Optimization of Injection Well Placement in Faulted Reservoir for Water Flooding Process

By

Syarifah Suliza Binti Wan Mat

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Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

Petroleum Engineering

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CERTIFICATION OF APPROVAL

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TRONOH, PERAK

September 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgement and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

………………………………….

SYARIFAH SULIZA WAN MAT

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Abstract

Waterflooding is one of the most economical and preferable method to increase oil recovery in a depleted reservoir. Waterflooding is the process of injecting compatible water under certain pressure into the reservoir in order to enhance or maintain the reservoir driving energy. This process was discovered by accident almost 100 years ago when water from a shallow water-bearing horizon break into a packer and then entered an oil column in a well thus resulting in declining of oil production of the respective well. However, it was noticed that the production of the offset wells that are producing from the same reservoir was increasing. Since then, the use of waterflooding has slowly grown until it becomes one of the most significant fluid injection recovery technique.

In order to improve the ultimate oil recovery during waterflooding, it is essential to find the optimum injection well placement. Thus, this project is focusing on the optimum placement of water injection well by using Genetic Algorithms (GA) as the optimization tool. A simple GA is proposed to be develop and used in determining the optimum well injector placement in a synthetic reservoir with cumulative oil production maximization as the objective function.

Injection well placement optimization is one of the most challenging and worrisome problems and it often arises due to lack of resources and appropriate tools, thus making it done on trial and error bases [1]. Drilling a water injection well at the wrong location may lead to more complicated problems such as further decreasing in oil production and early breakthrough of water in the production wells.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Waterflooding is generally considered as the second phase of useful oil production, sometimes known as secondary production. According to Erle. D. (1985) [2], the first, or primary production starts with the discovery of an oilfield using the natural energy to move the oil to the wells by expansion of volatile components and/or pumping of individual wells to assist the natural drive. However, due to continuous production over the years, the reservoir pressure starts to decrease, resulting in decline in production and water breakthrough into the wellbore. At this point, secondary production begins when extra energy is added to the reservoir by injection of water to enhance the reservoir driving energy.

There are many factors that must be taken into serious considerations when choosing the most suitable water flood candidate. The structure of a water flood candidate is often the least considered factor but its effect on the water flood performance can be very significant (Rottmann K., 1998) [3]. According to Rotmann K., the main impact of structure are faulting and degree of dip, whether it is homoclinal, anticlinal, or synclinal. Besides that, fault acts as a sealing boundary which may create a bounded reservoir where the reservoir pressure behavior is affected. This phenomena is also known as principle of superposition and it is further explained in Chapter 2.3.

The problem of optimizing the well location is a very complex task where there are too many parameters to consider in order to successfully locating the injection well. Factors that need to be consider include geological variable such as reservoir architecture, production variables; production well placement, well number, production rate, water injection rate, etc. and monetary variables such as oil and gas prices. [1] All these variables together with the reservoir geological uncertainty makes it hard to determine the objective function and its restrictions or limits. Therefore, an efficient algorithm is essential for computational feasibility. For this study, GA is proposed to be develop where it uses Darwin's survival of the fittest theory to evaluate different scenarios that may affect the well placement process.

1.2 Problem Statement

As many fields in the world are reaching maturity, its reservoir pressure starts to decline over years of production and affected the production rate. This problem is due to weak aquifer drive of the reservoir system where the natural driving energy is no longer able to move the oil into the wellbore. Therefore, secondary production such as water flooding is introduced in order to enhance the reservoir driving energy and to increase the oil recovery. However, the well injector placement is not an easy task to be implemented as it needs a very complex algorithm which took various parameters into account with the aim of to come up with the optimized well location. The well injector location must be taken into serious considerations in water flooding process because if there is any problem regarding the well injector, it may lead to further declining of oil production and more water breakthrough from all the producers from the same reservoir. Besides that, the cost to drill a new injector well is very expensive and the presence of fault in the reservoir structure further complicates the optimization process because it may affect the pressure distribution in the reservoir.

1.3 Objective and Scope of Studies

The main objectives of this project are;

- To study the effects of fault in waterflooding process by using Eclipse and determine the suitable Injection well placement by maximizing the cumulative oil production.
- To develop a genetic algorithm (GA) program to optimize injection well placement.

Scope of studies

- Simulations of genetic algorithm (GA) by using MATLAB to find the optimum well injector placement with maximization of cumulative oil production as the objective function.
- Simulation of waterflooding by using Eclipse to determine the oil recovery from various location of water injection well.

1.4 The Relevancy of the Project

There has been many researches that has been done in the field of well placement optimization. However, most of them did not fully evaluated the reservoir's structure effects on water flooding. The presence of fault in the reservoir system will affect the reservoir's pressure distribution because the fault will be a sealing boundary as if it is a bounded reservoir (Superposition's Principle). Thus, this project will fully study on the effects of fault in determining the well injector placement with the help of GA and by means of maximizing the cumulative oil production.

1.5 Feasibility of the Project

The following are the goals that were achieved during the first four months of FYP 1 period;

- Review of literature related to the topics
- Produced an extended proposal regarding the project

During the second semester period, a detailed simulations by using MATLAB and Eclipse was conducted. The detailed simulation was focused on obtaining the following;

- The optimized well location for water flooding process with consideration of existence of fault
- The cumulative oil production from the optimized well injector obtained by using GA.

The project was feasible to be done within the scope and time frame by following the key milestones that has been set from the early stage of this project. Besides that, all the simulations software needed are available in Petroleum Engineering laboratory thus making it easier for continuous access.

CHAPTER 2

LITERATURE REVIEW

2.1 Genetic Algorithm

Genetic algorithm is a randomized search algorithms mimic the process of natural evolution inspired by Darwin and the "survival of the fittest" principle. [4] In GA, some of the operators used such as the survival of the fittest among a population of individuals, selection criteria and reproduction strategies are copied from the natural life concepts. It combines survival of the fittest among string structures with a structured, yet randomized, information exchange that is somehow similar to the innovative flair of human search. GA used natural selection, mutation and crossover to modify a set of solutions (population) simultaneously, to develop the population to its global optimal solution. In every generation, a new set of artificial creatures (strings) is created using bits and pieces of the "fittest" from the old generation; an occasional new part is tried for better measurement.

According to Morales A.N., Nasrabadi H., and Zhu D. (2011) [5], in well placement optimization, an efficient algorithm is essential for computational feasibility. The algorithm must also be able to find global optima or a set of optimums, while avoiding getting stuck on a set of local extrema. This requires a stochastic, as opposed to a deterministic, approach to the problem.

Daniel P. Fitcher, the author of a study entitled Application of Genetic Algorithms in Portfolio Optimization for the Oil and Gas Industry [6] said that, a well-designed GA should be capable of handling problems small or large in scope, with any set of arbitrarily complex constraints applied. For this project, the constraint applied will be the presence of fault in the reservoir, thus GA is expected to overcome this constraint and find the global optima (optimum well location) for this problem.

There are many researches that has been done regarding well placement optimization by using Genetic Algorithm. Handels et al. (2007) and Wang et al. (2007) in their research has proposed different approaches for well placement optimization by implementing gradient-based optimization techniques by representing the objective function in a functional form. Gradient of this objective function is calculated and the steepest ascent direction is used to guide the search. The techniques were only applied to vertical wells and more difficulties were expected when this approach is applies to problems with arbitrary well trajectories in complex model grids. Besides that, they were having another issue on including the discontinuities in the objective function and convergence to local optima.

One of the earliest researches that were conducted on well placement optimization by evolutionary algorithms was conducted by Bittencourt and Horne [7]. In their studies, the designed algorithm was able to optimize the location of new wells in an existing field and optimized the field economic value based on a presented work proposal. The results of their research indicates that the profit had an increase of 6% compared to the original scenario proposed by the company. They used a Hybrid Genetic Algorithm (HGA) in their study which refers to any Standard Genetic Algorithm which has been modified to fit the addressed problem.

Optimization of nonconventional wells in complex oil reservoirs has also been done which included the possibility of several wells or multilateral wells being optimized by using Hybrid Genetic Algorithm (Yeten et al. 2003). Montes et al. (2001) has done a study on optimization of vertical well placements by using basic GA without any hybridization. Their studies were applied on two synthetic rectangular models and they found out that the ideal mutation rate should be variable with generation. Besides that, on their study of the population size, it suggested that an appropriate population size was equal to the number of the variables in the problem.

Genetic Algorithm structure.

In the following paragraphs, the different operators and parameters that make up a Genetic Algorithm and their variations are discussed in detail [1]. Figure 1 shows the flowchart of a genetic algorithm. Some of the GA vocabulary is summarized in Table 1 and both of GA and engineering vocabulary will be referred to in this study.

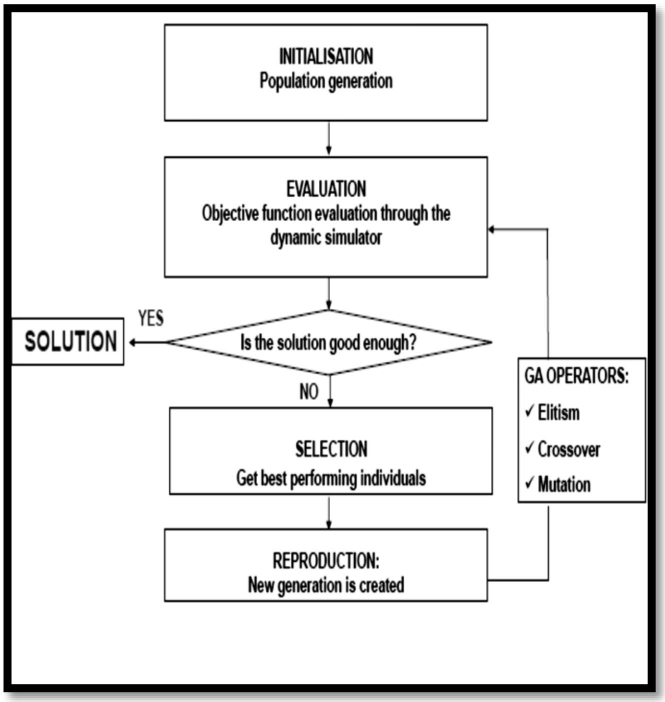


Figure 1 Genetic Algorithm Flow Chart

Table 1 The GA Vocabulary

GA Vocabulary	Engineering Vocabulary
Population	Set of solution vectors
Chromosome, string	Encoded solution vector
Gene	An element of the encoded string
Fitness	Function value
Individual	Data structure
Generation	GA iteration
Reproduce	Carry on to the next iteration

Individual

An individual is a member of a population that contains a potential solution to the optimization problem and can be represented as a binary string or a decimal string. Figure 2 shows the representation of binary and decimal string. Assuming that every 3 bits in the binary string represent a decimal number, we get V1 = 3, V2 = 2, V3 = 5

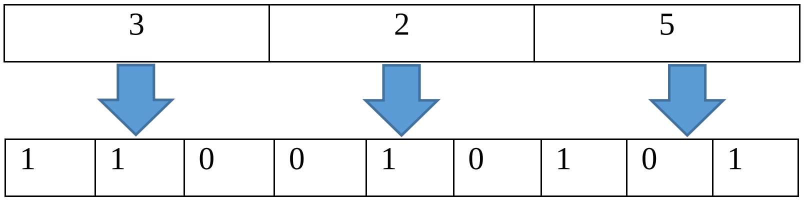


Figure 2 Decimal and binary individuals

Population Size

If a population size is 4, then four individuals will be grouped together to form a population

Population Generation

This is the first step of developing a genetic algorithm. At this point, the problem variables are codified to form a chromosome and an initial population is generated. The process of representing a solution in the form of string that conveys the necessary information is known as encoding process. Just as in chromosome, each gene controls a particular characteristics of the individual and can be defined as a block of DNA. Similarly, each bit in the string represents a characteristic of the solution. Each variable is codified usually in binary code and the chromosomes are strings of 1 and 0 where each position in the chromosome represents a particular characteristic of the problem.

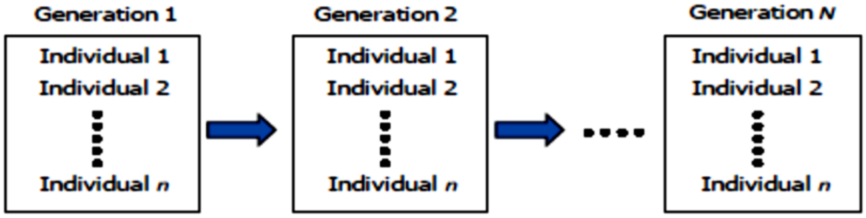


Figure 3 Presentation of generations within GA

Evaluation

In the evaluation steps all the chromosomes are evaluated where they will be ranked from best to worst. A fitness function value is used to quantify the optimality of a solution where a fitness value is assigned to each solution depending on how close it is actually to the optimal solution of the problem.

Fitness Value

A value is assigned to each individual according to how good the solution represented by the individual is. In this study, the fitness is represented as oil production as we are trying to maximize oil recovery. The highly fit individuals are given higher chance to “reproduce” or in carry out to the next generation. On the other hand, the least fit individuals are less likely to get selected to the next generation, and therefore die out.

Reproduction

Reproduction is the process during which new chromosomes are created. This process will determines which solutions are to be preserved and allowed to reproduce and which ones deserve to be discarded. The objective of this process is to emphasize the good solutions and discards the bad solutions in a population while maintaining the population size.

There are few methods to create a new generation and one of them is the tournament selection. For this method, several tournaments are played among a few individual which are chosen at random from the population pool and the winner for each tournament is selected for the new generation. The next method is the Roulette wheel selection where the parents are selected according to their fitness values and the better chromosomes have more chances to be selected. Roulette wheel selection method will have problem when the fitness values differ very much, resulting in the chromosomes with low fitness values to be less likely to be selected. This problem can be avoided using ranking selection where the chromosomes selected to mate based on their merit. In each generation, the operators such as elitism, crossover and mutation are used for reproducing new chromosomes.

Elitism

Elitism is mainly used to make sure that the best chromosomes are preserved in the population pool and would survived to the next generation. From this process, we can be assured that every new generation will be at least as good as the previous generations.

Parents

A couple of individuals are selected based on their fitness score and mated to produce new offspring to replace less fit individuals in the next generation.

Offspring

Offspring are individual that are created as result of mating two parents and it shares some best features taken from both parents.

Crossover

Crossover is an operator during which two chromosomes exchange some of their parts to develop a new offspring. The most popular crossover selects any two solution strings randomly from the mating pool and some of the portion of the strings is exchanged between the strings. In addition, a probability of crossover is also introduced to give freedom to an individual solution string to determine whether the solution would go for crossover or not. However, crossover does not always occur. Sometimes, no crossover occurs and the parents are copied directly to the new population. Normally the probability of crossover occurring is 60% to 70%.

Mutation

After the selection and crossover, there are new set of population full of individuals which some of them are directly copied from their parents and has been crossover. In order to ensure that the individuals are not exactly the same, mutation process will introduces some new features to the solution strings of the population pool to maintain diversity in the population. Usually the mutation probability is generally kept low between 10% and 20%.

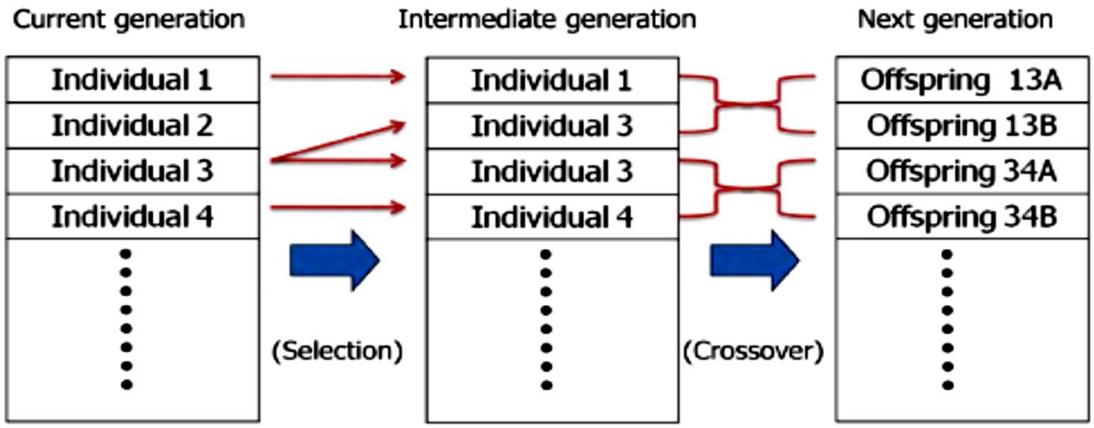


Figure 4 Transition from one generation to the next

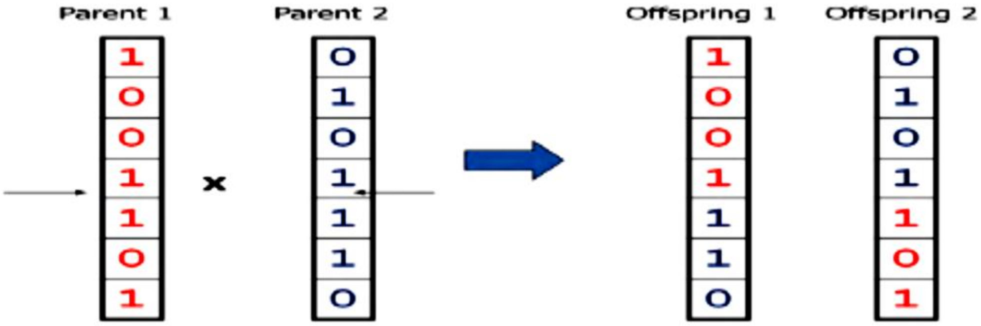


Figure 5 Crossover

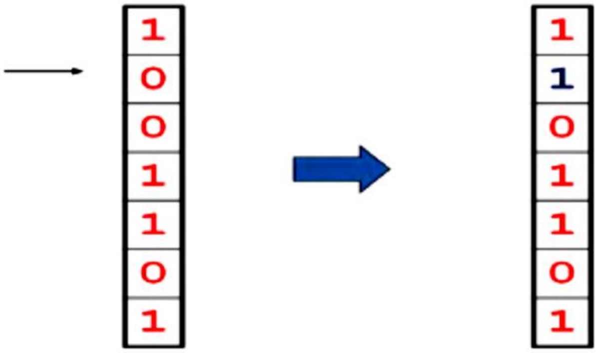


Figure 6 Mutation

2.2 Genetic Algorithm Simulator

MATLAB Genetic Algorithm Toolbox was used as the main optimization simulator for this problem. The GA Toolbox features a graphical user interface, the ability, to solve constrained problems, the flexibility to modify and create selection, crossover, and mutation functions and the capability for parallelization ("Genetic Algorithm and Direct Search Toolbox 2").

2.3 Water flooding

As many fields around the world are reaching maturity with over 30 years of production, the reservoir pressure starts to decrease and it will affects the well's production rate. In the case where the reservoir pressure is too low where it is enable to produce naturally, water flooding was introduced to be performed at these wells to enhance the hydrocarbon recovery. According to Jackson (1997) [9], secondary recovery is defined as production of oil or gas as a result of artificially augmenting the reservoir energy, as by injection of water or other fluid.

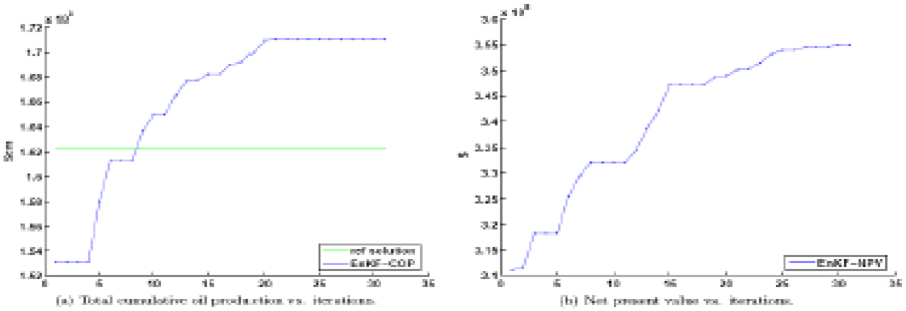
According to Sneider R.M. and Sneider J.S. (2000) [10] in the past, a variety of secondary oil recovery methods have been developed and applied to mature and depleted oil reservoirs. These methods help to improve oil recovery compared to primary depletion. On top of that, the significance to develop marginal field to meet the oil and gas demand are discussed by Sarma P. et al (2005) [11] the number of new discoveries of significant oil fields per year is decreasing worldwide and most of the existing major oilfields are already at their mature stages. Consequently, it is becoming increasingly necessary to produce these fields as efficiently as possible in order to meet the global increase in demand for oil and gas.

Conventional waterflood operations that are widely used in the industry nowadays involve injecting water into the reservoir to displace mobile oil to the producing wells for recovery. Usually, waterflood will commenced when reservoir pressure depletion occurs together with production decline processes occurs until the reservoir is at or near abandonment. In order to fully understand the processes that took place in water flooding, the major stages for a water flooding project will be discussed in details in the following lines.

Asheim [23] has developed an approach which uses only the control variables explicitly for numerical optimization. He was involved in the study of optimal control in waterflood reservoirs by using reservoir simulation models. In his study, he developed a method for numerical optimization of the net present value (NPV) of a natural water drive and water drive by injection in which the well rates were used as the controlled variables. The waterflooding scheme that maximized the NPV was numerically obtained by combining reservoir simulation with control theory practices of implicit differentiation and he was able to achieved an improved in sweep efficiency and delayed water breakthrough by controlling the well flow rates. In his study, there was a net present value improvement of 11%.

Brouwer and Jansen [24] has done a study on the optimization of waterflooding with fully penetrating, smart horizontal wells in 2-dimensional reservoirs with simple, large scale heterogeneities. Optimal control theory is used as the optimization algorithm for valve settings in smart wells and the objective of the study was to find the maximum recovery of NPV of the waterflooding process over a period of time. In this study, they implied that the injection and production rates in the wells were kept constant during the displacement process, until water breakthrough occurred. Although they observed a significant improvements, they believed that more improvements could be achieved by dynamic optimization of the production and injections. Thus, in a later study [25], they studied the same problem by using a dynamic optimization which means that, the inflow control valves were allowed to vary during the waterflooding process.

Lorentzen et al. [26] also carried out a study on dynamic optimization of waterflooding by controlling the chokes to maximize cumulative oil production or net present value. Their new approach uses the ensemble Kalman filter which were originally used for estimation of state variables but has been adapted as an optimization routine in their work. In their study, they showed the use of ensemble Kalman filter as an optimization routine on a simple 5 layer reservoir with different permeabilities and the results from this approach are shown in Figure 7 (a) and (b).



(a) Total cumulative oil production vs. iterations. (b) Net present value vs. iterations.

Figure 7 Development of Optimized value

2.4 Factors in Determining the Well Location for a Waterflooding Process

Many studies has been done on sensitivity analysis of dimensionless parameters for simulation of waterflooding reservoir. Yuhu et al [27] investigated the influence of gravitational force, capillary pressure and the compressibility of water, oil and rock in waterflooding process and sort out the dominant ones with larger sensitivity factors. They proved that among the attributes related to porous medium, the permeability has bigger influence on flows than others do. Besides that, among the fluid properties, density and viscosity are the most important factors as compared to gravitational force, compressibility of water, oil, rock and the capillary force. Thus, for this study, the author has implemented the results from this sensitivity analysis as the factors in determining the optimum well location. Detail discussion on the determining factors are shown in the following paragraphs.

Thomas, Mahoney, and Winter [28] pointed out that in determining the suitability of a candidate reservoir characteristics must be considered:

- Fluid properties
- Fluid saturations
- Lithology and rock properties

Fluid Properties

The physical properties of the reservoir fluids have some significant effects on the suitability of a given reservoir for waterflooding process. For example, viscosity of crude oil is considered the most important fluid property that affects the degree of success of a waterflooding process. It is important in determining the mobility ratio which in turns control the sweep efficiency.

Lithology and Rock Properties

Reservoir lithology and rock properties that affect flood ability and degree of success are:

- Porosity
- Permeability
- Clay content
- Net thickness

In a complex reservoir systems, only a small portion of the total porosity, for example the fracture porosity will have sufficient permeability to be effective in waterflooding projects. Although clay minerals present in some sands may clog pores by swelling when waterflooding is used, there are no exact data available as to the extent to which the clay swelling might occur and its effect in oil production. Besides that, a tight or low permeability reservoir with thin net thickness might have some problems in implementing waterflooding operation in terms of the desired water injection rate or pressure. The relationship of water-injection rate and pressure is shown in the following expression:

$$p_{inj} \propto \frac{i_w}{hk}$$

Where p_{inj} = Water- injection Pressure

i_w = Water-injection rate

h= Net thickness

k = absolute permeability

The expression suggests that to deliver a desired injection rate in a tight reservoir, the required injection pressure might exceed the formation fracture pressure.

Fluid Saturations

A high oil saturations that provides a sufficient supply of recoverable oil is the primary criterion for successful waterflooding operations. High oil saturations will increase the oil mobility that in turn, gives higher recovery efficiency.

2.5 Effects of Fault on Water flooding

Principle of superposition

Principle of superposition states that the total pressure drop at any point in a reservoir is the sum of the pressure drop caused by flow in each of the wells in the reservoir. [13] This concept can be applied to account for the following effects on the transient flow solutions; superposition in time and superposition is space. The applications of superposition in space include stimulation of pressure behavior in bounded reservoirs and effects of multiple wells.

Superposition principle can be used to stimulate pressure behavior in bounded reservoirs. Consider the well in Figure below, a distance L, from a single no-flow boundary (such as sealing fault). This problem is identical to the problem of a well a distance 2L from an “image” well (i.e. a well that has the same production history as the actual well). The reason behind this behavior is that a line equidistant between the two wells can be shown to be a no-flow boundary- i.e. along this line the pressure gradient is zero, which means that there can be no flow. [13]

Chapter 3

Methodology

In general, research methodology refers to a set of procedures used to conduct a research project. In here, the methodology includes:

- Research Methodology
- Project Activities
- Key Milestone
- Gantt Chart
- Tools

3.1 Research Methodology

Project Planning and Feasibility Study

For this phase it involves the review of related literature regarding the project from various journals, books, and research papers in order to increase the familiarity, better understanding and also to get a clear view about the research scope that will be carried out. The main information resources are from Optimization of Well Placement and Assessment of Uncertainty by Baris Guyaguler and some other research papers. After the reading has been done, a Gantt chart has been prepared which consist of several milestone and project activities so that the time will be allocated in the right way.

For feasibility study, a data analysis regarding the proposed field and various scenarios will be executed in order to determine the optimum well location.

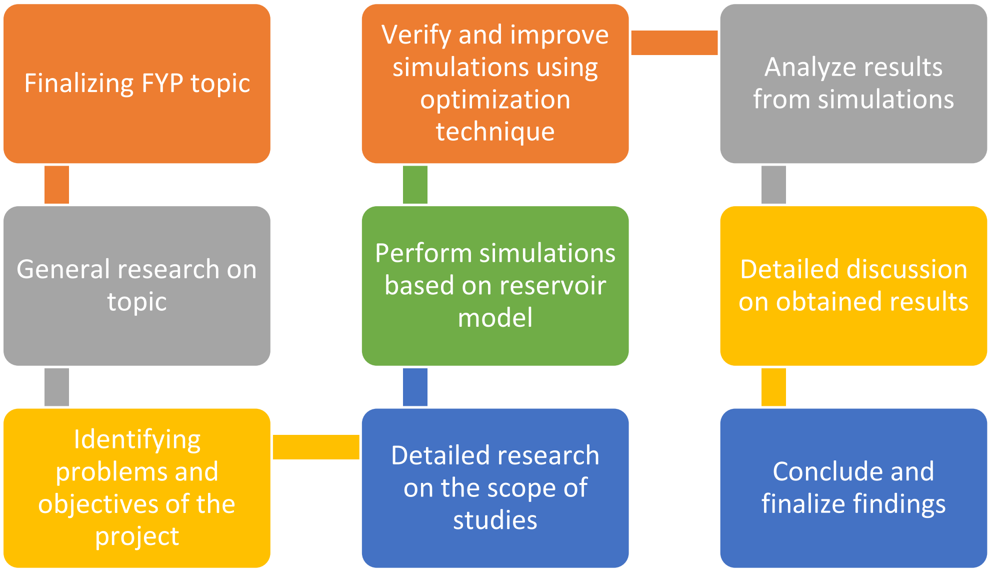


Figure 8 Project Flow Chart

3.2 Project Activities

In the beginning of the project, everything is focused on the theoretical reading and understanding of the project scope. A critical study on the literature of genetic algorithm (GA), water flooding mechanism and the reservoir structure were done in order to find the features that has not been developed yet or any weakness in existing solutions, so it could be applied in the new GA. The activities involved in this project are divided into three stages, which are early, middle and final research development. The activities involved in these stages are summarized in Figure 9 below.

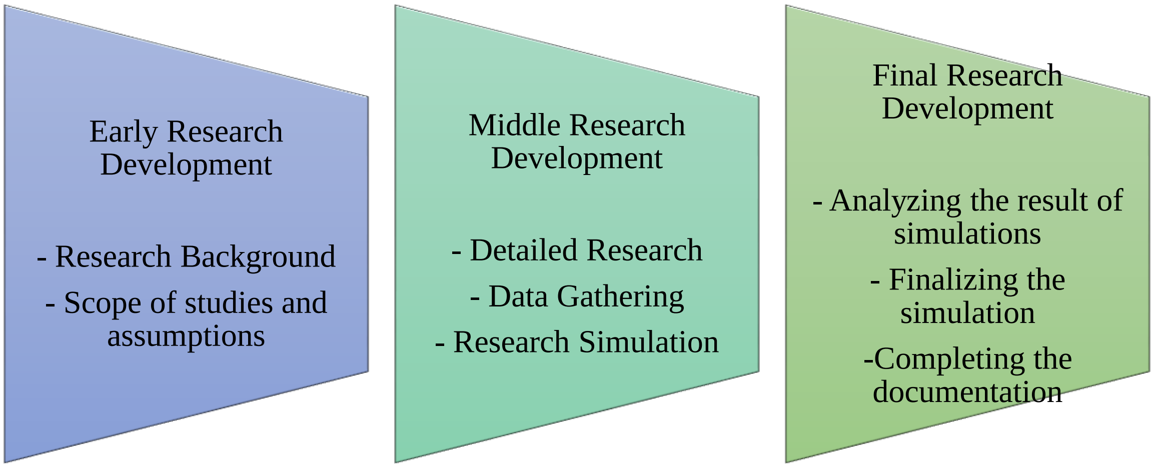


Figure 9 Project Activities

3.3 Key Milestone

Below are the key milestone that need to be achieve throughout both of the semester of final year project 1 (FYP I) final year project 2 (FYP II).

Semester 1

Table 2 Key milestone for FYP 1

Milestone	**Week**
Project Proposal	Week 3
Extended proposal (10%)	Week 6
Proposal Defense (40%)	Week 8
Interim Report (50%)	Week 11

Semester 2

Table 3 Key milestone for FYP II

Milestone	**Week**
Progress Report (10%)	Week 8
Pre-SEDEX (10%)	Week 11
Dissertation (40%)	Week 13
Technical Report (10%)	Week 13
VIVA (30%)	Week 14

3.4 Gantt Chart

No	Detail / Week	1	2	3	4	5	6	7		8	9	10	11
1	Selection of project topic		🟩	🟩					M				
2	Preliminary research work			🟩	🟩	🟩	🟩		I				
3	Literature review					🟩	🟩		D				
4	Submission of extended proposal							🟥					
5	Proposal defence								S	🟥	🟥		
6	Project planning								E	🟩	🟩	🟩	
7	Submission of interim draft report								M			🟩	
8	Submission of interim report												🟥

Legends:-

🟩 Project activities

🟥 Key milestones

3.5 Tools

This project is a simulation based project. Therefore, the tools that will be utilized are mostly software that previously has been used in undergraduate studies and can be easily accessed in the university. The tools that are needed in this project are;

- MATLAB R2009b
- Petrel 2010.2.2
- Eclipse I2009

3.6 Genetic Algorithm Workflow

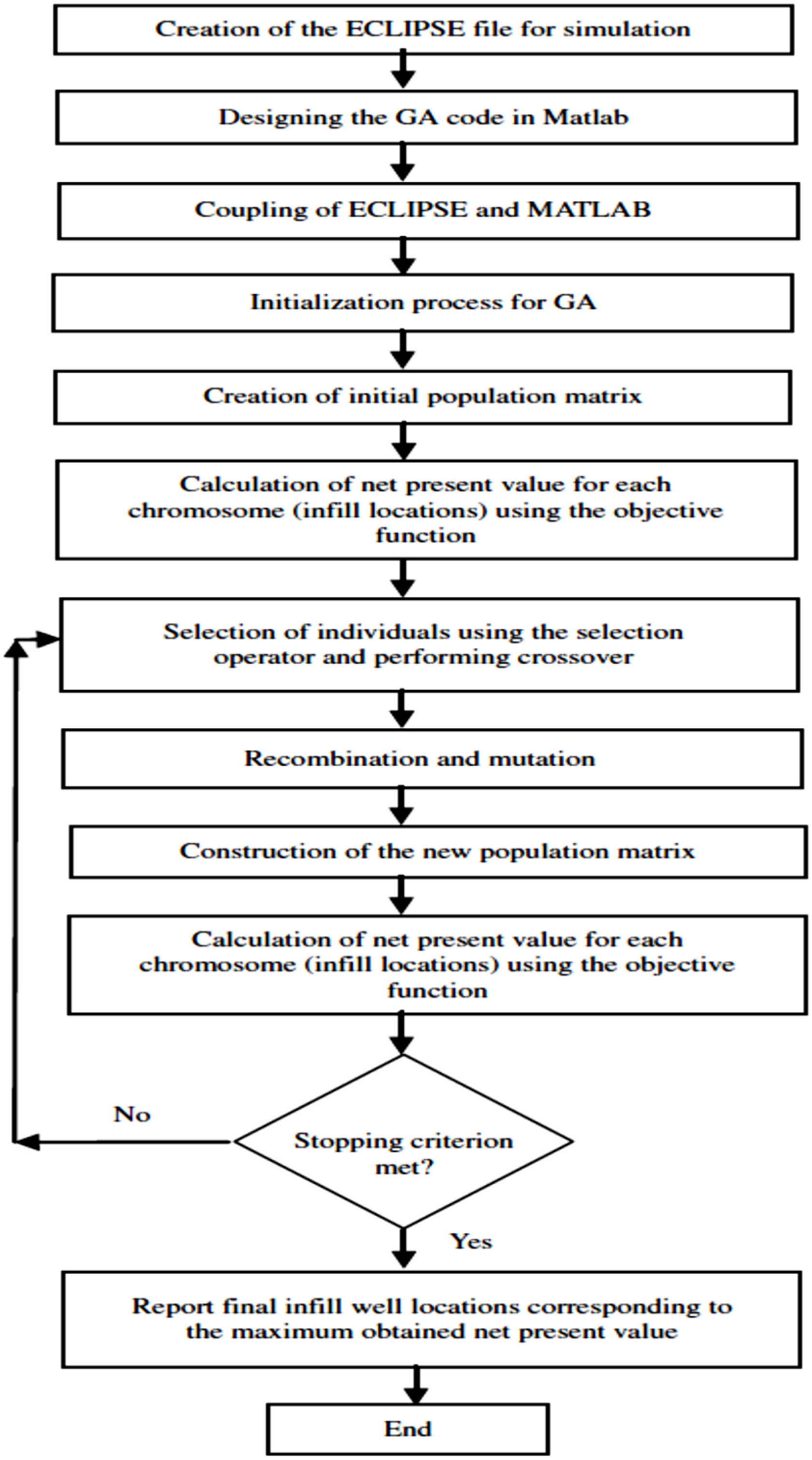


Figure 10 Flowchart of Integrated Framework

GA Parameters that are used in this study are tabulated below;

Table 4 GA Parameters

Population size	**7**
Data Structure	Integer
Crossover Probability	0.6
Mutation Probability	0.6
Selection method	Rank Based
Fitness	2.0
Number or elitists	1

CHAPTER 4

RESULT AND DISCUSSION

The project was divided into two parts. The first part was conducted in order to study the effects of fault in determining the injection well location. For the first part, the study was conducted in Gullfaks Field which is a highly faulted reservoir and the optimum well location was determined by using the highest cumulative oil production from after applying the waterflooding strategy. The second part is a study on the optimum single injection well location on a synthetic reservoir by applying Genetic Algorithm as the optimization tool. Both parts are described in details in the following paragraphs.

4.1 Optimizing Injection Well Placement in a Faulted Reservoir

Waterflooding strategy was applied in Gullfaks Field in which the operating companies has decided to run it for 25 years starting from 1st January 2014. All simulation runs were started with natural depletion strategy, with no operating constraints and with reasonable maximum number of wells that yield the highest achievable recovery as the base case. The first case study was conducted by placing the injection well near the fault and the second case was conducted with injection well located far from the fault. The optimum location was determined by using the highest cumulative oil production from the field after 25 years of production.

4.1.1 Reservoir Descriptions

For this project, the author is required to find the optimal location of water injection well for developing Gulfaks field. Gulfaks field is an oil field located in the Tampen area in the northern part of the North Sea, approximately 175km northwest of Bergen. The fields in the Gulfaks area are found in sandstones of early and middle Jurassic age, 1800-1400m of subsea. The water depth in the area is 130-220 metres. The Gullfaks reservoirs lie 1700-2000 metres below the sea level. The Gulfaks reservoirs consist of Middle Jurassic sand-stones of the Cook, Statfjord and Lunde Formations. The reservoirs lie 1700-2000 meters below the sea level.

Reservoir quality of this field is generally very high, with permeability ranging from tens of mD to several Darcys depending on layer and location. The Gullfaks Main field is over pressured, with an initial pressure of 310 bar and a temperature of 70^{o}C. The oil is undersaturated, with a saturation pressure of approximately 245 bar, depending on formation depth and location. The GOR ranges between 90 and 180 Sm^3/Sm^3 with stock tank oil gravity around 860 kg/m^3.

Structurally, the field is very complex and can be divided into three regions: “Domino Area” with rotated fault blocks in the west, a Horst Area in the east, and in between is a complex “Adaptation Zone”, characterized by folding structures. The North-South faults that divide up the field have throw up to 300 meters and in the western part, the faults slope typically around 28 degrees downwards to the east whereas in the eastern horst the slope is about 60-65 degrees downwards to the west. On top of that, the field is further cut by smaller faults, which throws of zero to few tens of meters, both in the dominant north-south as well as east-west direction. Many of these lesser faults have slopes of 50-80 degrees and these results in complex reservoir communication and drainage patterns, and is a major challenge in optimally placing wells in the reservoir.

The Gullfaks main field is now on decline, and production is reduced by a third from the peak year 1994, when oil production exceeded 30 MSm^3. Recoverable oil reserves are currently estimated at 360M MSm^3, of which approximately 330 MSm^3 have been produced by the end of 2006. The uppermost Brent sequence contains roughly 80% of the reserves, with the deeper Cook and Statfjord formations contributing the remainder. The Gullfaks satellite production varies from field to field, but as a whole they are still at plateau producing 4 MSm^3 of oil and 4 GSm^3 of gas per year. Recoverable oil reserves are currently estimated at 50 MSm^3, of which approximately 27 MSm^3 have been produced by the end of 2006 while 17 GSm^3 of gas have been produced to date. Currently, this field is producing from 20 producer wells and in order to increase production from this field, waterflooding has been selected as the recovery method.

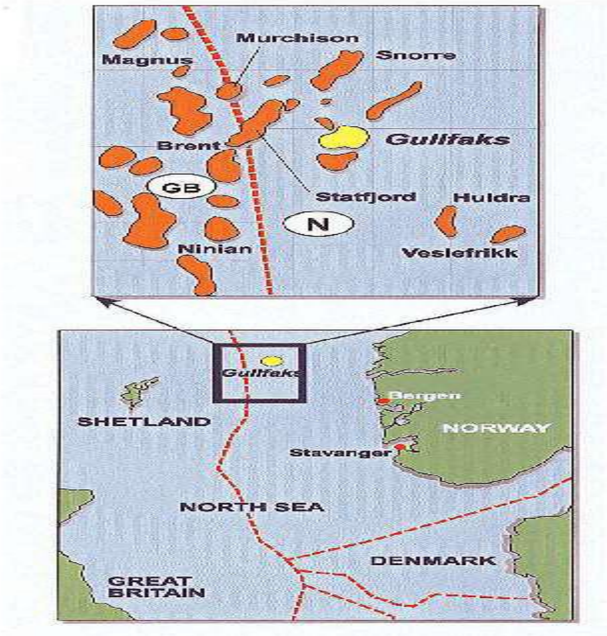


Figure 11 Geographical location of Gullfaks Field

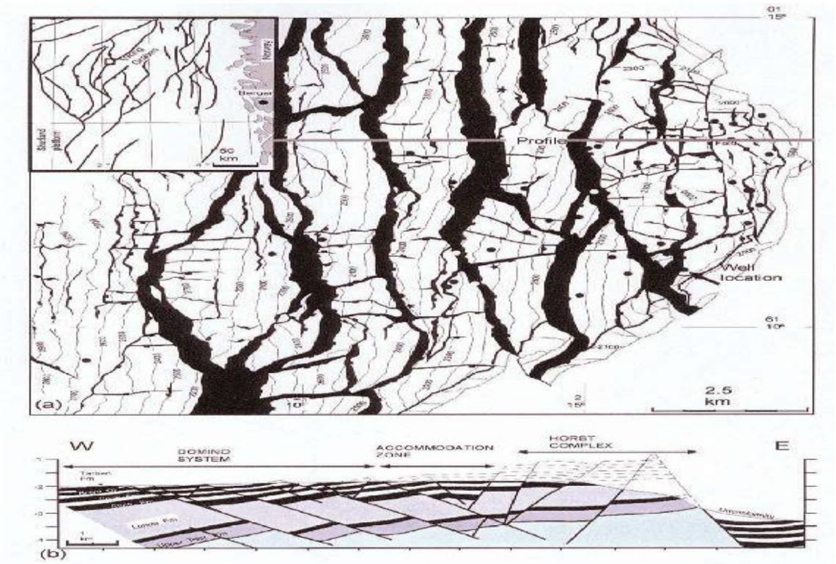


Figure 12 Structural map and cross section of Gulfaks Field

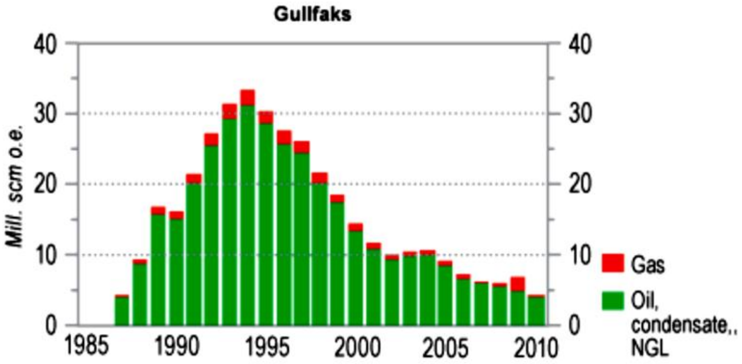


Figure 13 Production from Gullfaks is in tail production phase

The reservoir fluid contact is determined by using MDT (TVD versus formation pressure) plot. Later, the contact and gradient is confirmed by further assessing the contact using well log data and model developed. The pressure gradient and fluid contact of the reservoir are summarized in Table 5 and 6 below.

Table 5 Fluid and Pressure Gradient Data

Fluid	**Gradient (psia/ft)**
Gas	0.00953
Oil	0.253762
Fresh water	0.437752

Table 6 Fluid Contact and Depth Data

Contact	**Depth**	
	ft	m
Gas-Oil Contact	5570	1697.736
Oil-Water Contact	6250	1905

The maximum permeability measured from the core plugs was 239.4 mD with porosity of 0.26 while the maximum porosity was 0.275 with permeability of 49.326 mD. The porosity and permeability distribution of this reservoir is modelled in three dimension view by using Petrel (Figure 14-16).

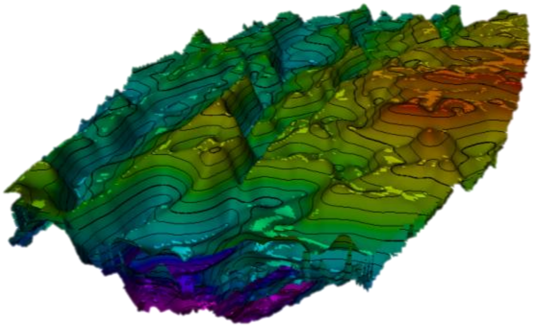


Figure 14 3D Model of Gullfaks Field. The color represents the depth of the field: Top: red, Lowest region: Purple

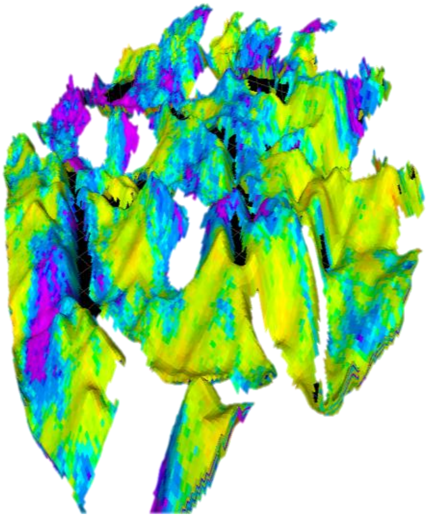


Figure 15 Porosity distribution

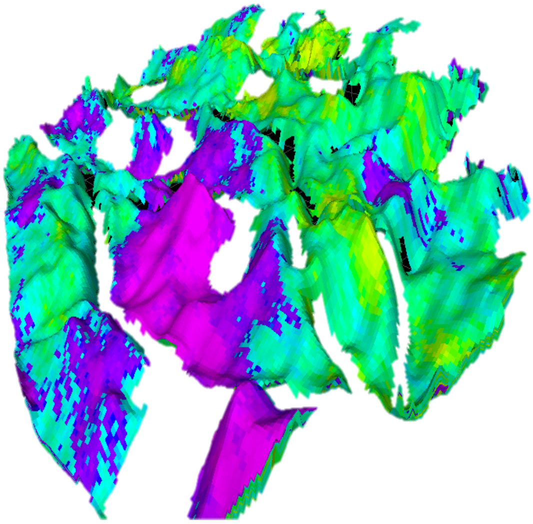


Figure 16 Permeability distribution

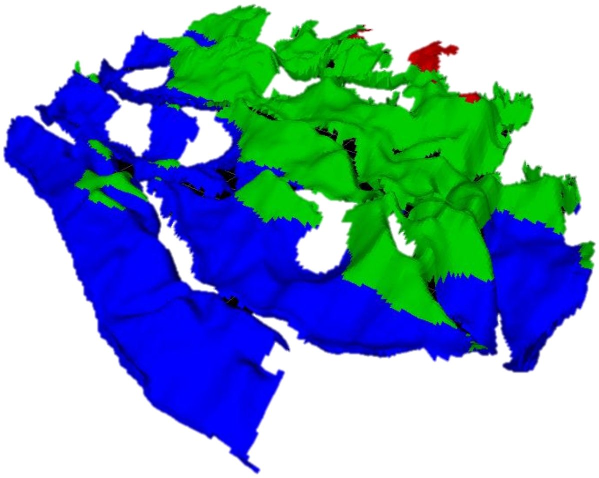


Figure 16 Fluid Contacts

The Stock Tank Oil Initially in Place (STOIIP) and Gas Initially in Place for each layer of Gulfaks field were calculated and summarized in Table 7 below.

Table 7 STOIIP and GIIP estimation

Layer	STOIIP (m^3)	GIIP (m^3)
Top Tarpet - Tarpet 2	9.3×10^7	1.25×10^8
Tarpet 2 – Tarpet 1	8.3×10^7	1.12×10^8
Top Ness – Ness 1	1.87×10^8	2.51×10^8
Total STOIIP	3.63×10^8 m^3	
Total GIIP	4.88×10^8 m^3	

The summary of Gullfaks reservoir fluid study is tabulated in Table 6 below;

Table 8 Summary of Final Results of Gullfaks Reservoir Fluid Study

Properties	Value
Reservoir Pressure, psia	2516
Reservoir Temperature, 0F	220
Bubble Point Pressure, psig	2516
Oil Formation Volume Factor, bbl/stb	1.169
Solution Gas Oil Ratio, scf/stb	130
Oil Density, lb/ft3	32

4.2 Study on the Effects of Faulting on Well Placement

In order to study the effects of fault in determining the injection well location, we have considered two cases: adding one well near the fault and one well located far from the fault. The objective is to determine which one of these two cases have the highest total production by comparing it to the total oil production from base case.

4.3 Findings

4.3.1 Base Case

Base case simulation run was started with natural depletion strategy, with no operating constraints and with reasonable maximum number of wells that yield the highest achievable recovery. The field are producing from 20 production wells for 25 years starting from 2014 until 2039. Peak production rate set for this base case was 1500 sm3/day, bottomhole pressure limit is 80 bar and water cut limit of 95%. The total oil production at the end of 25 years production is 70452387 sm^3. Figure 18 shows the producing wells locations.

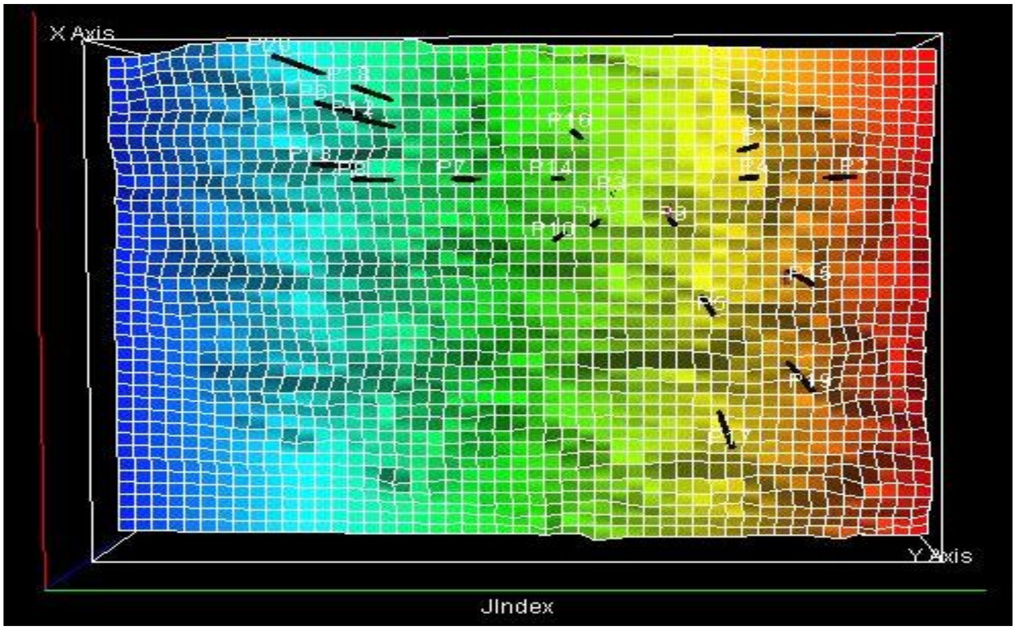


Figure 18 Producer Wells Location

4.3.2 Case 1 (Injection Well Near Fault)

The simulation for Case 1 was run by placing single injection well near fault and the simulation was repeated for three runs. The simulations has been carried out with an injection rate of 1500 sm^3/d for 25 years. Figure 19 shows the well location of I6. The total oil production from water injection strategy from single well I6 is 73057432 sm^3 with increment from base case of 2605045 sm^3. The simulation was repeated for two other wells; I3 and I2 and the cumulative oil productions were summarized in Table 9 below.

The highest increment of the cumulative oil production is from well I2 with increment of 3123397 sm3. All three wells; I6, I3 and I2 are located between the two major faults, thus affecting the oil production from the field. Assuming that the faults are sealing fault, it will permit any communications between the reservoirs, thus the waterflooding strategy will not be effective in maintaining the reservoir pressure and assist in oil production.

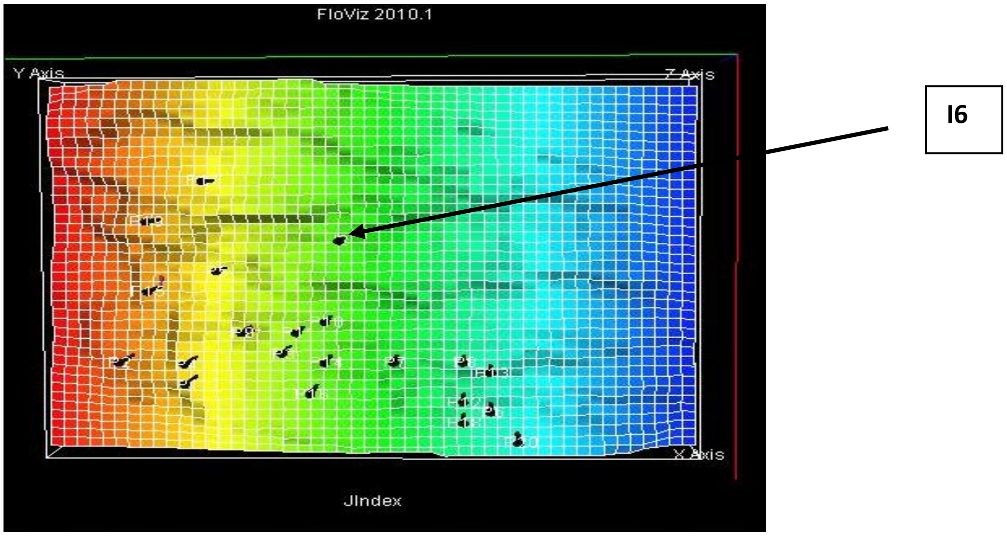


Figure 19 I6 Well Location

Table 9 FOPT from Case 1

Well	FOPT (sm3)	Increment in Oil Production (sm3)
I6	73057432	2605045
I3	73300744	2848357
I2	73575784	3123397

4.3.2 Case 2 (Injection Well Far from Fault)

The simulation for case 2 was run with the same operating constraints as Case 1 but the single injection well was placed far from fault. Figure 20 shows the well location of I5. The total oil production from water injection strategy from I5 is 76651400 sm^3 with increment from base case of 6199013 sm3. The simulation were repeated for two other wells; I9 and I12 and the summary of the cumulative oil production after 25 years of production is shown in Table 10.

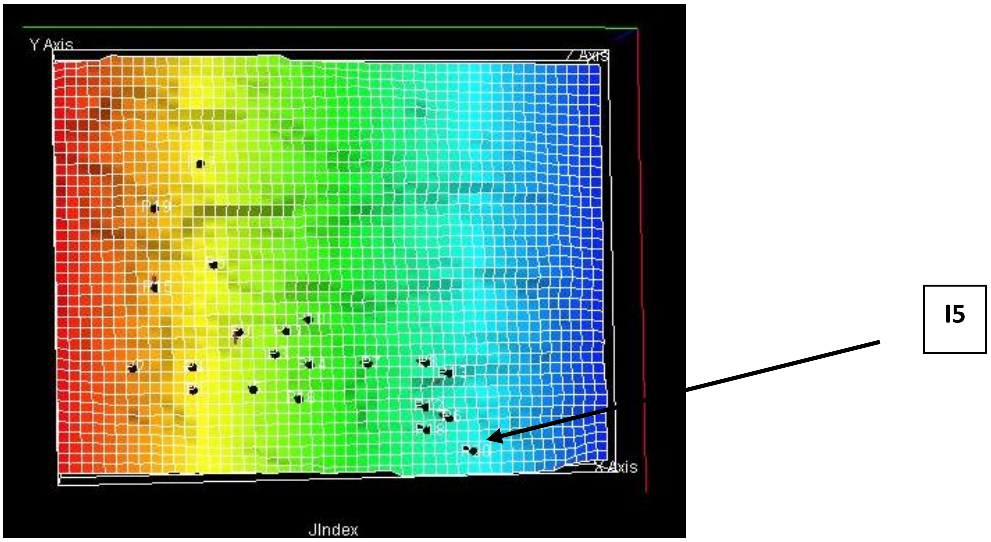


Figure 20 Well Location for I5

Table 10 FOPT for Case 2

Well	FOPT (sm3)	Increment in Oil Production (sm3)
I5	76651400	6199013
I9	77585734	7133347
I12	77457332	7004945

From the simulations done earlier, the total oil production from Case 2 gives a higher increment compared to Case 1, which means that locating a single injection well away from fault yields a better result. The results indicate that, existence of fault can affect the performance of a waterflooding process. Well I5, I9 and I12 are located far from fault which is in the southern part of the reservoir (Figure 20) where most of producers are located. By positioning the injection well at this area, it can increase the oil production as the flow of the injected water was not restricted by the fault.

However, the results might be different in case of optimizing multiple well locations but due to time constraints, the author has decided to study only on single injection well placement.

4.3 Optimization of Injection Well Placement by using Genetic Algorithm

For the second part of the project, the author has studied the optimization of single injection well placement in a synthetic reservoir by using Genetic Algorithm as the optimization tool. The synthetic reservoir has a dimension of 40 x 40 x1 and consist of only one producer. The optimum placement of a single injection well was seek by using cumulative oil production as the objective function. Figure 21 and 22 shows the porosity and permeability field of the synthetic reservoir.

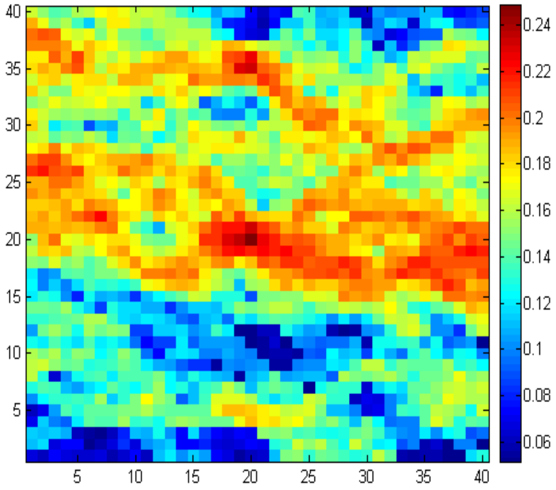


Figure 21a Porosity Model

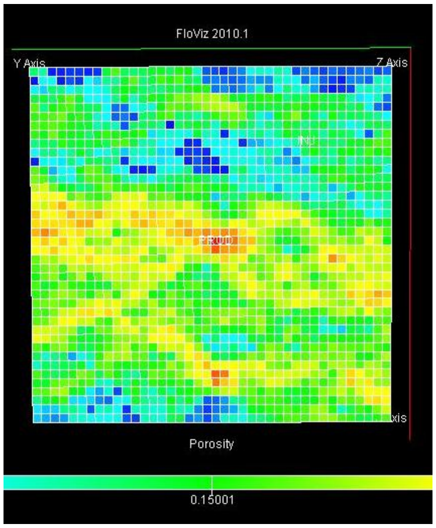


Figure 21b Porosity Distribution

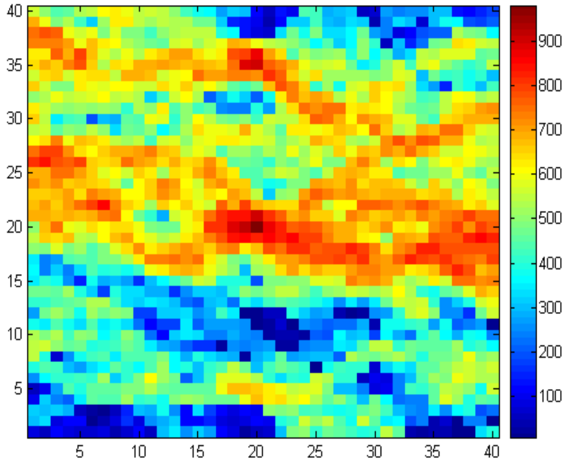


Figure 22a Permeability Model

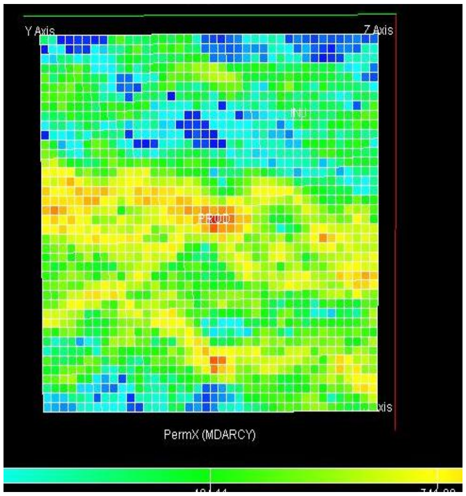


Figure 22b Permeability distribution

Table 11 shows the GA parameters used for the optimization process and the MATLAB codes used are shown in the Appendix.

Table 11 GA Parameters

Objective Function	**Maximum Cumulative Oil Production**
No of parameters	2
Lower and upper Boundary	[1 40]
Maximum iteration	25
Population Size	20
Mutation Probability	0.15
Crossover	Single-Point

The GA simulation was run by using MATLAB software and the time taken for the software to converge to its global optima is 643 seconds (~10 minutes). The simulation results show that the highest cumulative oil production is at the 6th iteration which is 5.998 x 10^5 STB and the simulations stopped after the 68th iterations. The well location proposed by the GA is (19, 2) which produce the highest oil after 5000 days of production. Figure 23 shows the performance plot at each iterations and Figure 24 shows the well location proposed by GA.

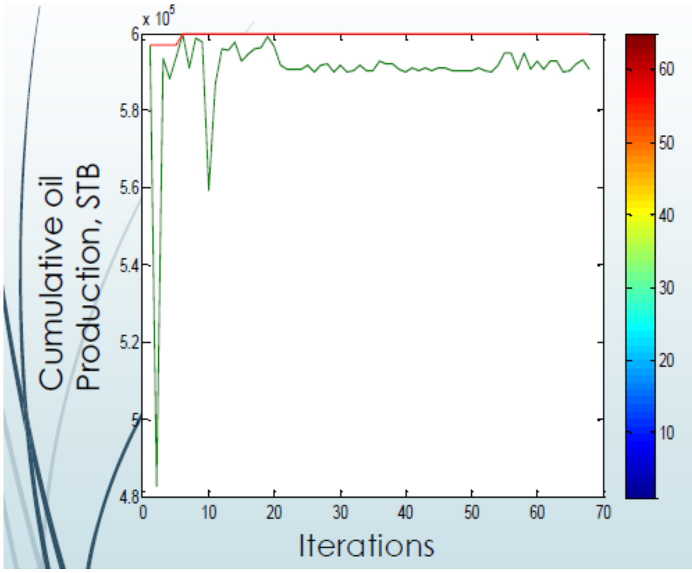


Figure 17 GA Performance Plot

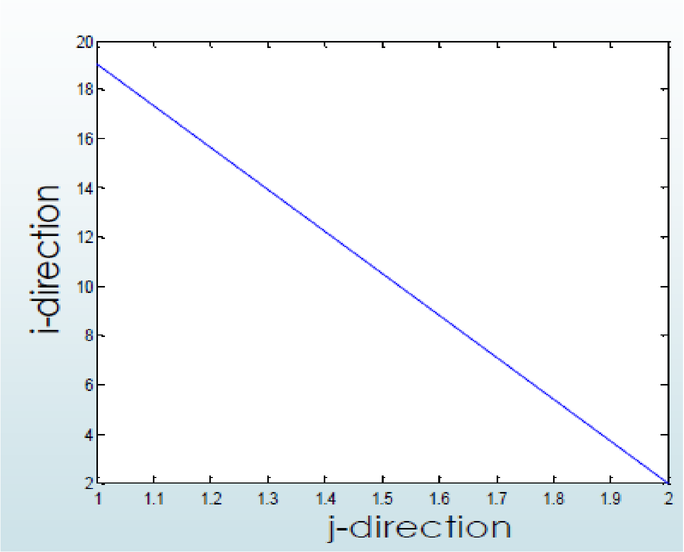


Figure 18 Well Location Proposed by GA (19, 2)

In order to verify the results obtained from GA, a simulation by using Eclipse was done by placing the injection well at the proposed location. The simulation result shows that the cumulative oil production is 599629.63 STB which is close to the value obtained from GA simulation. Thus, it can be conclude that Genetic Algorithm can be used as the optimization tool for well placement problem.

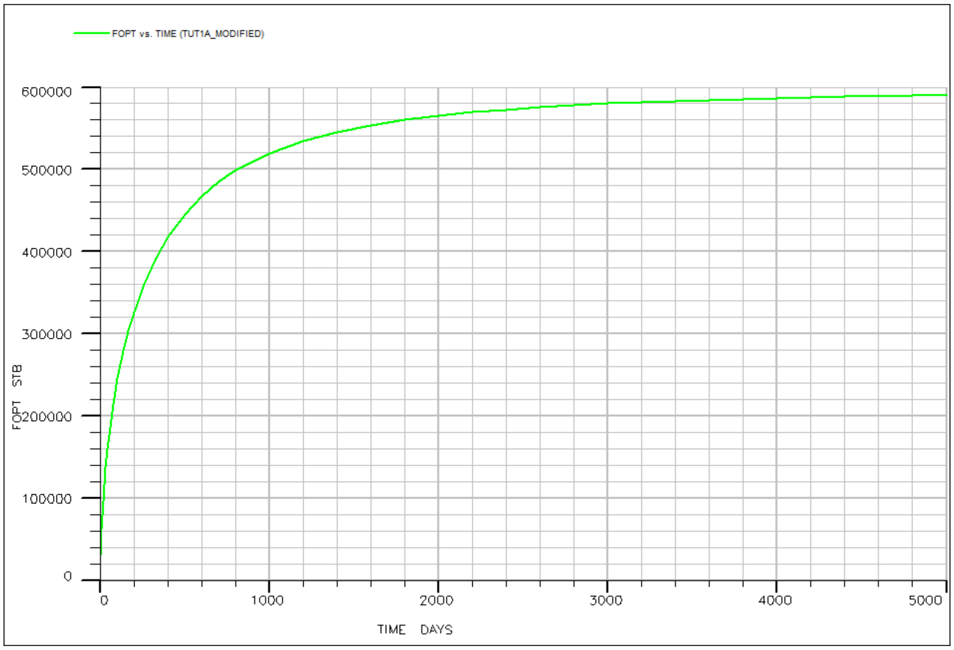


Figure 19 FOPT from Well (19, 2)

The optimization process by using GA is able to evaluate all the effects of possibly hundreds of factors in a straightforward and precise manner which is different from a human being approach. There are many factors that could affect the well placement optimization such as reservoir rock and fluid properties, physics of flow through porous media, economic parameters and these factors has been explained in details at Chapter 2. Most of these factors are hard to evaluate and is time consuming if it is to be done manually. Thus, the optimization tool is designed in order to reduce simulation time and to achieve a better result. From the simulation done earlier, GA was used to find the optimum injection well location which yields the cumulative oil production and the results were confirmed by using Eclipse. The simulations done by using Eclipse shows that, injection well located at (19, 2) produce **599629.63 STB** at the end of 5000 days of production days. Since the results obtained from Eclipse is close to the value obtained from GA, it can be assumed that GA can be used as the optimization tool for well placement problem with better accuracy and efficiency.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The introduction of the project has been discussed by the author at the early chapter of this report where she mentioned about the background study, problem statement, objective and scope of study, relevancy and feasibility of the project. Besides that, the author also discussed on the definitions of water flooding, GA and Principle of Superposition and some of the case studies that has been done related to this project.

From the simulations done at the earlier stage of this project, it can be concluded that the existence of fault plays a major role in determining the injection well location. Injection well located far from fault contributes better oil production compared to injection well located near fault. However, more details study should be carried out in order to fully validate that existence of fault will reduce the effectively of waterflooding process.

Genetic Algorithm was used as the optimization tool to find the optimum injection well placement in a 40 x 40 x 1 synthetic reservoir where the cumulative oil production of 5000 days was used as the objective function. The result shows that the optimum injection well is at (19, 2) which produce 5.998×10^5 STB. In order to verify the result obtained from GA, Eclipse simulation was run and the result obtained was close to the value from GA. Thus, it can be conclude that GA can be used as the optimization tool in determining the optimum well placement with better accuracy and efficiency.

In order to improve the results and findings of the project, several approaches can be taken which are by performing more simulation runs on the reservoir model and GA and do a detailed analysis on the results obtained from the simulations.

Appendix A

Gullfaks Eclipse Dataset (Base Case)

```
RUNSPEC

TITLE                                 -- Generated : Petrel
BASE_CASE

WELLDIMS                              -- Generated : Petrel
  20 54 2 20 /

START                                 -- Generated : Petrel
  1 JAN 2013 /

DISGAS                                -- Generated : Petrel

WATER                                 -- Generated : Petrel

OIL                                   -- Generated : Petrel

GAS                                   -- Generated : Petrel

PETOPTS                               -- Generated : Petrel
INITNNC /

EQLOPTS                               -- Generated : Petrel
  THPRES /

FAULTDIM                              -- Generated : Petrel
356 /

MONITOR                               -- Generated : Petrel

MULTOUT                               -- Generated : Petrel

METRIC                                -- Generated : Petrel

DIMENS                                -- Generated : Petrel
  39 49 60 /

TABDIMS                               -- Generated : Petrel
  3 1 33 190 1* 190 190 5* 3 /

AQUDIMS                               -- Generated : Petrel
  1* 1* 1* 1* 2 966 1 1 /

EQLDIMS                               -- Generated : Petrel
  1 /
```

```
GRID

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_GRID.INC' /

NOECHO                                    -- Generated : Petrel

GDFILE                                    -- Generated : Petrel
BASE_CASE_GRID.EGRID /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_PERMX.GRDECL' /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_PERMY.GRDECL' /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_PERMZ.GRDECL' /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_PORO.GRDECL' /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_NTG.GRDECL' /

ECHO                                      -- Generated : Petrel

EDIT

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_EDIT.INC' /

PROPS

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROPS.INC' /

REGIONS

NOECHO                                    -- Generated : Petrel

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_SATNUM.GRDECL' /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_PVTNUM.GRDECL' /

INCLUDE                                   -- Generated : Petrel
'BASE_CASE_PROP_ROCKNUM.GRDECL' /

INCLUDE                                   -- Generated : Petrel
```

```
'BASE_CASE_PROP_EQLNUM.GRDECL' /

ECHO                                -- Generated : Petrel

SOLUTION

INCLUDE                             -- Generated : Petrel
'BASE_CASE_SOL.INC' /

SUMMARY

INCLUDE                             -- Generated : Petrel
'BASE_CASE_SUM.INC' /

SCHEDULE

INCLUDE                             -- Generated : Petrel
'BASE_CASE_SCH.INC' /
```

Appendix B   Synthetic Reservoir Dataset

```
RUNSPEC

TITLE
3D - 2 Phase Model


--       Number of cells
--      NX      NY      NZ
--      --      --      --
DIMENS
           40      40      1 /

-- Phases
OIL
WATER

-- Units
FIELD

-- Maximum well/connection/group values
--     #wells  #cons/w  #grps  #wells/grp
--     ------  -------  -----  ----------
WELLDIMS
           2         3         2          1 /
```

```
-- Unified output files
UNIFOUT


-- Simulation start date
START
  1 Jan 2014 /

==========================================================
GRID


-- Size of each cell in X, Y and Z directions
DX
1600*50/

DY
1600*50/

DZ
1600*10/

--TVDSS of top layer only
--         X1  X2     Y1  Y2     Z1  Z2
--         --  --     --  --     --  --
BOX
              1    40    1   40      1    1 /

TOPS
1600*8000/

ENDBOX

-- Permeability in X, Y and Z directions for each cell

INCLUDE
'mall_avg_permfield.perm'
/

COPY
 'PERMX'  'PERMY'  /
/

COPY
 'PERMX'  'PERMZ'  /
/

-- Porosity of each cell
INCLUDE
'mall_avg_porofield.poro'
```

```
/

-- Output file with geometry and rock properties (.INIT)
INIT
==============================================================
PROPS

-- Densities in lb/ft3
--        Oil     Wat     Gas
--        ---     ---     ---
DENSITY
            49      63      0.01 /

-- PVT data for dead oil
--      P       Bo      Vis
--     ----    ----    -----
PVDO
          300      1.25     1.0
       800      1.20     1.1
      6000      1.15     2.0
/

-- PVT data for water
--      P       Bw      Cw        Vis    Viscosibility
--     ----    ----    -----     -----   -------------
PVTW
      4500      1.02      3.0E-06    0.8       0.0  /

-- Rock compressibility
--      P        Cr
--     ----     -----
ROCK
      4500       4E-06 /

-- Water and oil rel perms & capillary pressures
--      Sw      Krw     Kro     Pc
--     -----   -----   ---    ----
SWOF

-- table 1 for 1000mD
        0.15     0.0      0.9      4.0
        0.45     0.2      0.3      0.8
        0.68     0.4      0.1      0.2
        0.8      0.55     0.0      0.1  /

-- table 2 for 200mD
           0.25          0.0      0.9      9.0
           0.5           0.2      0.3      1.8
           0.7           0.4      0.1      0.45
           0.8           0.55     0.0      0.22  /
```

```
============================================================
SOLUTION

-- Initial equilibration conditions
--        Datum   Pi@datum    WOC    Pc@WOC
--        -----   --------   -----   ------
EQUIL
          8075     4500       8500    0.0 /

-- Output to Restart file for t=0 (.UNRST)
--     Restart file     Graphics
--     for init cond     Only
--     -------------    -------
RPTRST
       BASIC=2           NORST=1 /

============================================================
SUMMARY

-- Field average pressure
-- FPR

-- Bottomhole pressure of all wells
-- WBHP
/
-- Field Oil Production Rate
FOPR

-- Field Water Production Rate
FWPR

-- Field Oil Production Total
FOPT

-- Field Water Production Total
FWPT

-- Field Water injection rate
FWIR

-- field Recovery factor
--FOE

-- Water cut in PROD
WWCT
PROD /

-- CPU usage
TCPU
-- Create Excel readable Run Summary file (.RSM)
EXCEL
```

```
============================================================
SCHEDULE

-- Output to Restart file for t>0 (.UNRST)
--     Restart file
--      every step
--     ------------
RPTRST
       BASIC=2          NORST=1 /

INCLUDE
'wellfile.dat'
/
-- Number and size (days) of timesteps
TSTEP
25*200 /

END
```

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