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EOR SCREENING AND OPTIMIZING STUDY ON SANDSTONE RESERVOIRS

By:

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CERTIFICATION OF APPROVAL

EOR SCREENING AND OPTIMIZING STUDY ON SANDSTONE RESERVOIRS

By

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A project dissertation submitted to the

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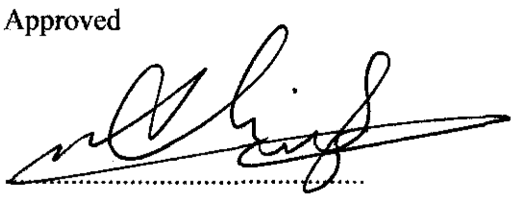
Approved



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Project Supervisor

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 acknowledgments and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

Over the decades, Enhanced Oil Recovery (EOR) methods have been used to boost the declining oil production with conventional methods. EOR consists of Thermal Recovery, Chemical Flooding, Gas injection, and the new technology, Microbial Injection. All of these methods have proven effective in recovering 25% to 65% more oil in place with thermal recovery as the most dominant (Taber *et al.*,1997). However it is believed that the current EOR screening is not sufficient in providing the best and suitable EOR application. Thus, this study was conducted for adequate and effectual **EOR SCREENING AND PRODUCTION OPTIMIZATION IN SANDSTONE RESERVOIR.** The screening that was used for this study was the conventional technical screening that is according to the SPE criteria, as well as a software named EORsc which was developed for this study that has screening purposes that can evaluate the suitable application of EOR with given data in a short time. The outcome of this study was successful in determining EOR methods for sandstone reservoir candidate using the screening methods above.

Keyword : Enhanced oil recovery; EOR; thermal recovery; chemical flooding; gas injection; microbial; EORSc

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CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Enhanced Oil Recovery (EOR) projects are expensive, time consuming and people intensive. All recovery methods beyond the natural drive should be considered as a part of EOR. The goal of EOR is to mobilize the remaining oil after primary recovery. No single process can be considered a 'cure all' for recovering additional oil from every reservoir. Each process has its specific application. Every well must be treated differently, as the nature of every well varies (Prats,1982 & Farouq Ali,1979). So screening must be done to determine which EOR method is the best and most efficient to be used on the selected well. Data of the well such as type of formation, permeability, viscosity, pressure, and fluid density must be taken into consideration and this will be the criteria of the screening process.

EOR projects have attracted much attention because of its potential to unlock more oil in depleted reservoirs. Extensive capitals are being invested into EOR projects, so the project implementation must also be looked from the economic perspective, whether it is economically feasible to use a type of method. A method may recover more oil comparing to another method, but economically, the gain profit may never cover the implementation cost, which will lead to loss financially (Hammershaib *et al.*, 1983).

Therefore, to implement an EOR method, screening must be done to select the best method for effective gain as well as it is economically viable to bring profit.

1.2 Problem Statement

1.2.1 Problem Identification

Enhanced Oil Recovery projects are done extensively all over the world as it significantly increases the production of oil. It is very essential to determine the suitable EOR method for efficient and economic recovery. However, it is believed that the current conventional screening methods are not enough. Application of an EOR method to a reservoir using insufficient screening can lead to wrong EOR method applied that cannot bring profit.

1.2.2 Significance of Project

Through this project, implementation of a better screening of EOR methods by using several screening methods that include collection of relevant reservoir and fluid data, screening of EOR according to SPE criteria (Taber *et al.*,1997), and application of software that can select the most technically applicable EOR method was conducted. Also note that this study mainly focused on the technical part of the EOR screening only.

1.3 Objectives

a) **To determine the best and most suitable EOR method for a sandstone reservoir.**

   There are many EOR methods implemented in fields around the world. However, this project focuses on the implementation of EOR on sandstone reservoir. Sandstone reservoirs have different characteristic as well as carbonate reservoirs or other type of lithology. By doing this project, the most suitable EOR to be applied based on the data of the several wells was determined.

b) **To conduct EOR screening that includes the usage of a software named EORSc that has the screening capability for EOR implementation as well as conventional screening methods.**

   EOR screening is one of the major steps before implementing an EOR method. Screening criteria that was proposed by Taber,1997 was used to give quick insight on which method to be applied. For this project, a software named EORSc was developed for the screening purposes. This software has the capability to do selection of suitable EOR based on the data provided.

c) **To understand and perceive the importance of implementing the right and suitable method on sandstone reservoir.**

   The implementation of a certain method is maybe the best according to the literature as well through screening. But it may have limitation whether on the reservoir itself, equipment or economically. So understanding from every point of view is very crucial for this project.

1.4 Scope of Study

The scope of study revolves around the selection of the best method to apply to a sandstone reservoir. It is very crucial to understand the importance and relevance of choosing the suitable EOR method. By doing this project, the awareness to carefully select the best method was gained as this will affect the production in all aspects.

The first part of this study was research on the geographical characterization of the reservoir, fluid and rock data, the existing screening criteria as well as the EOR methods. The parameters of each element must be familiarized before advancing to the second part.

The second part revolves around the selecting process of the suitable EOR method after all the data have been analyzed. The viscosity, depth and permeability are of importance data as they can provide quick application of screening criteria using the technical screening method (Taber & Martins,1983). A software named EORSc was developed and will also be used as the software provide predictions for the best EOR method for implementation.

1.5 The Relevancy of the Project

EOR played a vital role in the current and future field. There are many reports that show the contribution of EOR in total oil production has increase steadily throughout the last two decades. With improving technology advancement, it is foreseen that the coming future is very bright for EOR development. This research is relevant in improving the effectiveness of EOR screening. Not only will the screening be done using the conventional method, but also as well as using the EORSc software as an alternative and modernization of screening technique in line with the advancement of technology.

1.6 Feasibility of Project within Scope and the Time Frame

The author has achieved all the objectives in providing scientific findings and observations to give the best screening of EOR methods in sandstone reservoir that are based on the scope of study and the time frame set for the research. All the materials and equipments to conduct the experiments was used and utilised and the study was finished within the time frame.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The Enhanced Oil Recovery processes are characterized by the introduction of fluids into the reservoir that alters the properties of reservoir fluid and rocks as well as their interaction (Alvarado, 2008). These processes improve the reservoir in terms of displacement efficiency as well as sweeping efficiency. Displacement efficiency is increased by decreasing the oil viscosity or by reducing the capillary forces or interfacial tension while sweeping efficiency is improved by increasing viscosity of the displacing agent. Enhanced Oil Recovery may be classified into 4 major categories which are :-

- Thermal Recovery
    - Steam injection
    - Cyclic steam injection
    - In-situ combustion
- Gas Injection
    - Carbon dioxide flooding
    - Natural gas flooding
    - Nitrogen floding
- Chemical Recovery
    - Polymer flooding
    - Micellar-polymer flooding
    - Alkaline Flooding
- Microbial Flooding.

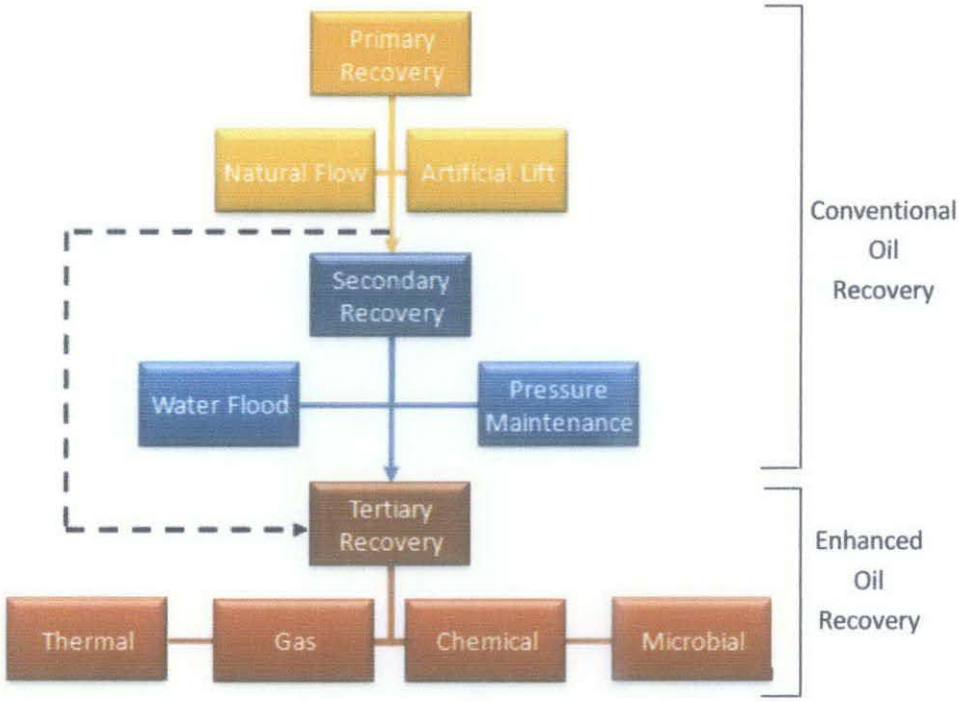

Figure 1 : Oil Recovery Methods

2.2 Sandstone Reservoirs

One of the screening considerations for EOR methods is the lithology of the formation. This is due to the fact that lithology frequently limiting the implementation of a certain EOR method (Taber *et al.*,1997).

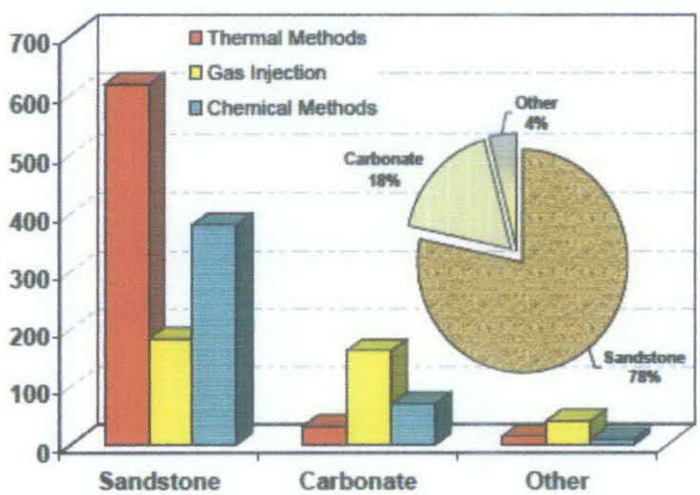

Figure 2 : EOR Methods by Lithology

E. Manrique *et al.*, 2010

From the figure 2, we can see that thermal methods and chemical methods are mostly used on sandstone formations compared to other lithology. Sandstone reservoirs show the highest potential to implement EOR methods as this lithology has been tested with most of the technologies at pilot and commercial scale.

2.3 EOR Method for Sandstone Reservoir

2.3.1 Thermal Recovery

Thermal recovery comprises of Steam flooding, Cyclic Steam Stimulation (huff & puff) and In Situ Combustion. These methods have been known effective for extracting heavy and extra heavy oil. This is because the method's general concept is heating the heavy oil resulting in expansion and reducing its viscosity and making it more fluid. Thermal method is also the most cost efficient EOR method (Prats, 1978).

a) Steam flooding

In Steam Flooding, high temperature steam is injected into the well and heats the oil, resulting in the expansion of oil and reducing its viscosity. Thus making the oil easier to flow to the production well. This method is generally used in heavy oil recovery to overcome its high viscosity that hinders the movement of oil (Wu, 1977).

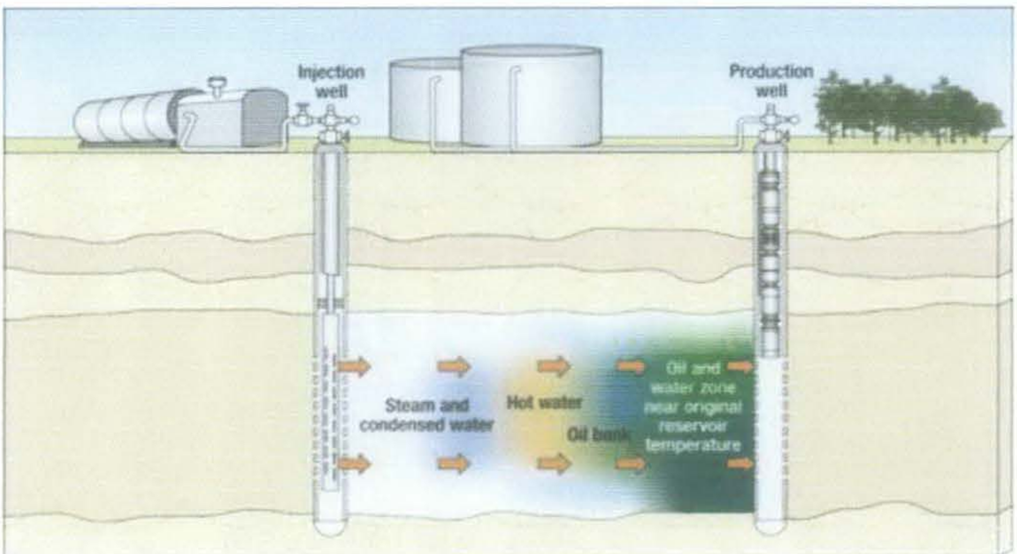

Figure 3 : Steam Flooding

Typical steam flooding recovery is 50 to 60% of oil in place, though recovery can range up to 75%. The steam flooding method is widely used around the world, with Duri Field in Indonesia as one of the largest steam flood projects.

b) Cyclic Steam Injection

Cyclic Steam Injection is also known as the Huff and Puff Method. Steam is injected into the well, and the well is shut in to allow the steam to heat the formation. The heat reduces the viscosity of fluids and thereby improves the mobility. The well is opened back after a sufficient time when the heat has dissipated with the production fluids.

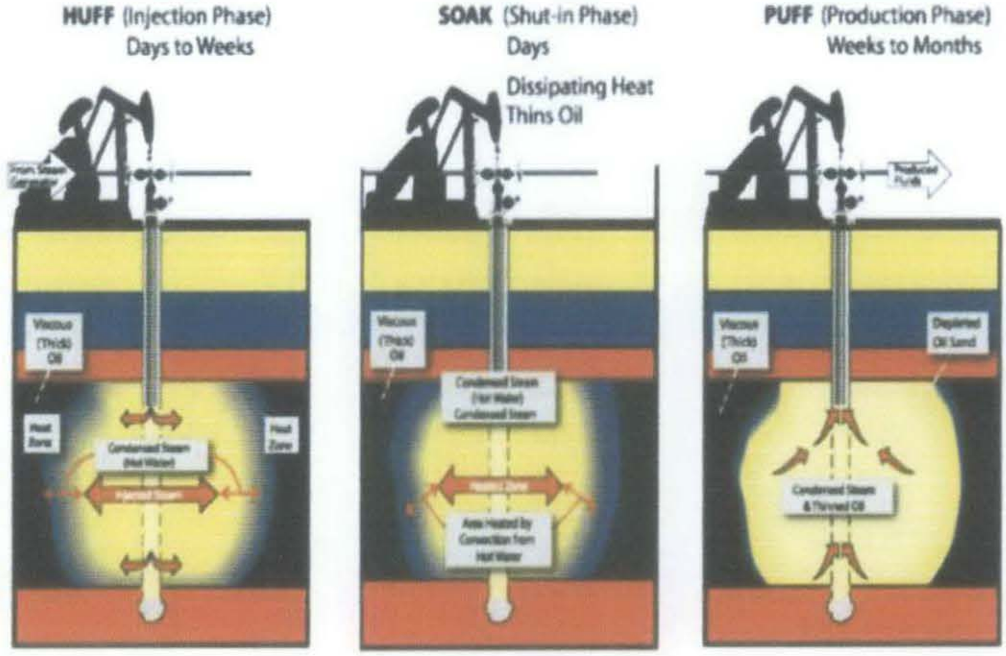

Figure 4 : Cylic Steam Injection

When oil production declines to a point below the economical rate, the whole cycle is then repeated again. With every cycle, water cut increases, oil production declines and the cycle becomes longer. After few cycles, this method is converted to steam flooding method. This method has been used for nearly four decades and it is still the main enhanced recovery process to recover heavy and extra heavy crude (Trebolle *et al*., 1993).

c) In Situ Combustion

In Situ Combustion or Fire Flooding is commonly used in a reservoir that has heavy oil that is too viscous to produce with conventional method. The combustion is generated by igniting the oil in situ by injection air to create a combustion zone that moves through the formation to the production well. The intense heat will result in oil to vaporized and become steam form.

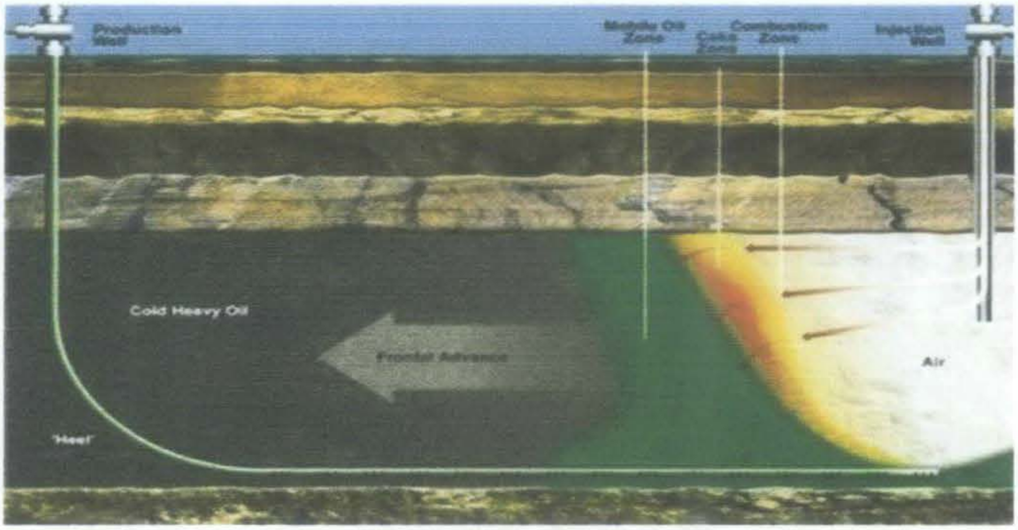

Figure 5 : In Situ Combustion

Forward Combustion

In this process, the lighter fractions of crude oil is vaporized by the heat of combustion and drives them ahead of a slow moving combustion front created as some of the heavier hydrocarbons are burned (Van Poolen, 1980). At the same time, water is vaporized in the combustion zone. The resulting combination of gas, steam and hot water with thinning of oil moves the oil to the production well from injection well.

Reverse Combustion

The air injection in the injection well is switched with the production well. Resulting the oil bank to moves in the direction of the air flow while the combustion front moves towards the injection well. This method allows heavy crude to be heated up to 700° F, reducing the viscosity greater. Reversed combustion is developed for extra heavy oil. However, many pilot field tests have failed because it tends to revert to forward combustion as oil is ignited near combustion zone cuts off oxygen supply.

Wet Combustion

Wet combustion can be started by injecting water together with air after the combustion front has reached a short distance away from the air injection well. Advantage of wet combustion is that it is effective in scavenging the remaining heat left behind and transporting it forward. This method also requires less fuel and air rates. However, lower fuel consumption results in higher combustion velocity, which reduces the life of the project.

2.3.2 Gas Injection

Miscible gas is injected into the reservoir and will dissolve in the oil. Techniques for miscible gas injection are by Carbon Dioxide Flooding, Nitrogen Flooding and Natural Gas Injection. By injecting these gases into the reservoir, it will mix with the oil and making the oil lighter, thus easier to produce. This method has been implemented widely for recovering light, condensate and volatile oil (Manrique *et al.*, 2010). Gas like CO_2 is also easy to get from natural sources and it is also cheap.

a) Carbon Dioxide (CO_2) Flooding

When Carbon Dioxide (CO_2) is injected into the well, it will dissolve in the oil, making the oil less viscous. The CO_2 gas then pushes the oil to the producing wells from the reservoir. The initial CO_2 Injection is then followed by alternate water and again CO_2 injection. The water serves to improve the sweeping efficiency. This process is called Water Alternating Gas (WAG) (Holm, 1974).

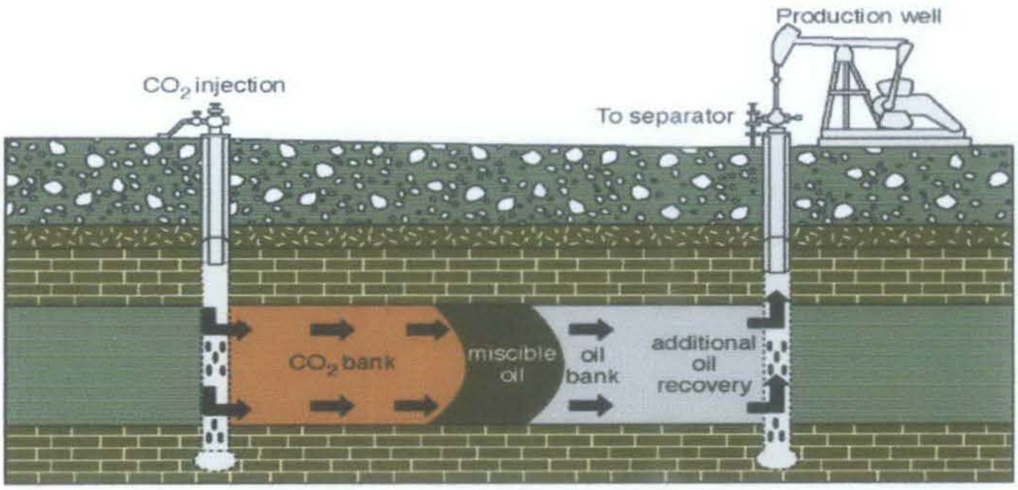

Figure 6 : CO_2 Flooding

This method is suitable for moderate light to light oil reservoirs, deep enough to be above MMP. CO_2 flooding is considered as a better method compared to other miscible methods, in view of its higher viscosity and greater density than methane. However, CO_2 is soluble in water, which could lead to loss if not controlled.

b) Nitrogen(N_2) Flooding

Nitrogen Flooding is commonly used to recover light oil. However, the nitrogen must me injected more than 5000 ft deep to withstand the high injection pressure necessary for the oil to mix with the nitrogen without fracturing the formation.

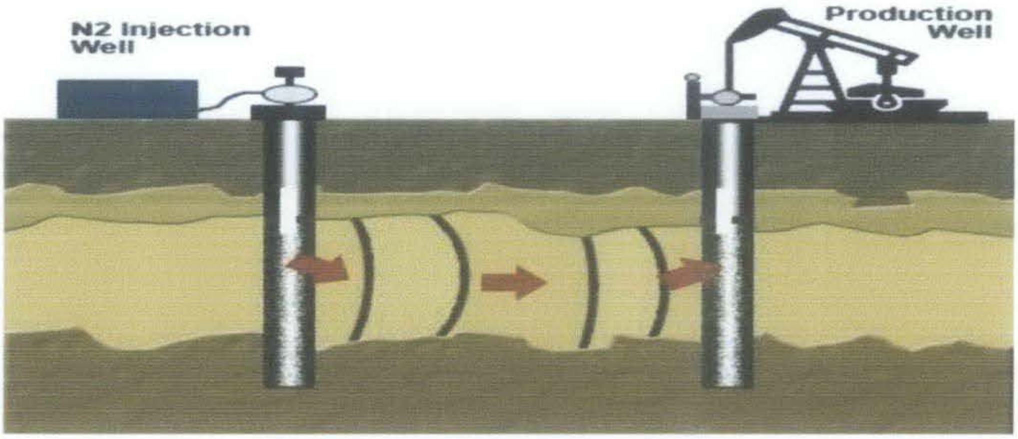

Figure 7 : Nitrogen Flooding

Nitrogen is considered as the cheapest gas that can be injected other than compressed air. In addition to its low cost, nitrogen is the most inert of all other injection gas. However, it has the highest MMP, so it must be injected in very deep light oil reservoir (Taber, 1997).

c) Natural Gas Injection

Natural gas injection is one of the oldest EOR methods. Usually Liquefied Petroleum Gas (propane, butane) is used for this injection. LPG is injected into the well to mix with the oil to make the oil lighter and making it easier to produce. Usually this method is used when there is a large supply of natural gas available but there is no means of transportation to the market. However from the economic point of view, it is better to use other gases if available because more natural gas can be made usable in domestic use or export (Manrique, 2010).

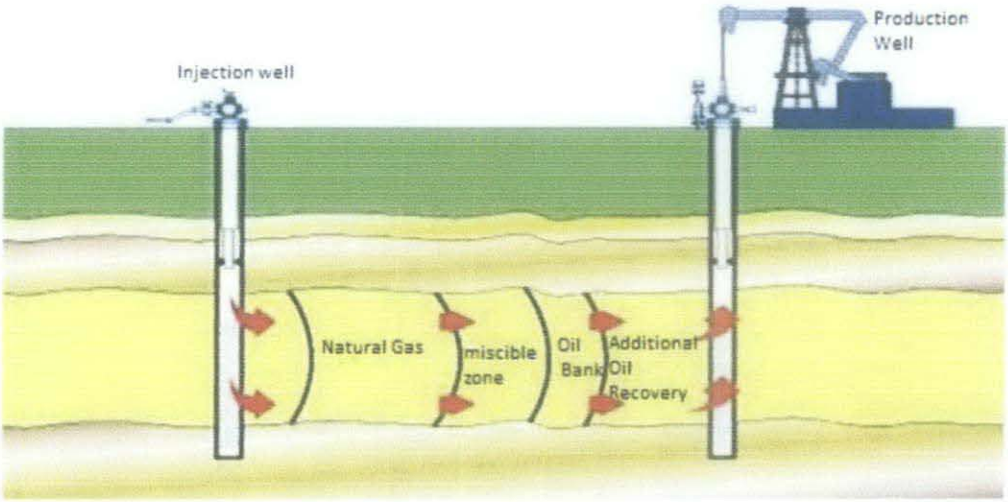

Figure 8 : Natural Gas Flooding

2.3.3 Chemical Recovery

The methods for this recovery include Polymer Flooding, Micellar-Polymer Flooding and Alkaline Flooding. By injecting the chemicals into the reservoir, it will reduce the surface tension of the oil, making the oil easier to move (Burnett & Dann,1981). These methods can be used mainly for sandstone reservoirs because carbonates absorb the surfactants. Although these methods are declining in use, the chemical method is growing in interest as new technologies developing the method are showing very promising results. Although chemical flooding can improve the oil recovery if designed properly, many limitations exist because of the chemical, the fluid, rock, and reservoir properties.

a) Polymer Flooding

This method is the most applied EOR chemical method in sandstone reservoir. It is also considered as a mature technology. The Polymer flooding method works by adding a water soluble polymer into the well, which will result in thickening of water, making it more viscous. Thus, improving the sweeping efficiency (Islam & Farouq Ali, 1990). This method has greatest potential in reservoirs with moderately heterogeneous, contain moderately viscous oil and have adverse water-oil mobility ratio.

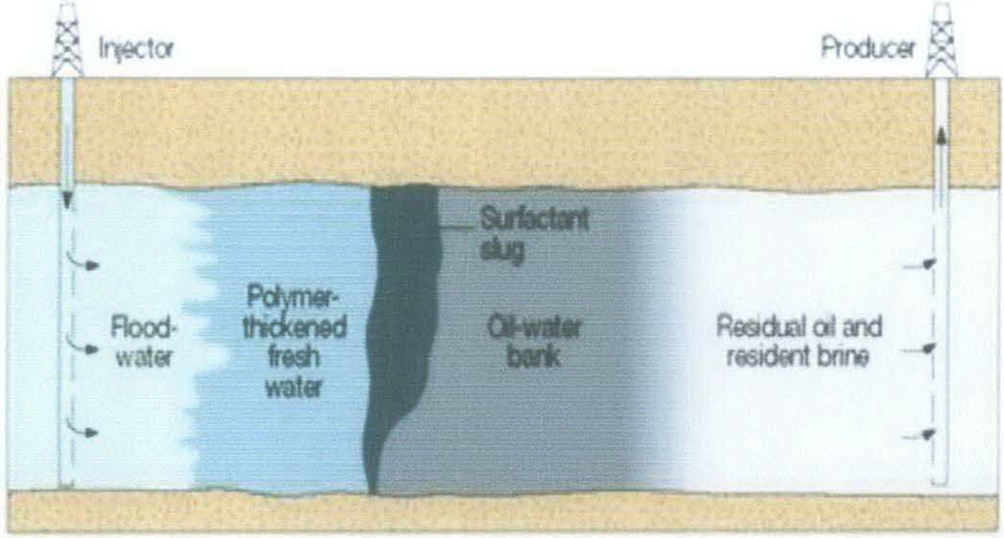

Figure 9 : Polymer Flooding

b) Micellar-Polymer flooding

In a Micellar-Polymer flood, a micellar slug is injected containing surfactant, polymer and other chemicals. The surfactant acts as a detergent, reducing the surface tension of oil washing the oil out of the pore space. The oil will form small droplets called microemulsion. Then the polymer will drive the microemulsion towards the producing well (Burnett & Dann,1981). This is one of the most efficient EOR project but it is expensive to implement. The slug must be designed specifically for crude oil type, reservoir temperature and water salinity.

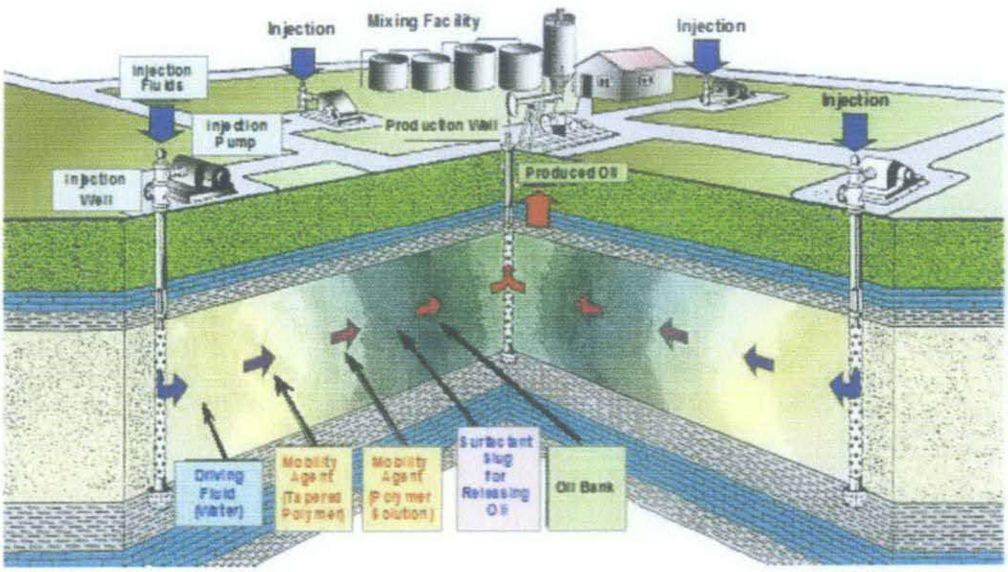

Figure 10 : Micellar-Polymer flooding

c) Alkaline Flooding

Alkaline Flooding method used alkaline chemicals to improve oil recovery by interfacial tension reduction, emulsifying of oil and wettability alteration. Injecting alkaline chemicals that react with petroleum acids will form surfactant that will reduce surface tension making the oil move more easily through the reservoir (Cooke, 1974). This method is known for almost 70 years, but due its applicability to only certain types of crude oils and the complex mechanism involved, large scale, commercial field operations of this process have not been undertaken.

2.3.4 Microbial Flooding (MEOR)

This method involves injecting a solution of micro-organism and nutrients into the reservoir. The micro-organism will feed on the nutrient, and they metabolically produce products ranging from surfactants and acids to certain gas such as hydrogen and CO_2. These products affect the oil in many ways, making it easier to move to the producing well (Dietrich *et al.*, 1996). The mechanisms that help to enhance oil production are reduction of oil viscosity, production of CO_2 gas, production of biomass, selective plugging and production of biomass

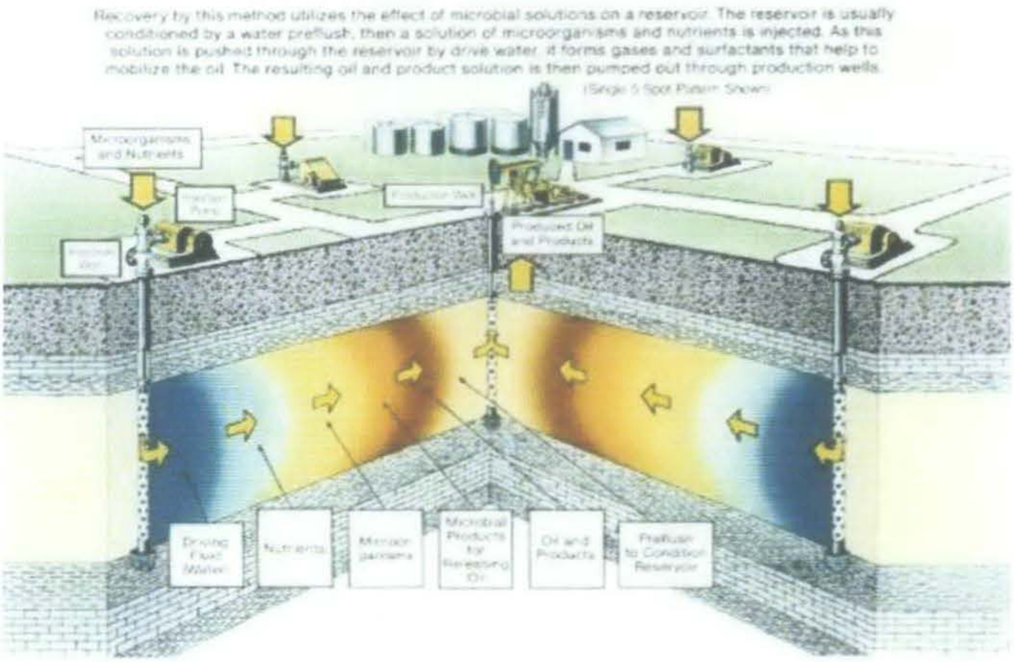

Figure 11 : Microbial Flooding

2.4 EOR Screening

Taber *et al*, 1997 has proposed screening criteria for all EOR methods. Analyses on field data from all around the world have been conducted and the best field criteria have been observed and noted. Below is the API gravity of oil for the current EOR methods.

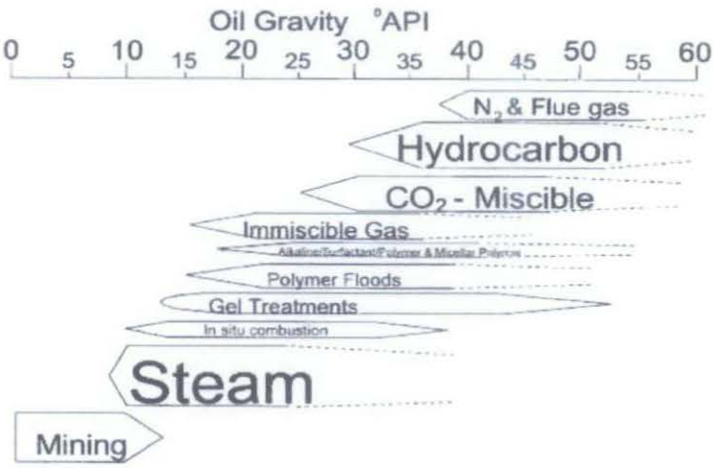

Figure 12 : Oil Gravity Range that is Effective for EOR Methods

Taber *et al*, 1997

The screening criteria that Taber has proposed are based on the oil recovery mechanism and both field results. Steam flooding continues to dominate as the most used EOR method, but CO_2 injection is showing increasing use. If the selection of criteria is based on oil gravity only, it is very easy to determine which method can be used for which field, as thermal is the best choice for heavy oil, chemical for moderate light oil, and gas recovery for light oil. However, there is many overlaps that need be considered like the well properties, type of lithology, and economically feasibility of the method. However, the screening criteria that Taber proposed is an excellent guideline to early screening process of EOR implementation project.

Table 1 : Summary of Screening Criteria for EOR Method (Taber *et al.*, 1997)

		Oil Properties			Reservoir Characteristics					
Detail Table in Ref. 16	EOR Method	Gravity (°API)	Viscosity (cp)	Composition	Oil Saturation (% PV)	Formation Type	Net Thickness (ft)	Average Permeability (md)	Depth (ft)	Temperature (°F)
Gas Injection Methods (Miscible)										
1	Nitrogen and flue gas	>35 ↗ 48 ↗	<0.4 ↘ 0.2 ↘	High percent of C_1 to C_7	>40 ↗ 75 ↗	Sandstone or carbonate	Thin unless dipping	NC	>6,000	NC
2	Hydrocarbon	>23 ↗ 41 ↗	<3 ↘ 0.5 ↘	High percent of C_2 to C_7	>30 ↗ 80 ↗	Sandstone or carbonate	Thin unless dipping	NC	>4,000	NC
3	CO_2	>22 ↗ 36 ↗ [a]	<10 ↘ 1.5 ↘	High percent of C_5 to C_{12}	>20 ↗ 55 ↗	Sandstone or carbonate	Wide range	NC	>2,500[a]	NC
1–3	Immiscible gases	>12	<600	NC	>35 ↗ 70 ↗	NC	NC if dipping and/or good vertical permeability	NC	>1,800	NC
(Enhanced) Waterflooding										
4	Micellar/ Polymer, ASP, and Alkaline Flooding	>20 ↗ 35 ↗	<35 ↘ 13 ↘	Light, intermediate, some organic acids for alkaline floods	>35 ↗ 53 ↗	Sandstone preferred	NC	>10 ↗ 450 ↗	>9,000 ↘ 3,250	>200 ↘ 80
5	Polymer Flooding	>15	<150, >10	NC	>50 ↗ 80 ↗	Sandstone preferred	NC	>10 ↗ 800 ↗ [b]	<9,000	>200 ↘ 140
Thermal/Mechanical										
6	Combustion	>10 ↗ 16 → ?	<5,000 ↓ 1,200	Some asphaltic components	>50 ↗ 72 ↗	High-porosity sand/ sandstone	>10	>50[c]	<11,500 ↘ 3,500	>100 ↗ 135
7	Steam	>8 to 13.5 → ?	<200,000 ↓ 4,700	NC	>40 ↗ 66 ↗	High-porosity sand/ sandstone	>20	>200 ↗ 2,540 ↗ [d]	<4,500 ↘ 1,500	NC
—	Surface mining	7 to 11	Zero cold flow	NC	>8 wt% sand	Mineable tar sand	>10[e]	NC	>3:1 overburden to sand ratio	NC

NC – not critical.
Underlined values represent the approximate mean or average for current field projects.
[a] See Table 3 of Ref. 16.
[b] >3md from some carbonate reservoirs if the intent is to sweep only the fracture system.
[c] Transmissibility >20 md-ft/cp
[d] Transmissibility >50 md-ft/cp
[e] See depth.

Beside the technical screening criteria that are being used for EOR screening, screening softwares are widely being used to make repetitive analysis in a simpler way (Trujillo *et al.*,2010). The software screening criteria is based on a complete database which has proven effective in evaluation of EOR potential.

CHAPTER THREE

METHODOLOGY

3.1 Research Methodology

Research Methodology is divided in two parts:

1. Project Research : Enquire about the current EOR methods used around the world, with more specific towards the implementation of EOR on sandstone reservoir. Research on characteristic of each EOR methods as well as real sandstone field data.

2. Experimental Research : Collecting real sandstone field data either from literature or from organization. Experiment will be conducted after the acquisition of data to determine the best EOR method to implement using the technical screening guidelines (Taber *et al.*, 1997) and using a screening software called EORSc.

3.2 Project Activities

- **Phase I – Compilation of Reservoir Data**

For this study, data from several reservoirs were gathered. The data were obtained from the literature of EOR projects around the world. The reservoir data include formation type, temperature, depth, permeability, porosity, oil saturation, pressure, water salinity, oil density and viscosity, vertical permeability, oil mobility, oil content and all other relevant information.

- **Phase II – Screening of EOR**

From the data collected, the screening for the best EOR method was done. The technical screening is based on the statistic of successful EOR projects criteria in the world (Taber *et al.*, 1997). The data were compared with the criteria to select the specific EOR method which to will likely to succeed. In the case of insufficient data, a conditional pass was considered and assumed that it will fit according to the most criteria.

However, the screening of the data, if done manually will consume a considerable amount of time. A software was developed for fast screening evaluation and to take the hardship out of manual screening and evaluation of EOR methods. The software is named EORSc.

The function of EORSc are :-

1. To check the reservoir data against the screening criteria.
2. Select and determine the EOR method that are technically feasible for the reservoir.

- **Phase III – Analysis of the Screening Results**

  After getting the result(s), the study was continued by doing analysis whether the EOR method suggested from the screening is viable to be implemented. In case of several EOR results, the best method was chosen based on the analysis done. Comparison with the literature is also performed to confirm the analysis results.

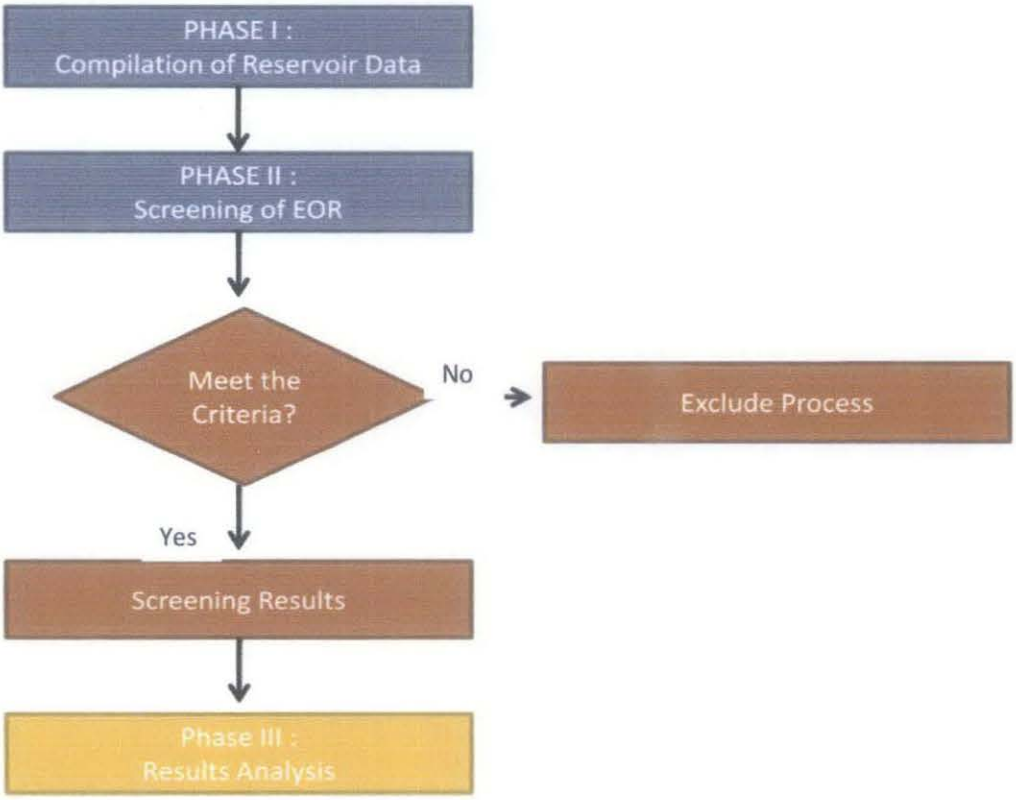

Figure 13 : Flowchart of the Project

3.3 Key Mileston

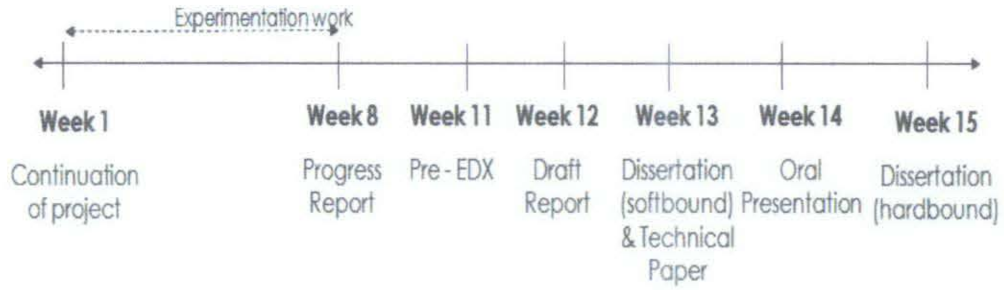

Figure 14 : Key Milestone for FYP II

The project was completed by week 11 with results prior to the pre – EDX and dissertation report as well as the technical papers.

3.4 Gantt Chart

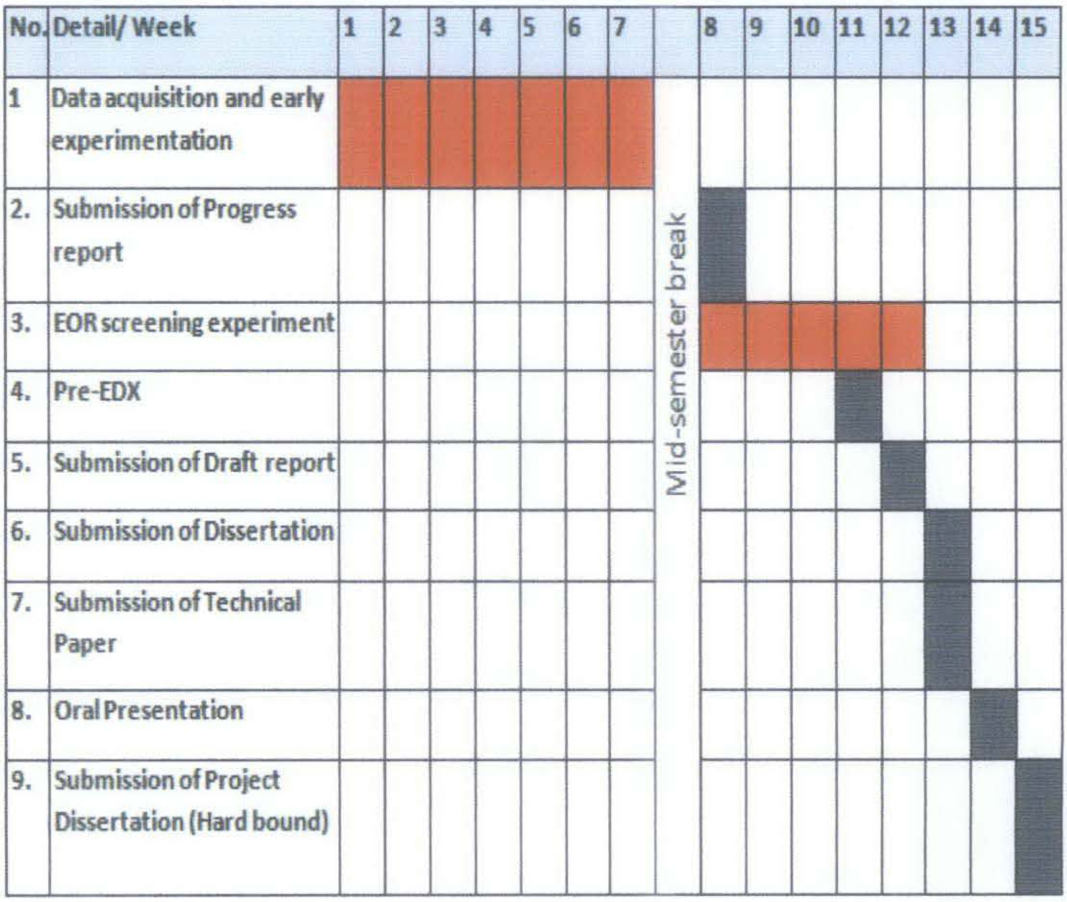

Figure 15 : Gantt Chart for FYP II

3.5 Tools

For this project, a software named **EORsc** was developed and was used for the simulation screening. This software has the capability to screen EOR method and makes prediction based on data. The screening criteria are based on a complete database which has good acceptance for its effectiveness in the evaluation of EOR potential around the world which was proposed by Taber et. al.

The software was developed using Visual Basic C++. It uses the IF and ELSE command as the base coding for the selection criteria.

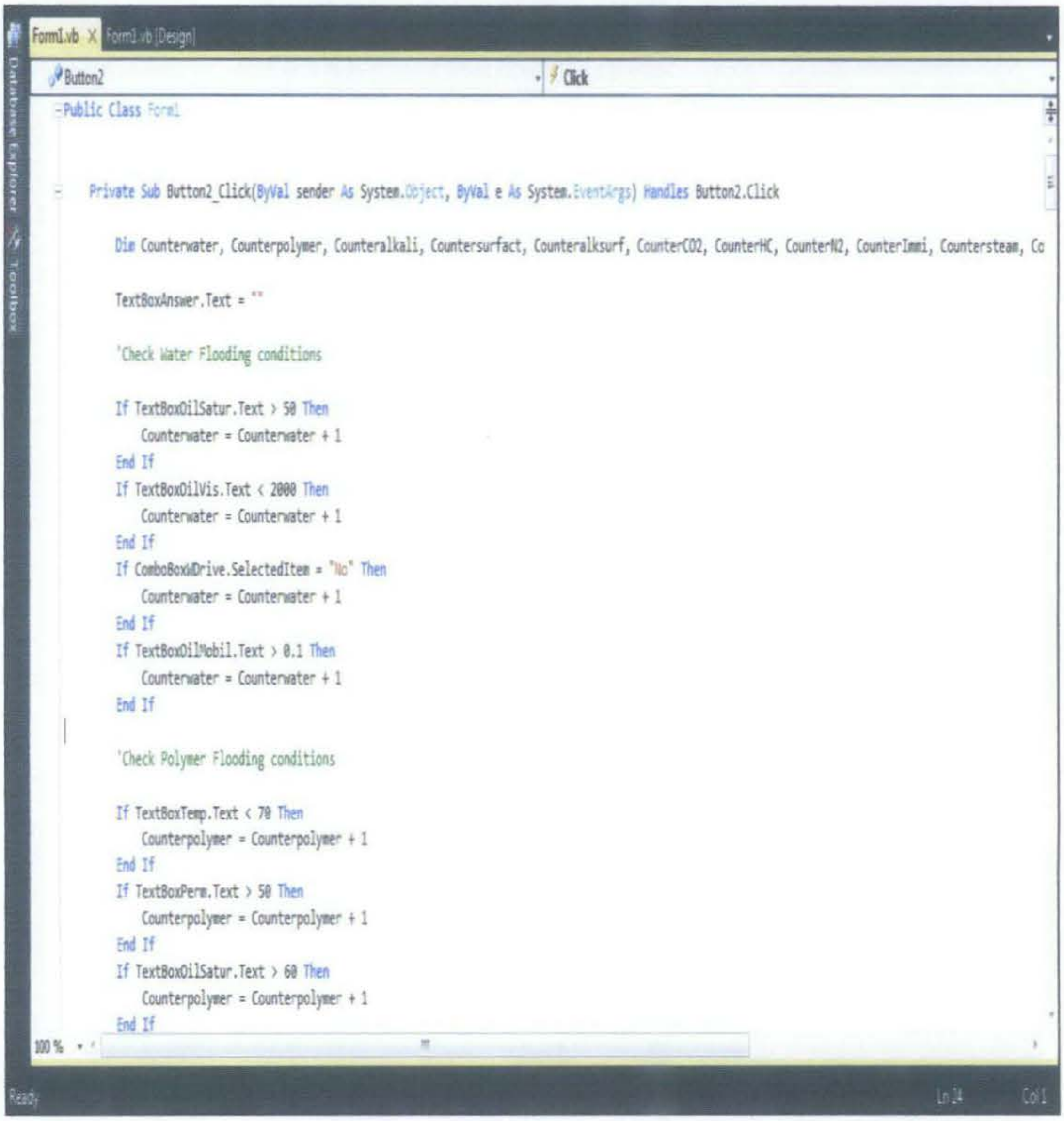

Figure 16 : A Screenshot of the C++ Coding of the EORSc Software

CHAPTER FOUR

RESULTS & DISCUSSION

4.1 Data Gathering

For this study, several reservoir data has been acquired for the screening process. These data are from projects all around the world. Data that was obtained from the literature are :

- 16 wells from the North Sea
- Garzan Field, Turkey
- Saskatchewan Field, Canada
- Unity Oil Field, Southeast Sudan

4.2 Screening Process

The data from every respective reservoir is key in into the software. The software then automatically screen through the data and it will crosscheck the relevant data with the criteria.

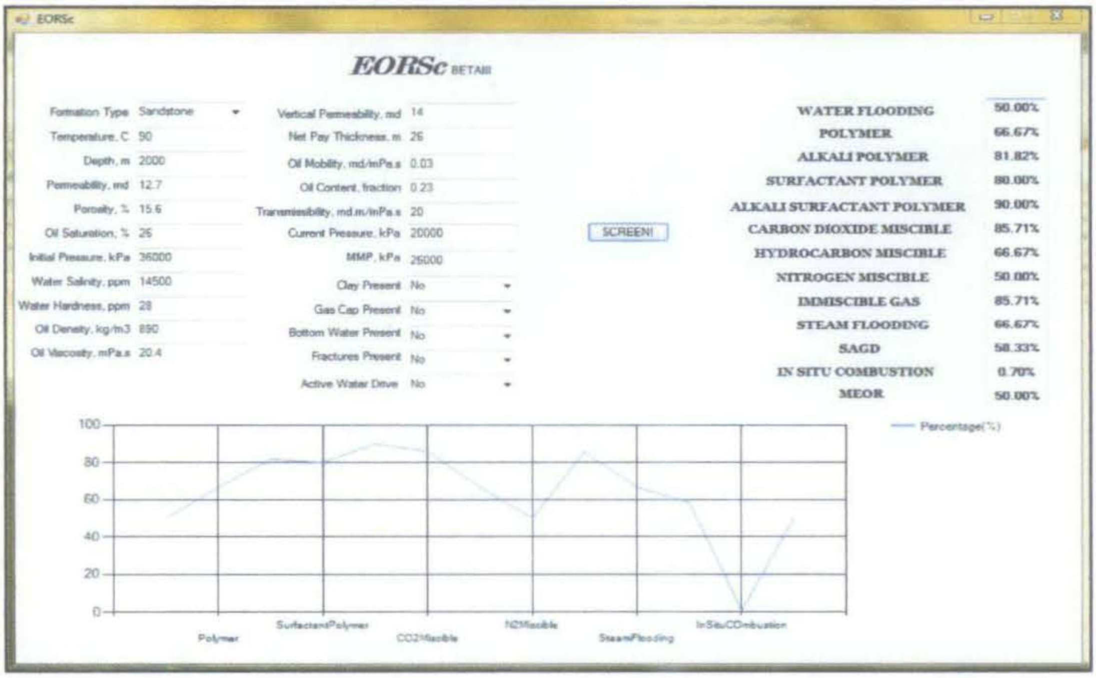

Figure 17 : EORSc Software

The result will show the EOR method that can be implemented on the field. However, the software is just a tool to assist the user in screening. The analysis that is done after the screening will determine which method from the screening is the best. For this study, a comparison with the literature was done to check and confirm the results acquired in the analysis part.

4.3 Results & Analysis Of Data

4.3.1 North Sea

The **North Sea** is a marginal sea of the Atlantic Ocean located between Great Britain, Scandinavia, Belgium, and the Netherlands.

A series of data for 16 wells in the North Sea Field have been screened using the screening software. The wells are :-

- Beryl
- Statfjord A
- Brent
- Alwyn North
- Smorbukk South
- Snorre
- South Brae
- Magnus
- Thistle
- Gulfaks
- Brage
- Statfjord B
- Oseberg
- Siri
- SnA

Data that was compiled and used for the analysis are as below :-

Table 2 : Data of North Sea Wells.

Name	Depth (m)	Temperature (°C)	Porosity (%)	Permeability (md)	Viscosity (mPa.s)	Salinity (ppm)	Initial Pressure (kPa)	MMP (kPa)	Net Thickness (m)	Fracture
Beryl	3200		17	400			33700		124	no
Statfjord A	2575	99	21	750	0.29	14000	40400	35200	63	no
Brent	2744	103	25	2000	0.25	24000	42300	407	27	no
Alwyn North	3110	113	15	5--2000	0.3	30000	45000	375	95	no
Smorbukk South	3800	165		30--300			50000	400		no
Snorre	2300	90	24	200--2000	0.4-0.9	34000	38300	283	40	no
South Brae		123	11	130	0.3		49200	272		no
Magnus	2709	116	20	10--1000			45900		185	no
Thistle	2804	102	20	80-1220	1.1		41800		117	no
Gulfaks	1740	74	31	80-4500	1.12	41300	31000	200	190	no
Brage	2080	87.5	25	1-200	0.56	41700	21500	329	40	no
Statfjord B	2360	92	28	2300	0.31	14800	38500	414	115	no
Oseberg	2770	113	19	1-1000		38000	31900			no
Siri	2070		30	1-1000			23200		25	no
SnA	2300	90	24	400-3500	0.4-0.9	340000	38000	280	12	no

All the data was input into the software. The results from the screening were :-

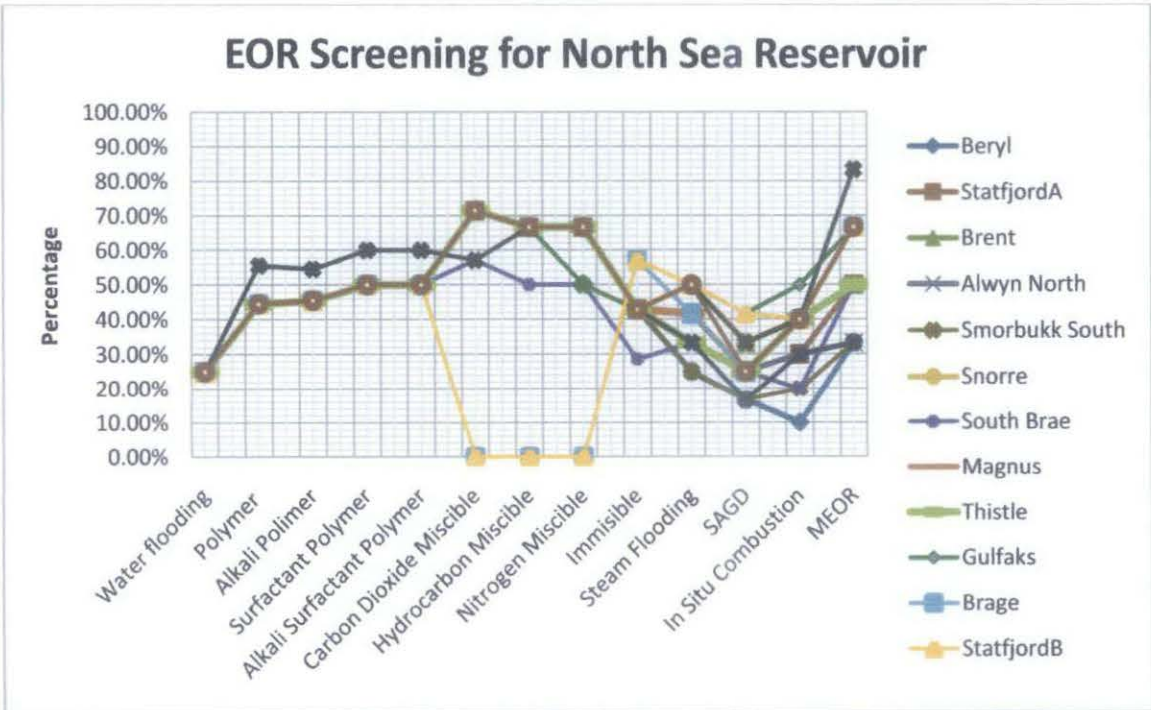

Figure 18 : EOR Screening for North Sea Reservoir

Table 3 : Screening Results of the North Sea Wells

EOR Method	Beryl	StatfjordA	Brent	Alwyn North	Smorbukk South	Snorre	South Brae	Magnus	Thistle	Gulfaks	Brage	StatfjordB	Oseberg	Siri	SnA
Water flooding	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%	25.00%
Polymer	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	44.44%	55.56%	44.44%
Alkali Polimer	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	45.45%	54.55%	45.45%
Surfactant Polymer	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	60.00%	50.00%
Alkali Surfactant Polymer	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	60.00%	50.00%
Carbon Dioxide Miscible	71.43%	71.43%	71.43%	71.43%	71.43%	71.43%	57.14%	71.43%	71.43%	71.43%	0.00%	0.00%	71.43%	57.14%	71.43%
Hydrocarbon Miscible	66.67%	66.67%	66.67%	66.67%	66.67%	66.67%	50.00%	66.67%	66.67%	66.67%	0.00%	0.00%	66.67%	66.67%	66.67%
Nitrogen Miscible	66.67%	66.67%	66.67%	66.67%	66.67%	66.67%	50.00%	66.67%	66.67%	50.00%	0.00%	0.00%	66.67%	66.67%	66.67%
Immisible	42.86%	42.86%	42.86%	42.86%	42.86%	42.86%	28.57%	42.86%	42.86%	42.86%	57.14%	57.14%	42.86%	42.86%	42.86%
Steam Flooding	25.00%	41.67%	50.00%	41.67%	25.00%	50.00%	33.33%	41.67%	33.33%	50.00%	41.67%	50.00%	33.33%	50.00%	50.00%
SAGD	16.67%	25.00%	33.33%	25.00%	16.67%	33.33%	25.00%	25.00%	25.00%	41.67%	25.00%	41.67%	16.67%	33.33%	25.00%
In Situ Combustion	10.00%	30.00%	40.00%	30.00%	20.00%	40.00%	20.00%	40.00%	40.00%	50.00%	40.00%	40.00%	30.00%	40.00%	40.00%
MEOR	33.33%	50.00%	50.00%	33.33%	33.33%	66.67%	50.00%	50.00%	50.00%	66.67%	66.67%	66.67%	33.33%	83.33%	66.67%

Analysis of Screening Results

- The methods that are proposed in this field according to the literature are HC miscible gas injection while MEOR is on pilot testing.
- Water flooding have the percentage of success at all of the reservoirs with about 25%.
- The miscible gas injection with CO_2 at 71%, HC at 66.7% and also N_2 at 50-60%. Only 2 wells (Brage & StatfjordB) that have 0% because the initial pressure is less than the MMP.
- MEOR method with percentage of success from 33.3% to 66.7% and even up to 83.3% at the Siri well.
- All the wells at the North Sea have been implemented with Water flooding. This is because the water mobility is very favorable. The water flooding has also lowered the reservoir temperature.
- Miscible Flooding is conducted in several of the North Sea wells. The gas that is used for the miscible flooding is HC as the resource is abundant here.
- MEOR is only in pilot testing at one well. The conditions at the North Sea are very suitable for this method. It is also the cheapest EOR method.
- Chemical method is not implemented at the North Sea. Although the percentage of success is also high, but it is not economical to implement as it is very expensive.
- The trending of all the wells are almost the same, with EOR methods that are the priority are HC miscible flooding and MEOR.
- The similarity of the wells is due to the fact that all the wells are in the same area and have almost the same characteristic.

4.3.2 Garzan Field, Turkey

Field Background

The Garzan field is located in the Batman Province, in the Southern Anatolia Region. It was discovered in 1951 and began production in 1956. The total proven reserves of the Garzan field are around 163 million barrels.

Field Data

- 24^{o} API
- Viscosity 6.75cp
- Reservoir temperature 70 ^{o}C
- Initial pressure 9688 kPa
- Current pressure 5000 kPa
- MMP 25100 kPa
- Porosity 12.6 %
- Permeability 15.7 md
- Viscosity 6.75 mPa.s
- Net Pay Thickness 11m
- Connate water saturation 20%
- Bubble point pressure 713 psi
- Initial oil formation volume factor 1.053 RB/STB
- Initial solution gas – oil ratio 122 scf/STB

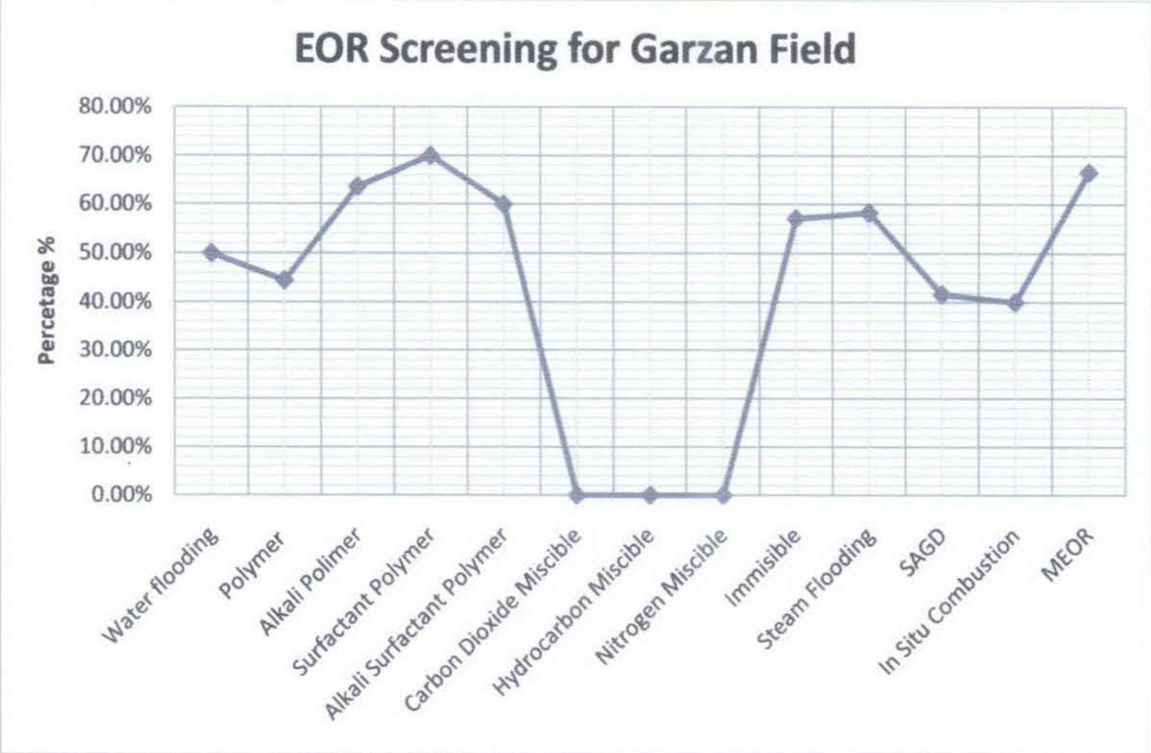

Figure 19 : EOR Screening for Garzan Field

Table 4 : Screening Results for Garzan Field

EOR Method	Percentage %
Water flooding	50.00%
Polymer	44.44%
Alkali Polymer	63.64%
Surfactant Polymer	70.00%
Alkali Surfactant Polymer	60.00%
Carbon Dioxide Miscible	0.00%
Hydrocarbon Miscible	0.00%
Nitrogen Miscible	0.00%
Immiscible	57.14%
Steam Flooding	58.33%
SAGD	41.67%
In Situ Combustion	40.00%
MEOR	66.67%

Analysis of Screening Results

- The method that is proposed in this field according to the literature is CO_2 immiscible gas injection.
- Water flooding has 50% percentage of success. This field is already under peripheral water injection.
- The Initial pressure of Garzan field is much lower than the MMP, so the miscible gas injection is not possible. This is why the CO_2, HC and N_2 method has 0% success rate, while the immiscible gas injection has 57.14%.
- The gas that can be used for the immiscible gas injection in this field is CO_2 as the gas can be acquired locally in high volume from Dodan Field up north.
- All the thermal methods have high rate of success with steam flooding at 58.33%, SAGD at 41.67% and In Situ Combustion at 40.00%.
- However the thermal method is not viable due to their high energy consumption.
- Chemical method is not implemented at the Garzan field. Although the percentage of success is also high, but it is not economical to implement as the chemical cost is very expensive.
- The MEOR method has one of the highest success rates. However, because this is a new technology and no pilot project is done, this method is disregard.
- The Immiscible gas injection is the most preferable as it is incrementally viable over water flooding from both economic standpoint and hydrocarbon recovery. The immiscible method is also favoured because of the inexpensive CO_2 supply.

4.3.3 Southwest Saskatchewan Field, Canada

Field Background

Saskatchewan field is located near the city of Regina. It was discovered in 1943. Most of the reservoirs of this field are located at the southeast, southwest and near the western border. The total proven oil reserve is 3.1 billion barrels for the southwest field which contains medium oil.

Field Data

- 22.8° API
- Depth 2400m
- Oil Density 893.0 kg/m^3
- Viscosity 18.4 mPa.s
- Temperature 50 °C
- Water salinity 4800 ppm
- Water hardness 28 ppm
- Oil saturation 38%
- Permeability 58md
- Net thickness 2 – 8 m

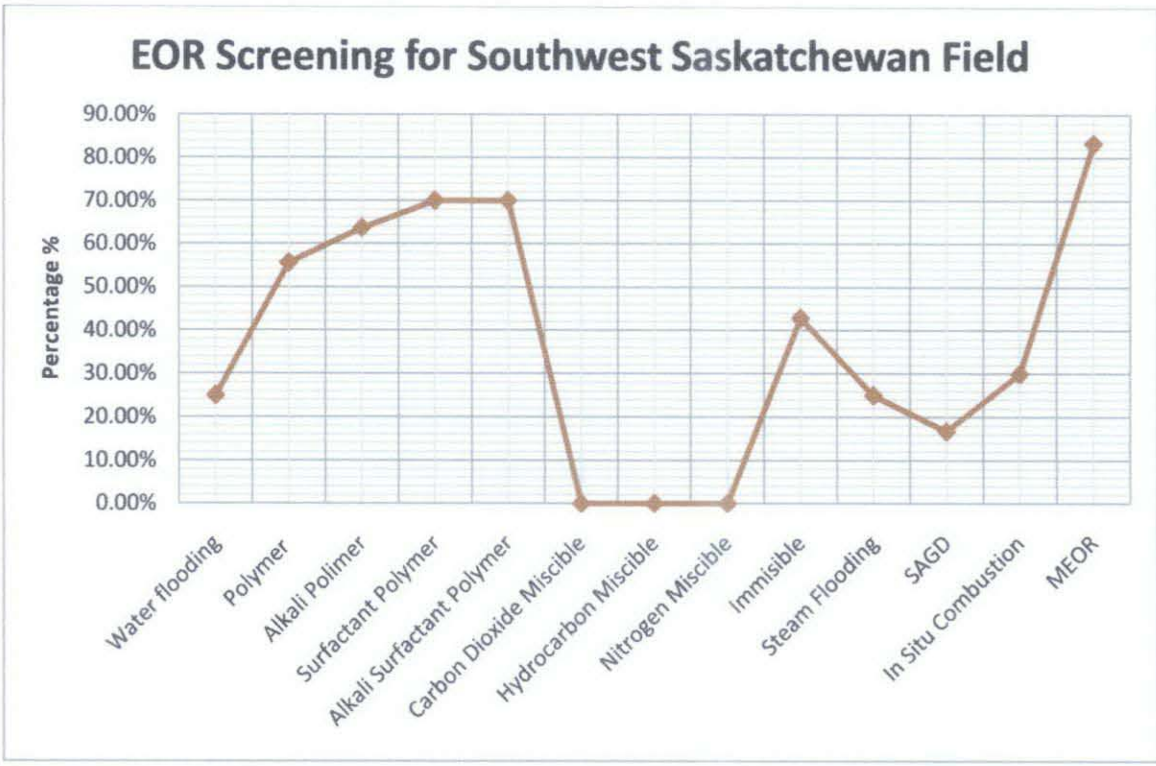

Figure 20 : EOR Screening for Southwest Saskatchewan Field

Table 5 : Screening Results for South Saskatchewan Field

EOR Method	Percentage %
Water flooding	25.00%
Polymer	55.56%
Alkali Polymer	63.64%
Surfactant Polymer	70.00%
Alkali Surfactant Polymer	70.00%
Carbon Dioxide Miscible	0.00%
Hydrocarbon Miscible	0.00%
Nitrogen Miscible	0.00%
Immiscible	42.86%
Steam Flooding	25.00%
SAGD	16.67%
In Situ Combustion	30.00%
MEOR	83.33%

Analysis of Screening Results

- The methods that are proposed in this field according to the literature are the chemical recovery methods.
- All the chemical methods have a relatively high percentage of success with polymer flooding at 55.56%, alkali polymer flooding at 63.64%, surfactant polymer flooding at 70.00% and alkali surfactant polymer flooding at also 70.00%
- The MEOR method has the highest success rate with 83.33%. While water flooding is low with only 25.00%
- The probability for the thermal method is also quite low, with steam flooding at 25.00%, SAGD at 16.67% and in situ combustion at 30.00%.
- The gas injection here cannot be properly analysed as the data was insufficient.
- Several fields here have been implemented with water flooding. While this method has achieved additional oil and also economic benefits, these fields have experienced water breakthrough and high water cut because of high oil to water viscosity ratio.
- The reservoirs at this field are very thin. So thermal recovery is not suitable as the heat will be loss to the underburden as well as the overburden.
- The reservoirs characteristic is very favourable for chemical recovery. This is why all the chemical methods have high percentage of success.
- Further study on the chemical methods can determined which method can be used for most optimum oil recovery.
- MEOR also has the highest because the criteria are almost similar with chemical recovery method. If MEOR method is to be chosen, it needs to be researched in further detail as to what bacteria and nutrients are suitable for the field.

4.3.4 Unity Oil Field, Southeast Sudan

Field Background

Unity Oil field is located in the east of Fula Basin. The field was discovered during the 1970s. This field is shallow and has heavy oil with strong bottom water. It is estimated that this field contains 150 million barrels of oil.

Field Data

- Depth 520m
- Temperature 46 °C
- Porosity 26%
- Permeability 3000md
- Net pay thickness 31m
- Viscosity 3500 mPa.s
- Oil saturation 72%
- Bottom water present

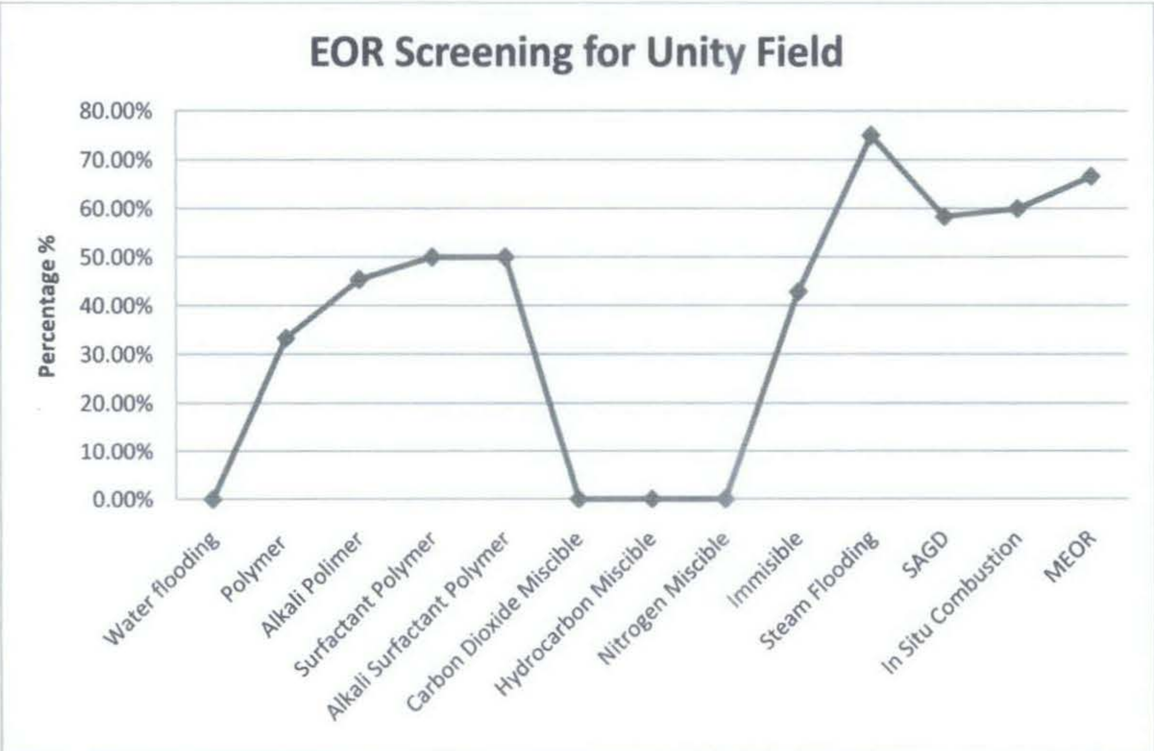

Figure 21 : EOR Screening for Unity Field

Table 6 : Screening Results for Unity Field

EOR Method	Percentage %
Water flooding	0.00%
Polymer	33.33%
Alkali Polymer	45.45%
Surfactant Polymer	50.00%
Alkali Surfactant Polymer	50.00%
Carbon Dioxide Miscible	0.00%
Hydrocarbon Miscible	0.00%
Nitrogen Miscible	0.00%
Immiscible	42.86%
Steam Flooding	75.00%
SAGD	58.33%
In Situ Combustion	60.00%
MEOR	66.67%

Analysis of Screening Results

- The methods that are proposed in this field according to the literature are the thermal recovery methods.
- Based on the screening results, thermal recovery methods gave the highest success rate with Steam flooding at 75.00%, SAGD at 58.33% and in situ combustion at 60.00%.
- Chemical methods rate are the second highest with polymer at 33.33%, alkali polymer at 45.45%, surfactant polymer and alkali surfactant polymer at 50.00%.
- Water flooding has the rate of 0%, this is maybe because water flood is not expected to succeed due to extremely high oil viscosity.
- For this case, because of insufficient data, the gas injection method is disregard.
- MEOR also gave a high rate of success, the bacteria reacts with the heavy oil to degrade the heavy oil by reducing its viscosity. However this field viscosity is too high and it is not enough to increase the heavy oil recovery at large scale. This promising technology needs further research to work.

- This is also the same case with the chemical method. The chemical must be adequately researched and use specifically with respect to the characteristics and properties of the field's heavy oil.
- The cost of using the chemicals might be too expensive and makes the project not viable to implement, even if it gives high oil recovery.
- The field characteristic is very favourable with thermal recovery method. The heating of the heavy oil will expand the oil and the viscosity reduced, thus making the oil more fluid.
- The thermal recovery method is also cost effective.

CHAPTER FIVE

CONCLUSION & RECOMMENDATION

5.1 CONCLUSION

The main objective of this project is to identify the EOR method that can be used on a sandstone reservoir using the technical screening method as with the aid of a screening software. This research focused mainly on the technical part of the screening that determined which EOR method is the best to be implemented. Economic feasibility is reviewed generally. In order to achieve the objectives, all the experimental framework was carefully prepared, which was completed within the time frame of the research, while taking into consideration of the availability of the equipment and, materials. After doing all the technical screening, it is proven that EOR method cannot be implemented without a thorough analysis and screening. This study proves that EOR screening can provide an insight to a well for EOR implementation. It is also proven that by using a software to assist, the screening process can be completed and analyze in much faster time than just using manual screening that is time consuming.

5.2 RECOMMENDATION

From this whole planning work done by the author, there are rooms for improvement for this research. After doing this project for two semesters, the author has gained the awareness and the importance of EOR screening. The main objective of this project is to determine the best and most suitable EOR method for a sandstone reservoir. It is recommended to do the screening using local field data, which can be beneficial for the implementation of EOR in Malaysia in the future. Furthermore, if a software is to be developed for EOR screening purposes, it is recommended to work together with the IT department to create a more sophisticated software. The software could also be integrated with more option of calculating oil recovery. It is also recommended to use the latest EOR screening criteria that are updated with the current technology.

REFERENCE

Alvarado, V., "Screening Strategy for Chemical Enhanced Oil Recovery in Wyoming Basins", paper SPE 115940, 2008 SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, 21-24 September 2008.

Burnett, D., and Dann, M., "Screening Tests for Enhanced Oil Recovery Projects", paper SPE 9710, 1981.

Cooke, C.E., Jr., Williams, R.E. and Kolodzie, P.A.: "Oil Recovery by Alkaline Flooding," J. Pet. Tech., 1974

Dietrich, F.L., Brown, F.G., Zhou, and Maure, M.A., "Microbial Technology Advancement : Case Study of Successful Projects" Paper SPE 36746, SPE Annual Conference and Exhibition, Denver, Colorado, Oct 6 – 9, 1996

Farouq Ali, S.M. and Meldau, R.F., "Current Steamflood Technology," J. Pet. Tech (Oct. 1979) 1332 – 1342.

Farouq Ali, S.M. and Thomas, S., "The Promise and Problems of Enhanced Oil Recovery Methods" University of Alberta, 1996.

Hammershaib, E.C., Kuuskraa, V.A., and Stosur, G., "Recovery Efficiency of Enhanced Oil Recovery Methods," paper SPE 12114, SPE 58th Annual Technical Conference & Exhibition, San Francisco, Oct. 5 – 8, 1983.

Holm, L.W., and Josendal, V.A., Mechanisms of Oil Displacement by Carbon Dioxide; *Journal of Canadian Petroleum Technology, 1974.*

Islam,M.R. & Farouq Ali, S.M., "New Scaling Criteria for Chemical Flooding Experiments." *Journal of Canadian Petroleum Technology. 1990.*

Manrique, E., Thomas, C., Ravikiran, R., Izadi, M., Lantz, M., Romero, J. TIORCO LLC, and Alvarado, V., "EOR : Current Status and Opportunities", paper SPE 130113, 2010 SPE Improved Recovery Symposium, Tulsa, Oklahoma, USA, 24-28 April 2010.

Prats, M., A Current Appraisal of Thermal Recovery, J. Pet. Tech. (August 1978) 1129 -1136

Prats, M., Thermal Recovery, Monograph Series, SPE, Dallas (1982) 7, 161, 14.

Taber, J.J. and Martin, F.D, "Technical Screening Guides for the Enhanced Recovery of Oil", paper SPE 12069, SPE 58th Annual Technical Conference & Exhibition, San Francisco, Oct. 5 – 8, 1983.

Taber, J.J., Martin, F.D., and Seright, R.S, "EOR Screening Criteria Revisited: Part 1 – Introduction to Screening Criteria and Enhanced Recovery Field Projects", *SPERE*, August 1997.

Trebolle, R.L., J.P. Chalot, and R. Colmenares. "The Orinoco Heavy-Oil Belt Pilot Projects and Development Strategy." Paper SPE 25798 presented at the 2nd International Thermal Operations Symposium, Bakerfield, CA, February 1993.

Trujillo, M., Mecado, D., Maya, G., Castro, R., Soto, C., Perez, H., Gomez, V., and Sandoval, J., " Selection Methodology for Screening Evaluation of Enhanced Oil Recovery Methods", paper SPE 139222, SPE Latin America & Carribean Petroleum Engineering Conference, Lima, Peru, 1-3 December 2010.

Van Poolen, H.K., and Assoc., Inc Fundamentals of Enhanced Oil Recovery. Tulsa: PennWell, Co. 1980.

Wu, C. W., "A critical Review of Steamflood Mechanisms" paper SPE 6550 presented at the California Regional Meeting of SPE, Bakerfield, CA, April 1977.