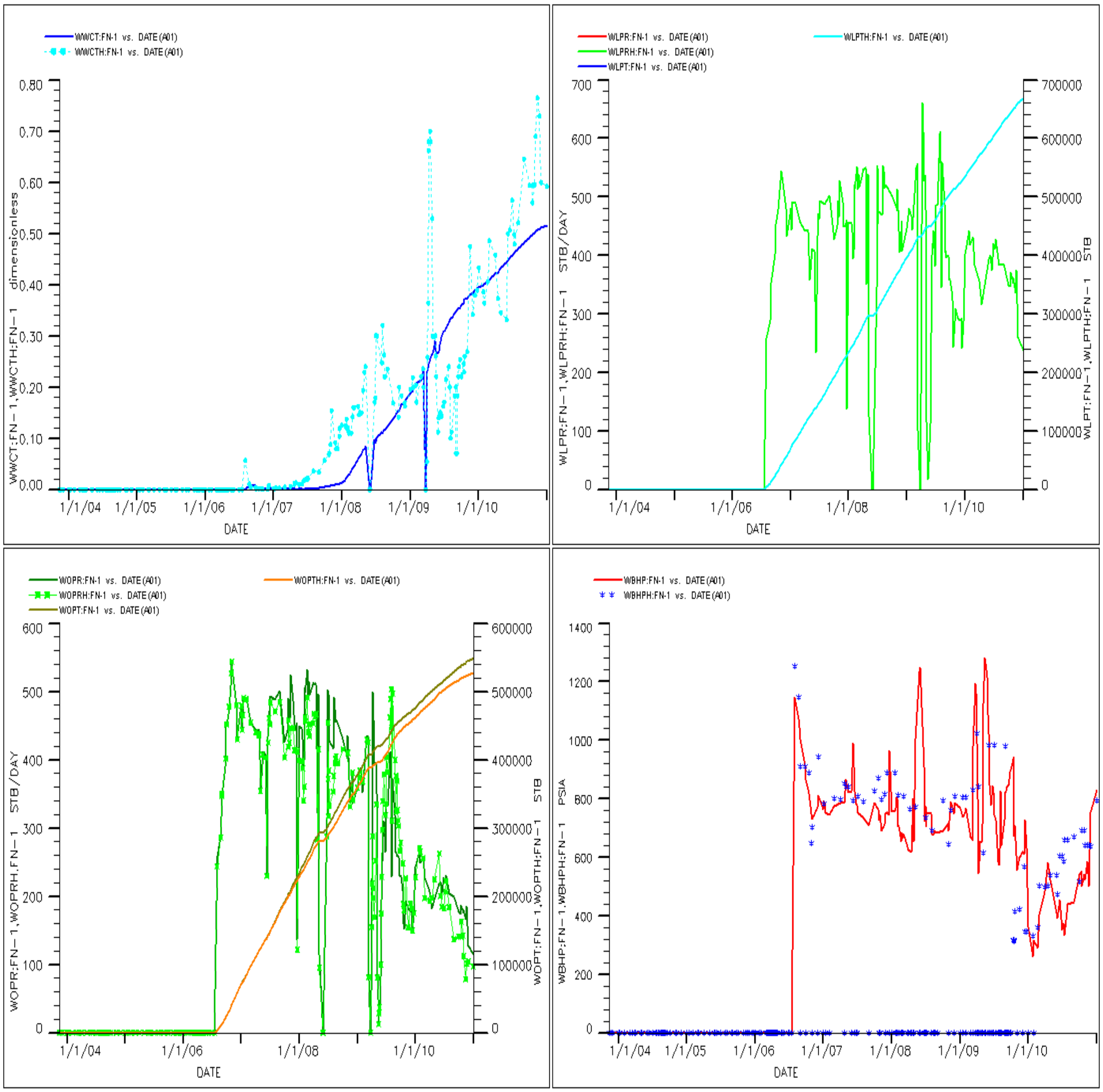

Figure 3-5 History Match Plots of Well FN-1 (Petro-Energy, 2011).

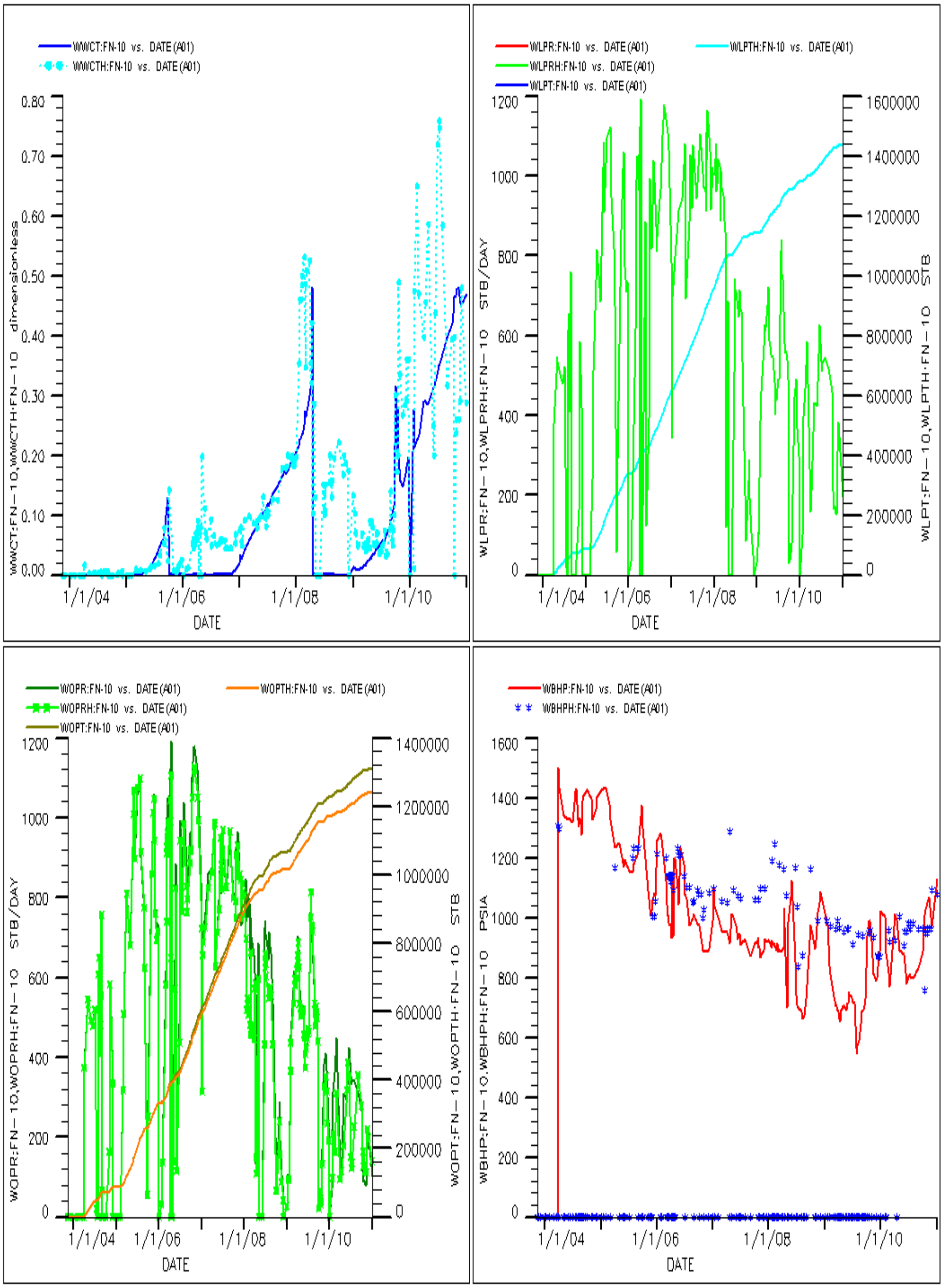

Figure 3-6 History Match Plots of Well FN-10 (Petro-Energy, 2011).

3-2-3 Objects of Reservoir Simulation:

Reservoir Simulation is needed to predict cash flow, analyze reservoir behavior and recovery processes, maximize recovery, and create development plans. Reservoir simulation must answer questions such as:

I. What is the most efficient well spacing?
II. What are the optimums wells injection locations?
III. What is the optimum wells injection rate?
IV. What are the optimum production strategies?
V. What are the external boundaries locations?
VI. What are the intrinsic reservoir properties?
VII. What is the production recovery mechanism?
VIII. When and how should we employ infill drilling?
IX. When and which improved recovery technique should we employment?

3-2-4 Steps of Simulation Study:

I. Setting concrete objective for the study.
II. Selecting the proper simulation approach.
III. Preparing the input data.
IV. Planning the computer runs.
V. Analyzing the result

3-2-5 Introduction to Eclipse

Eclipse is used widely in the petroleum industry, because it has been tested and found valid. It has the capacity of wide spread ways of modelling features of development situations; it also provides the different means of preparing data and processing results; Eclipse Office, PVTI, SCAL, FloGrid, FloViz, PSEUDO and GRAF. It has a wide variety of geometry options, fluid flow options and well futures solved fully implicit and also with the economic constraints. Eclipse has two simulators contained in it, they include: Eclipse 100 and Eclipse 300.

Eclipse 100 is a fully-implicit, three phases, three dimensional, general purpose black oil simulator with gas condensate option. Programs are written in FORTRAN77 and operate on any computer with an ANSI-standard FORTRAN77 compiler and with sufficient memory. It can be used to simulate 1, 2 or 3 phase systems. Two phase options (oil/water, oil/gas, gas/water) are solved as two component systems saving both computer storage and computer time. In addition to gas dissolving in oil (variable bubble point pressure or gas/oil ratio), Eclipse 100 may also be used to model oil vaporizing in gas (variable dew point pressure or oil/gas ratio).Both corner-point and conventional block-center geometry options are available in Eclipse 100. Radial and Cartesian block-center options are available in 1, 2 or 3 dimensions. A 3D radial option completes the circle allowing flow to take place across the 0/360 degree interface. To run simulation needs an input file with all data concerning reservoir and process of its exploitation. Input data for Eclipse 100 is prepared in free format using a keyword system. Any standard editor may be used to prepare the input file. Alternatively Eclipse 100 Office may be used to prepare data interactively through panels, and submit runs. The name of input file has to be in the following format: FILENAME.DATA. An Eclipse 100 data input file is split into sections, each of which is introduced by a section-header keyword. Eclipse 300 for compositional fluid model.

3-2-6 Fluid Flow Equations:

A mathematical model of the single or multiphase flow system is obtained by combining appropriate forms of Darcy's Law and the equation of mass conservation and this is base theory of the simulator.

Water Injection Rate Calculation:

The rate of oil recovery and therefore the life of awaterflood project depend on the water injection rate into reservoir. The variables affecting the injection rates are: Rock and fluid properties, mobility of fluids, area related to swept and unswept regions and oil geometry (well pattern, spacing and wellbore radius). Injection into a particular well is obviously controlled by the reservoir in the immediate area of the well .using Darcy's equation for flow of an oil bank followed by a water bank, Carig (1955) showed that the injection rate before interference is described by:

$$i_w = \frac{7.07 \times 10^{-3} hk\Delta p}{\frac{\mu_w}{k_{rw}}\ln\frac{r}{r_w} + \frac{\mu_o}{k_{ro}}ln\frac{r_o}{r}} \quad \text{(3-1)}$$

Where:

i_w = water injection rate, bbl/d h = formation thickness, ft

k = absolute permeability, md. μ_w = water viscosity at reservoir conditions, cp.

k_{rw} = relative permeability to water. r = radius of the external boundary, ft

r_w = well radius, ft. μ_o= oil viscosity at reservoir conditions, cp

k_{ro}= relative permeability to oil. r_e= outer radius of the oil bank, ft and

$\Delta p= p_e - p_w$, psi

3-2-7 Injection Wells Locations Selection Criteria

Injection wells in a waterflood may be converted from producing wells or drilled specifically as injection wells. Conversion of existing production wells to injection requires a careful analysis of the available wells. Assuming that the existing well pattern and spacing allows the use of these wells as injectors, each well must be studied for economic suitability. In some cases, the cost of obtaining an adequate injection well by conversion may be more than drilling a new one. The condition of the existing well is usually the determining factor. The temptation may be strong to convert marginal or low capacity producers to water injection with the object of minimizing oil production loss; however, the poor productivity may be a result of low net pay or permeability values that would also cause low injectivity. It is frequently more economical to accept the higher initial loss of production to have a shorter response time for the waterflood. Drilling new injection wells depending on such factors as existing well spacing, formation thickness, reservoir heterogeneity, directional permeability and formation fracture direction.

3-3 Simulation and Cases

Because there are some microscopic structures within oil bearing area in Aradeiba-D, different injector's position (in irregular flood pattern) compared to identify the affections of the injectors' location also drilled new producers in the potential area in order to select the proper pattern that will provide the injection fluid with the maximum possible contact with the crude oil system. Simulation study made for 20 years with 30 days time step for all cases. Base (do nothings) case, converting some production wells to injection wells and drilling new wells simulation studies were carried out for comparisons as shown below:

3-3-1 Base (Do Nothings) Case

Simulation made by existing wells to predict the reservoir performance under current condition, figure (3-7) shows the wells location of the base case.

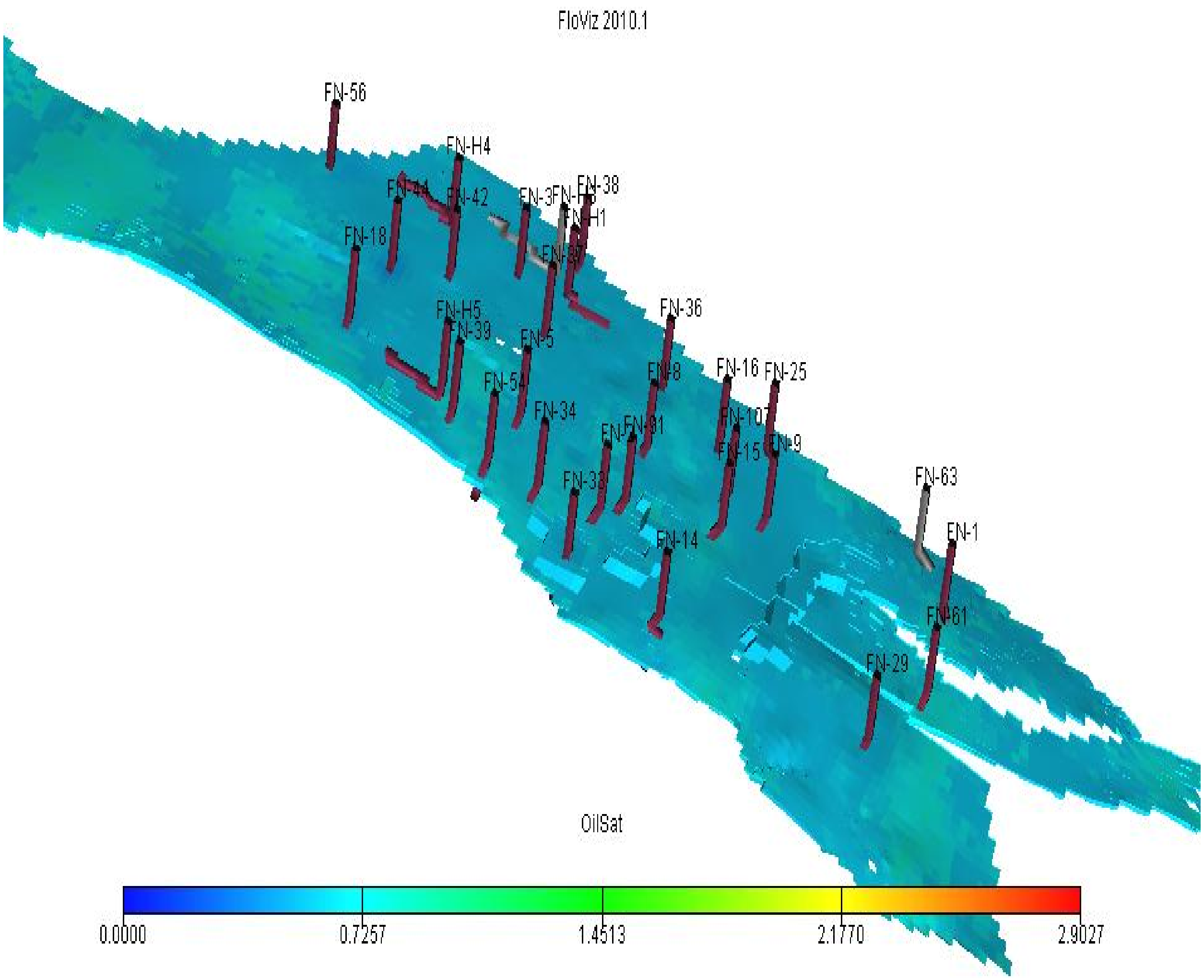

Figure 3-7 Base Case Wells Locations

3-3-2 New Production Wells Case

Based on the base case the simulator run by adding six new wells as producers in the potential area in order to recover more oil, table (3-4) show the new wells details and figure (3-8) show the new production wells locations.

Table 3-4 New Production Wells Details

Well label	Well location			Well type	Rate STB/DAY
	I	J	K		
FN-P1	160	43	2	Producer	400
FN-P2	76	34	2	Producer	400
FN-P3	72	20	2	Producer	400
FN-P4	51	36	2	Producer	400
FN-P5	54	24	2	Producer	400
FN-P6	22	27	2	Producer	400

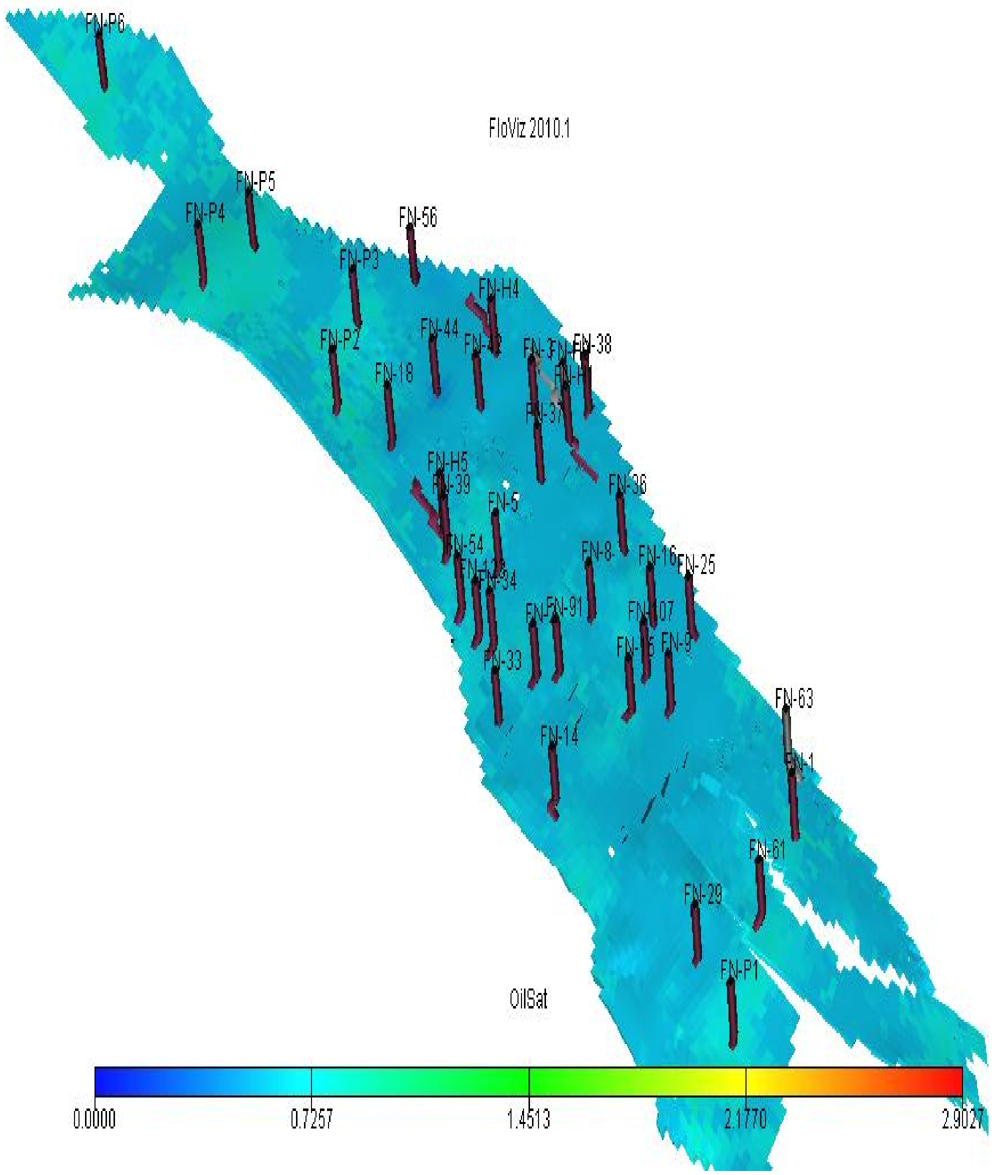

Figure 3-8 New Production Wells Locations

3-3-3 Convert Some Production Wells to Injection Wells Case

Based on the new production wells the simulator run by converting three from existing wells of the base case which has low production rate to injection wells for economic purpose, the injection rate is 700STB/D for each well; figure (3-9) show the Convert some production wells to injection wells case.

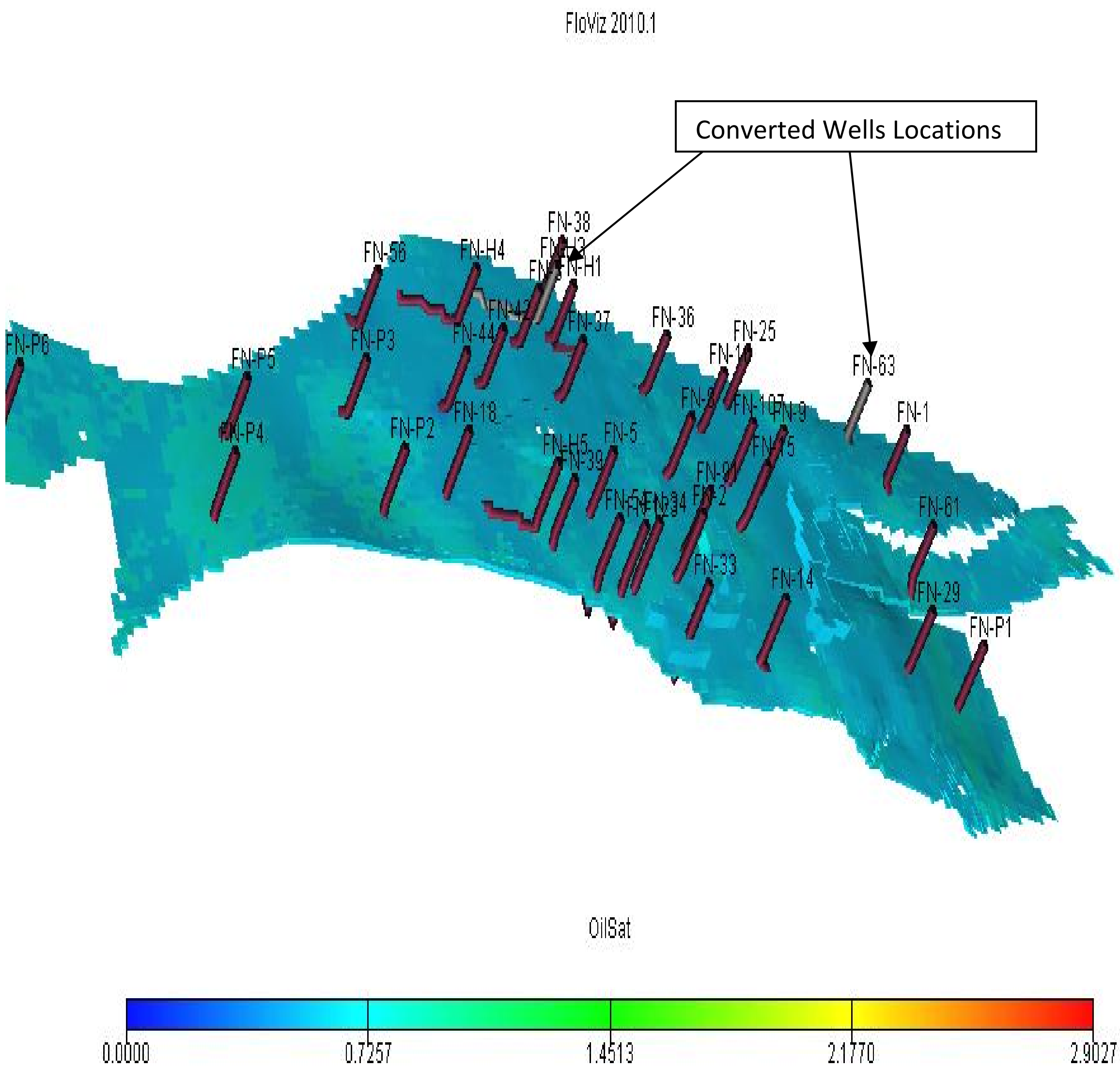

Figure 3-9 Convert Case Wells Locations

3-3-4 Drill New Injection Wells Option One Case

Based on the new production wells the simulator run by adding three new wells as injectors, table (3-5) show the new wells option one details and figure (3-10) show its locations.

Table 3-5 New Injection Wells Option One Details

Well label	Well location			Well type	Rate STB/DAY
	I	J	K		
FN-WI1	72	14	2	Injector	700
FN-WI2	98	39	2	Injector	700
FN-WI3	132	30	2	Injector	700

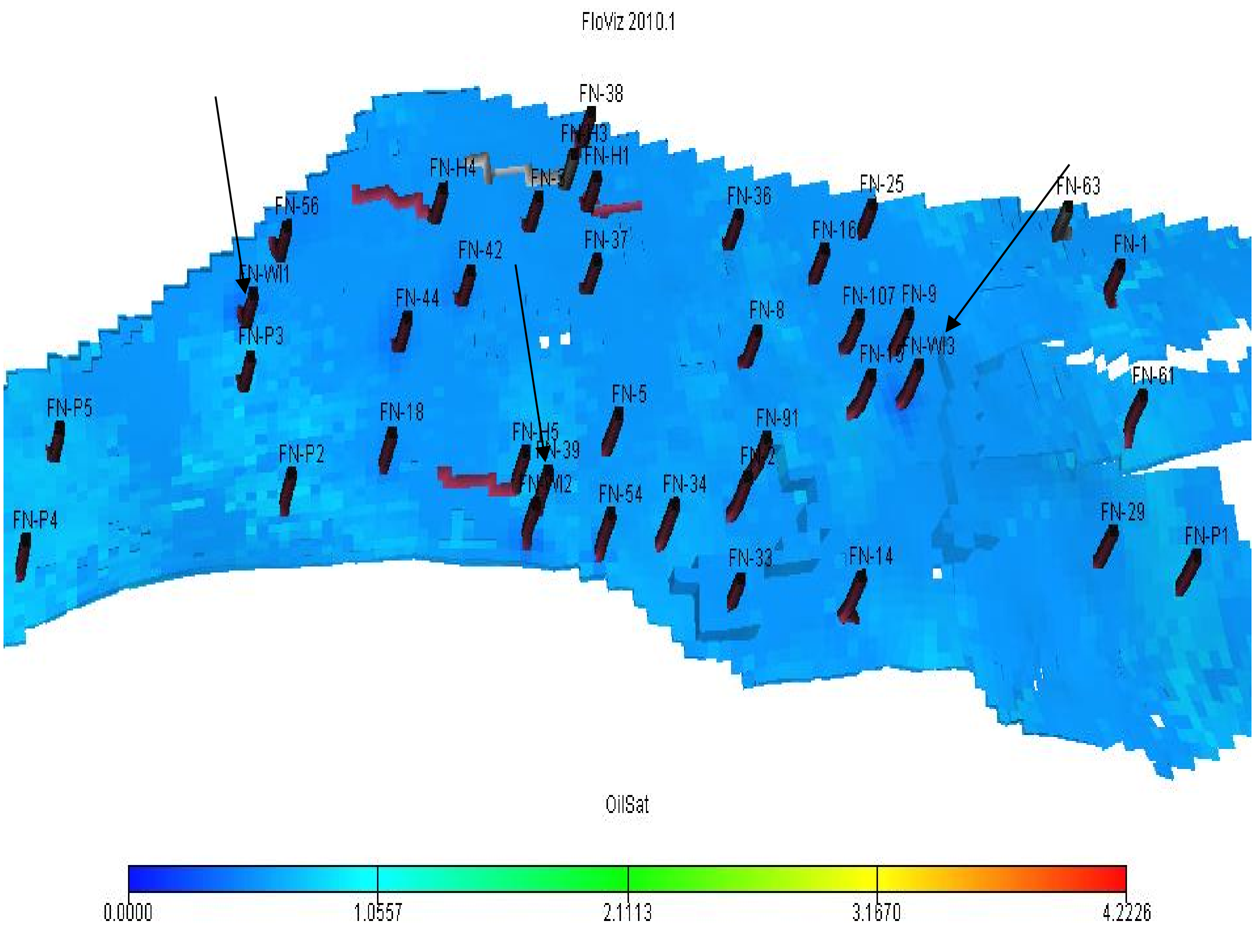

Figure 3-10 New Wells Option One Case Wells Locations

3-3-5 Drill New Injection Wells Option Two Case

Based on the new production wells the simulator run by adding three new wells as injectors in different locations from that wells of option one, table (3-6) show the new wells option two details and figure (3-11) show its locations.

Table 3-6 New Injection Wells Option Two Details

Well label	Well location			Well type	Rate STB/DAY
	I	J	K		
FN-WI4	16	26	2	Injector	700
FN-WI5	69	22	2	Injector	700
FN-WI6	114	12	2	Injector	700

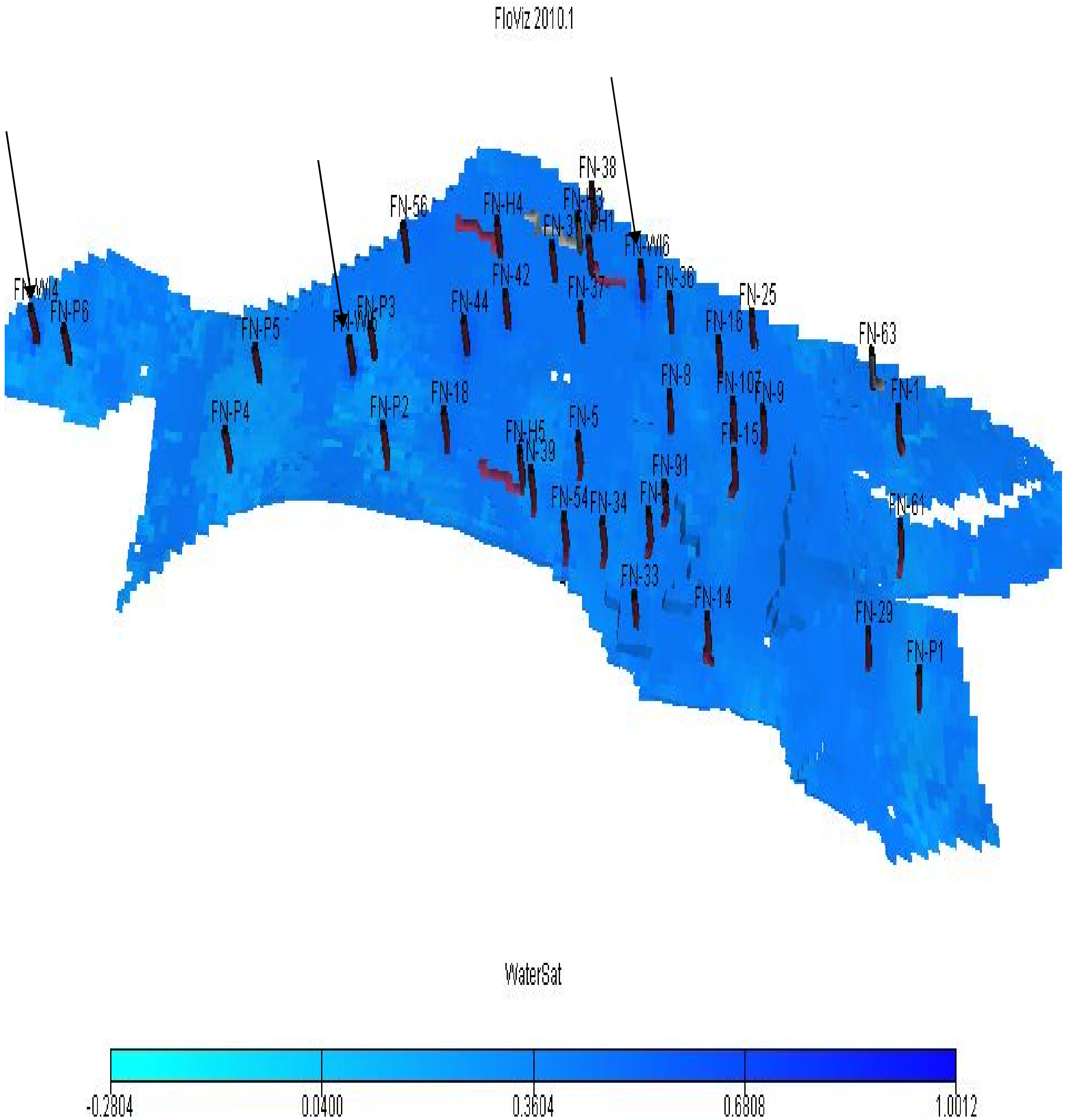

Figure 3-11 New Wells Option Two Case Wells Locations

3-3-6 Drill New Injection Wells Option Three Case

Based on the new production wells the simulator run by adding three new wells as injectors in different locations from that wells of option one and option two, table (3-7) show the new wells option three details and figure (3-12) show its locations.

Table 3-7 New Injection Wells Option Three Details

Well label	Well location			Well type	Rate STB/DAY
	I	J	K		
FN-WI7	49	28	2	Injector	700
FN-WI8	83	11	2	Injector	700
FN-WI9	151	43	2	Injector	700

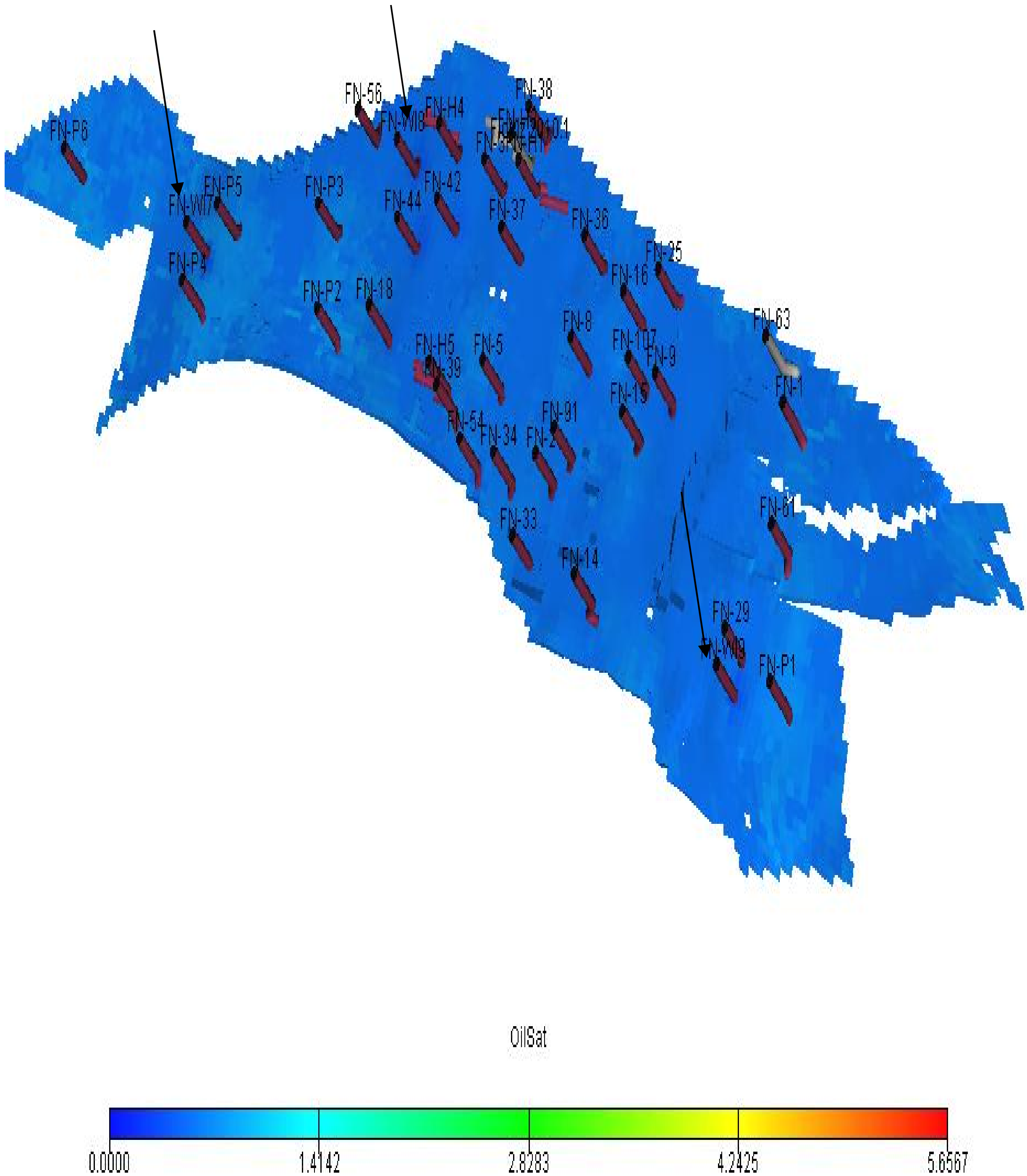

Figure 3-12 New Wells Option Three Case Wells Locations

The appendixes of all simulation steps cases are given in the end of the thesis.

Chapter Four

Simulation Results and Discussing

Chapter Four

Simulation Results and Discussing

The simulation results are (RPR, ROPT, RWPT and ROE). These are described below as tables and figures.

4-1 Aradieba-D Average Pressure (RPR) For All Cases:

The simulator results shown that the pressure of new injection wells option two is highest among other by the end of the study, new injection wells option one pressure is close to the base case by the end of the study and convert case pressure more than the new injection wells option three by the end of the study as below table and figure.

Table 4-1 Aradieba-D Average Pressure (RPR) For All Cases

Case no.	Case name	RPR PSI (2030)
1	Base case	179.356
2	New production wells case	126.392
3	Convert case	406.89
4	New injection wells option one case	205.434
5	New injection wells option two case	623.77
6	New injection wells option three case	357.804

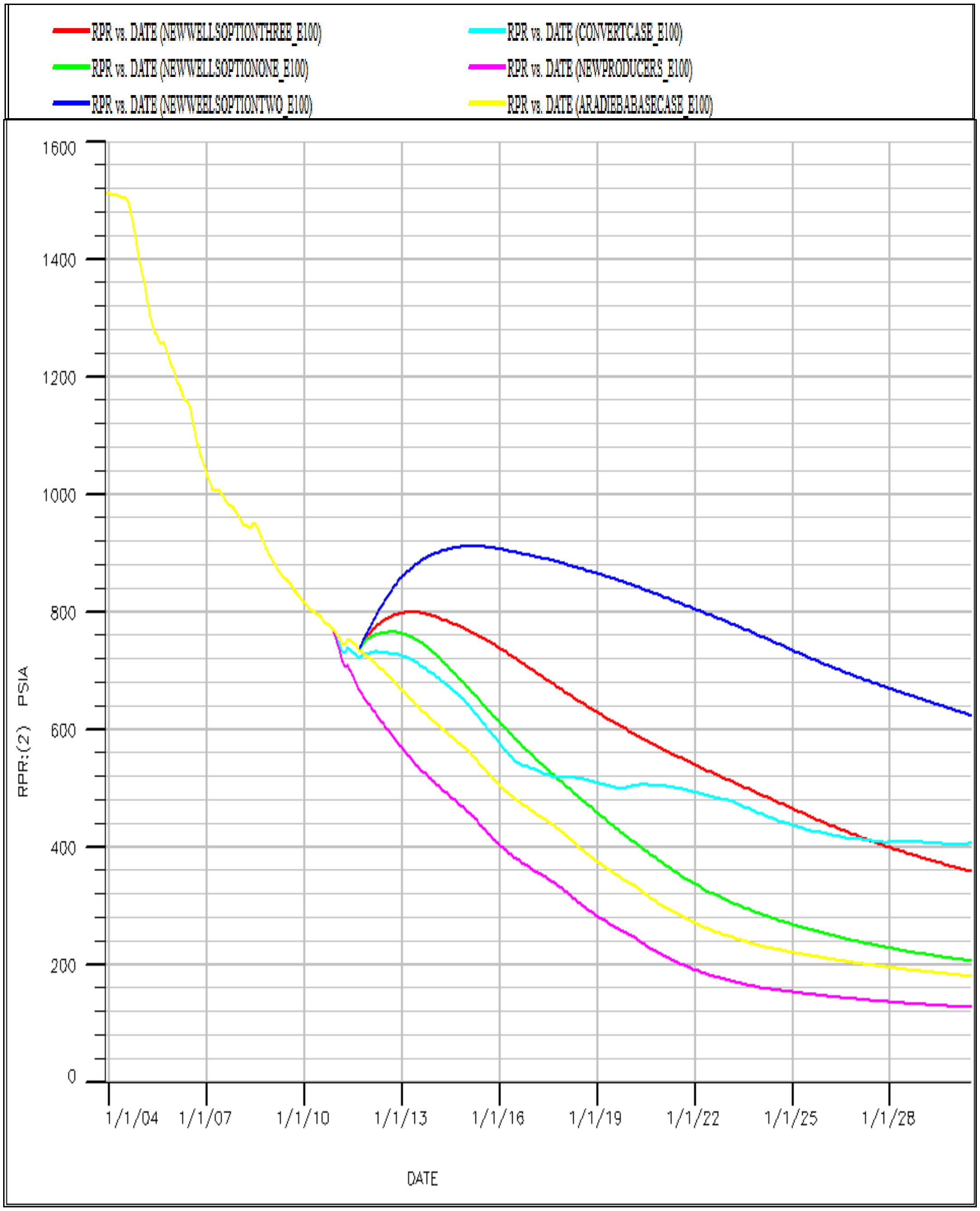

Figure 4-1 Aradieba-D Average Pressure (RPR) For All Cases

4-2 Aradieba-D Oil Production Total (ROPT) For All Cases

The simulator results shown that the new injection wells option two gave the highest cumulative oil production, new injection wells option three is close to convert case, new injection wells option one increased the cumulative oil production but less than convert case and new producers case gave little more cumulative oil production than the base case as below table and figure.

Table 4-2 Aradieba-D oil Production Total (ROPT) For All Cases

Case no.	Case name	ROPT STB (2030)
1	Base case	5531530
2	New production wells case	5842020
3	Convert case	7990040
4	New injection wells option one case	7437400
5	New injection wells option two case	9817420
6	New injection wells option three case	7983920

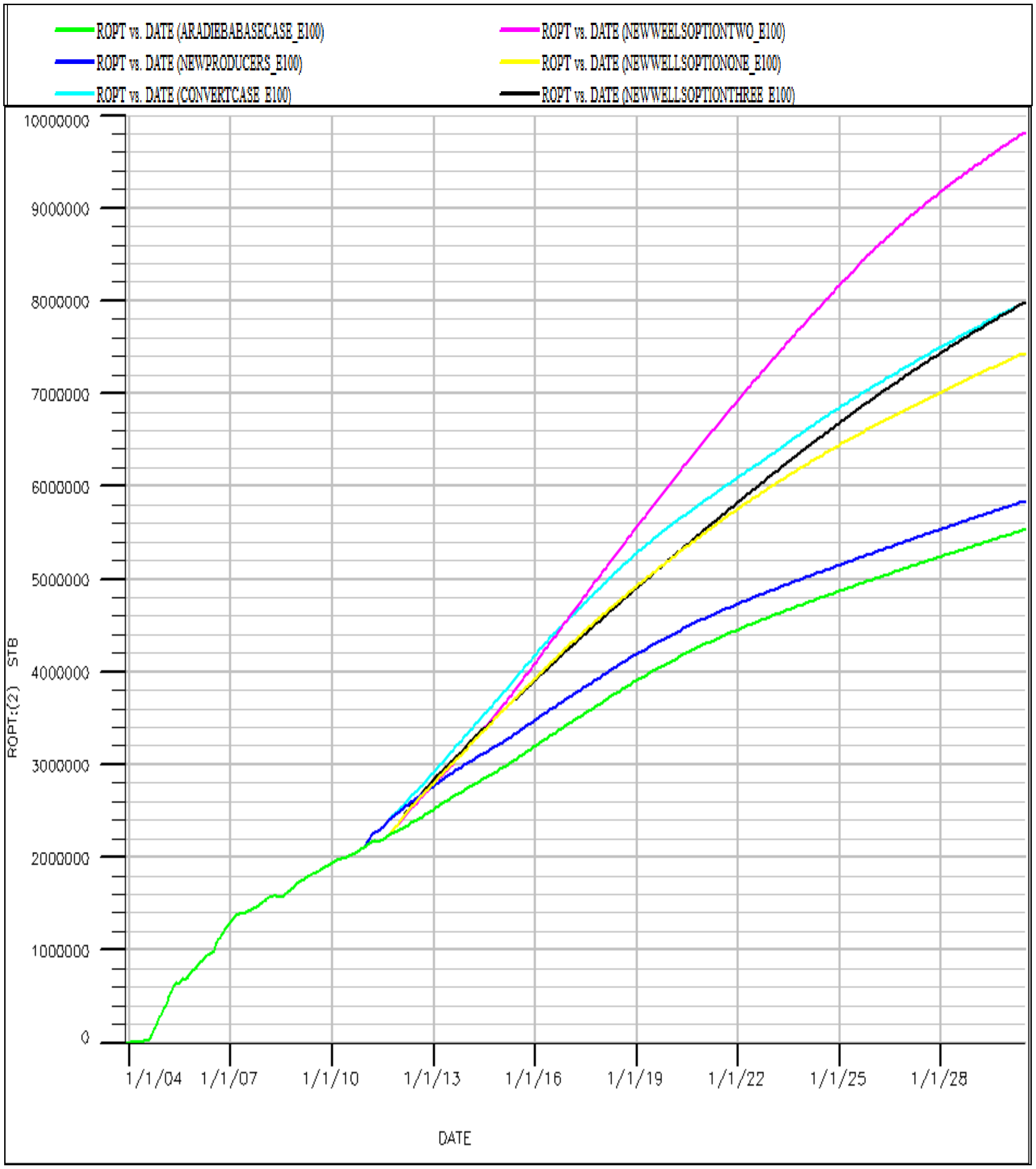

Figure 4-2 Aradieba-D Oil Production Total (ROPT) For All Cases

4-3 Aradieba-D Recovery Factor (ROE) For All Cases

The simulator results shown that the new wells option tow gave the best recovery factor, new injection wells option three is close to convert case and new production wells case gave little more recovery factor than base case as below table and figure.

Table 4-3 Aradieba-D Recovery Factor (ROE) For All Cases

Case no.	Case name	ROE (2030)
1	Base case	0.056365
2	New production wells case	0.060266
3	Convert case	0.100046
4	New injection wells option one case	0.091442
5	New injection wells option two case	0.128503
6	New injection wells option three case	0.103987

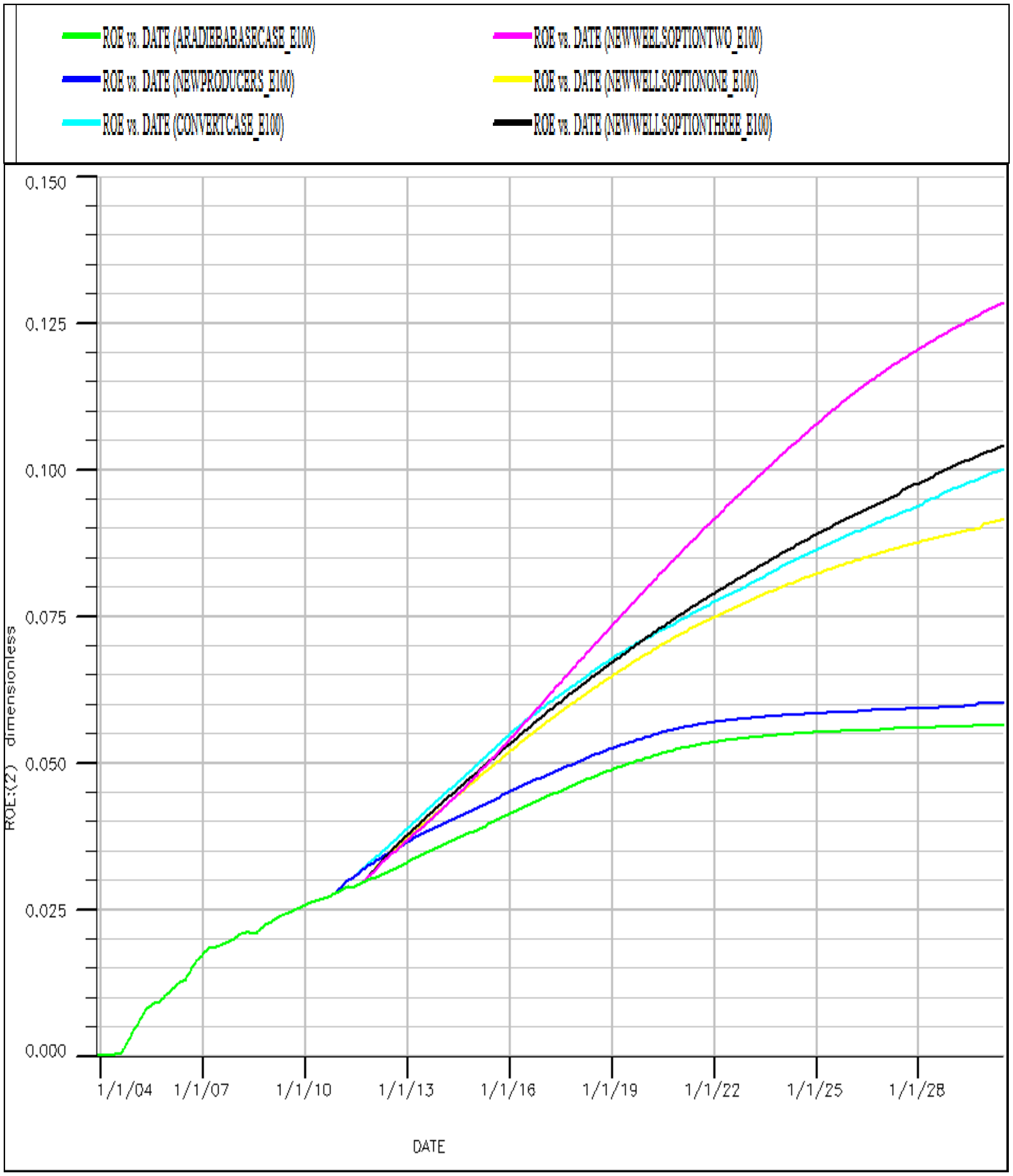

Figure 4-3 Aradieba-D Recovery Factor (ROE) For All Cases

4-4 Aradieba-D Water Production Total (RWPT) For All Cases

The simulator results shown that the new wells option one gave the highest water cumulative and very far from basic case, new production wells case and base case gave typical water production cumulative and new injection wells option two gave cumulative water production less than the new injection wells option one and less than the new injection wells option three as below table and figure.

Table 4-4 Aradieba-D Water Production Total (RWPT) For All Cases

Case no.	Case name	RWPT STB (2030)
1	Base case	925031
2	New production wells case	933219
3	Convert case	3353660
4	New injection wells option one case	11436700
5	New injection wells option two case	6590440
6	New injection wells option three case	9341580

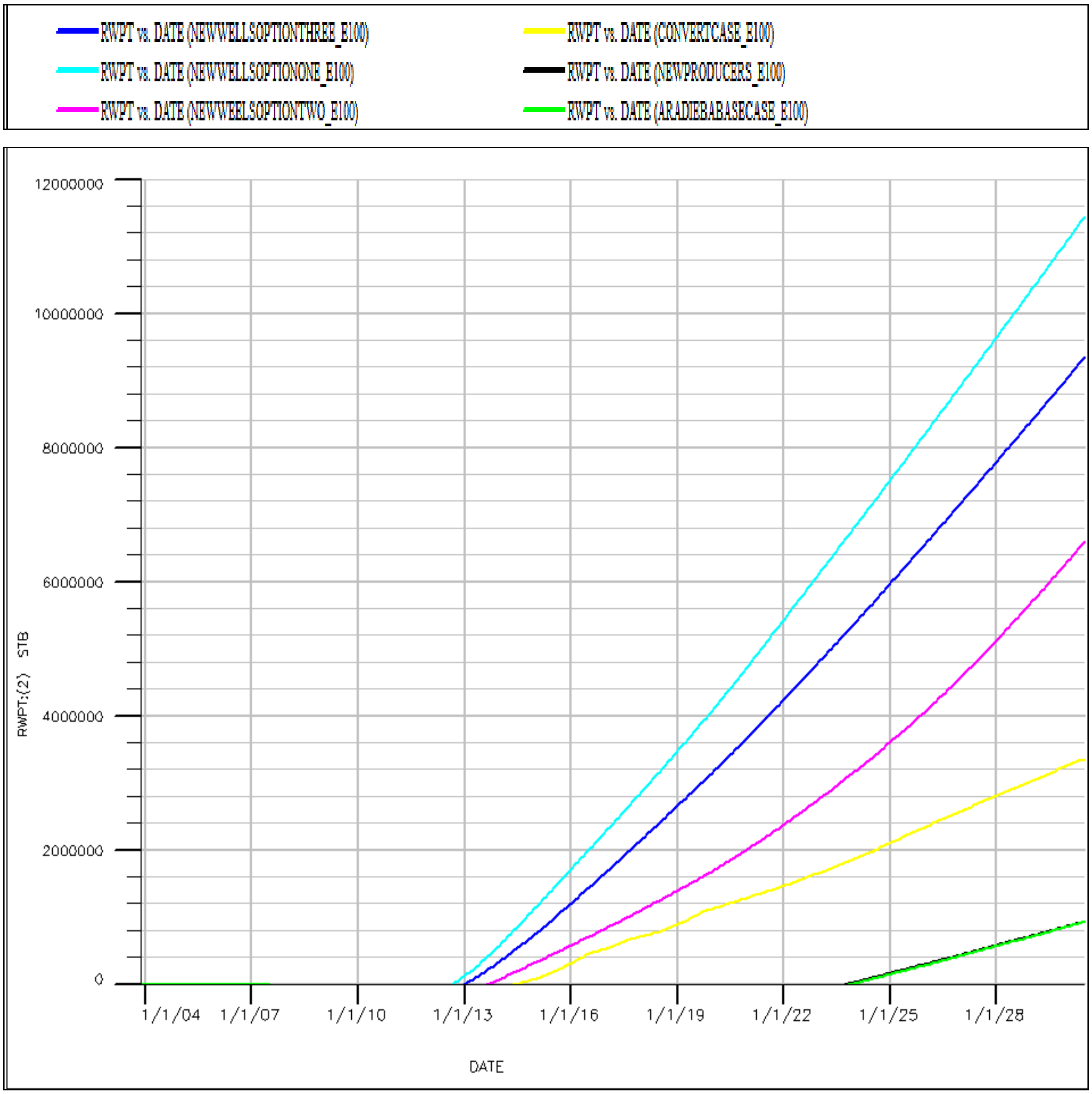

Figure 4-4 Aradieba-D Water Production Total (RWPT) For All Cases

Chapter Five

Conclusion and Recommendations

Chapter Five
Conclusion and Recommendations

5-1 Conclusion

Aradeiba-D formation simulation results analyses showed that the new injection wells option two gave the highest pressure, highest cumulative oil production and best recovery factor among the other by the end of the study.

New injection wells option two gave cumulative water production less than the new injection wells option one and less than the new injection wells option three by the end of the study.

Convert some wells from producers to injectors gave results better than the new injection wells option one and new injection wells option three.

5-2 Recommendations

Water injection is highly recommended in Aradeiba-D development because of its weak natural energy supplement and the simulation study showed the good results for pressure, cumulative oil production and recovery factor in some cases.

Well pattern needs to be optimized for the purpose of better control on main production zone and enhancement of its recoverable reserves.

Suggested to increase injection wells in other area for the purpose of better control on production zone and enhancement of its recoverable reserves, drill Infill production wells at the areas where good remaining oil potential exists to improve recovery in Aradeiba-D formation and convert low production wells or high water cut wells to injection wells should be consider for economic purposes.

Make economic study and evaluation to compare the profitability of converting case and new wells option two case then can select the best flood pattern for Aradieba D formation.

Implementation of the thermal methods either steam flooding or hot water flooding may give good results with Aradeiba D formation (heavy crude) so thermal evaluation study should be consider in the future development.

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Appendixes

Appendixe (A) Simulation Steps of Aradeiba D Formation Base Case

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Appendixe (B) Simulation Steps of Aradeiba D Formation New Producers Case

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Appendixe (C) Simulation Steps of Aradeiba D Formation Converting Case

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Appendixe (D) Simulation Steps of Aradeiba D Formation New Wells Option One Case

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 2 /

INIT

INCLUDE
'ARADIEBA_GOPP.INC'  /

INCLUDE
'ARADIEBA_GGO.INC'  /

INCLUDE
'ARADIEBA_GPRO.INC'  /

INCLUDE
```

```
'ARADIEBA_GOTH.INC'  /


EDIT

INCLUDE
'ARADIEBA_EDIT.INC'  /


PROPS

INCLUDE
'ARADIEBA_PVT.INC'  /

INCLUDE
'ARADIEBA_SCAL.INC'  /


REGIONS

INCLUDE
'ARADIEBA_REG.INC'  /


SOLUTION

INCLUDE
'ARADIEBA_INIT.INC'  /


SUMMARY

INCLUDE
'ARADIEBA_SUM.INC'  /


SCHEDULE

INCLUDE
'ARADIEBA_SCH.INC'  /


END
```

Appendixe (E) Simulation Steps of Aradeiba D Formation New Wells Option Two Case

```
--
-- ---------------------------------------------------------------------
-------
-- Office Simulation File (DATA) Data Section Version 2010.1 May 28 2010
-- ---------------------------------------------------------------------
-------
--
-- File: NEWWEELS-22_E100.DATA
-- Created on: Jun-21-2015 at: 16:29:02
--
--
*************************************************************************
****
-- *                                      WARNING
*
-- *                  THIS FILE HAS BEEN AUTOMATICALLY GENERATED.
*
-- *            ANY ATTEMPT TO EDIT MANUALLY MAY RESULT IN INVALID DATA.
*
--
*************************************************************************
****
--

RUNSPEC

TITLE
title

START
 11 'NOV' 2003 /

FIELD

UNIFIN

UNIFOUT

OIL

WATER

ENDSCALE
 'DIRECT' 'IRREVERS' 1 20 /

GRIDOPTS
 'YES' 0 0 /

MONITOR
```

```
RSSPEC

NOINSPEC

MSGFILE
 1 /

SMRYDIMS
 1000000 /

AQUDIMS
 2 2 2 10 3 11424 0 3 /

FAULTDIM
 300 /

DIMENS
 204 56 44 /

EQLDIMS
 4 100 100 1 20 /

REGDIMS
 13 1 0 0 /

TABDIMS
 7 4 21 20 13 20 20 1 /

WELLDIMS
 300 80 286 127 /

MESSAGES
90000 100000 90000 1200 3000 1* 90000 90000 90000 100000 100000 100000
/


GRID

GRIDFILE
 2 /

INIT

INCLUDE
'ARADIEBA_GOPP.INC'  /

INCLUDE
'ARADIEBA_GGO.INC'  /

INCLUDE
'ARADIEBA_GPRO.INC'  /

INCLUDE
```

```
'ARADIEBA_GOTH.INC'  /


EDIT

INCLUDE
'ARADIEBA_EDIT.INC'  /


PROPS

INCLUDE
'ARADIEBA_PVT.INC'  /

INCLUDE
'ARADIEBA_SCAL.INC'  /


REGIONS

INCLUDE
'ARADIEBA_REG.INC'  /


SOLUTION

INCLUDE
'ARADIEBA_INIT.INC'  /


SUMMARY

INCLUDE
'ARADIEBA_SUM.INC'  /


SCHEDULE

INCLUDE
'ARADIEBA_SCH.INC'  /


END
```

Appendixe (F) Simulation Steps of Aradeiba D Formation New Wells Option Three Case

```
--
-- ------------------------------------------------------------------------
-------
-- Office Simulation File (DATA) Data Section Version 2010.1 May 28 2010
-- ------------------------------------------------------------------------
-------
--
-- File: NEWWELLS-3_E100.DATA
-- Created on: 18-Jun-2015 at: 20:30:17
--
--
*************************************************************************
****
-- *                                      WARNING
*
-- *                  THIS FILE HAS BEEN AUTOMATICALLY GENERATED.
*
-- *            ANY ATTEMPT TO EDIT MANUALLY MAY RESULT IN INVALID DATA.
*
--
*************************************************************************
****
--

RUNSPEC

TITLE
title

START
 11 'NOV' 2003 /

FIELD

UNIFIN

UNIFOUT

OIL

WATER

ENDSCALE
 'DIRECT' 'IRREVERS' 1 20 /

GRIDOPTS
```

```
 'YES' 0 0 /

MONITOR

RSSPEC

NOINSPEC

MSGFILE
 1 /

SMRYDIMS
 1000000 /

AQUDIMS
 2 2 2 10 3 11424 0 3 /

FAULTDIM
 300 /

DIMENS
 204 56 44 /

EQLDIMS
 4 100 100 1 20 /

REGDIMS
 13 1 0 0 /

TABDIMS
 7 4 21 20 13 20 20 1 /

WELLDIMS
 300 80 286 127 /

MESSAGES
90000 100000 90000 1200 3000 1* 90000 90000 90000 100000 100000 100000
/


GRID

GRIDFILE
 2 /

INIT

INCLUDE
'ARADIEBA_GOPP.INC'  /

INCLUDE
'ARADIEBA_GGO.INC'  /

INCLUDE
```

```
'ARADIEBA_GPRO.INC'  /

INCLUDE
'ARADIEBA_GOTH.INC'  /


EDIT

INCLUDE
'ARADIEBA_EDIT.INC'  /


PROPS

INCLUDE
'ARADIEBA_PVT.INC'  /

INCLUDE
'ARADIEBA_SCAL.INC'  /


REGIONS

INCLUDE
'ARADIEBA_REG.INC'  /


SOLUTION

INCLUDE
'ARADIEBA_INIT.INC'  /


SUMMARY

INCLUDE
'ARADIEBA_SUM.INC'  /


SCHEDULE

INCLUDE
'ARADIEBA_SCH.INC'  /


END
```