EOR Screening and Optimizing Study on Carbonate Reservoirs

by

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CERTIFICATION OF APPROVAL

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

NOR SUZAIRIN BINTI MISTOR

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ABSTRACT

By times, production of oil will decrease eventually. Not all the oil in the reservoirs will be produced during the process. A substantial amount of oil will remain in place or is called as residual oil saturation (Sor) due to a partial sweep of the reservoir and oil is trapping by capillary forces in the invaded zones. Therefore, researches have been developed and Enhanced Oil Recovery (EOR) is the trusted technology to improve the production and recovery in the oil fields. The objectives of EOR are (1) to improve the sweep efficiency, by reducing the mobility ratio between injected and in-placed fluids, (2) to eliminate or reduce the capillary forces and thus improve displacement efficiency, and (3) to act on both phenomena simultaneously.

Different fields acquire different methods of EOR. Hence, in order to find the best method, a screening process has been done. The criteria and properties of both method and reservoirs are taken into account in order to choose the exact method for the specific reservoir. The properties are based on the successful field projects and continuous research. In this project, which is focusing on the carbonate reservoirs lithology,all the EOR methods and fields properties will be screened by using two methods which are (1) manual screening and (2) by using EOR screening. EOR screening is software that has been developed by the author using the macro visual basic in Microsoft Excel 2007. About 48 previous projects in carbonate reservoirs' field has been tested using this software and the result shows gas injection as the mostly suitable method for this lithology.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATION AND NOMENCLATURE

ASP: Alkaline-Surfactant-Polymer

EOR: Enhanced Oil Recovery

FAWAG: Foam Assisted Water Alternating gas

HPAI: High Pressure Air Injection

IFT: Interfacial tension

M: Mobility ratio

MMP: Minimum Miscibility Pressure

Nc : Capillary number

SWAG: Simultaneous Water and Gas Injection

SP : Surfactant-Polymer

Swi: Initial Water Saturation

Sor: Residual Oil Saturation

WAG: Water alternating gas

CHAPTER 1

INTRODUCTION

1.1 Project Background

Reservoirs firstly producing oil using natural reservoir energy until a certain stage of depletion reached and production rates become uneconomic. This is known as primary production phase. Recoveries by secondary methods such as water or gas injection are implemented when the natural recovery processes are insufficient. Tertiary recovery comes afterwards. The term secondary and tertiary recovery or Enhanced Oil Recovery (EOR) describes the order of which methods are used. EOR also can be described as the recovery methods by other than natural production.

Declining in oil discoveries years ago make the researcher from oil and gas industry to find the way to meet the energy demand in years to come and as the result, EOR technologies is proven as the key for the recovery to continue (Vladimir and Eduardo, 2010). EOR can be divided into two major types of techniques which are thermal and non-thermal recovery. For thermal, it consists of steam injection, hot waterflooding and in situ combustion. While for non-thermal recovery, it can be divided into three (3) types which are chemical flood, waterflood and gas drive (Duraya, 2007).

Worldly known carbonates reservoirs have very complex characteristics. It has heterogeneities of porosity and permeability. Therefore, the choosing of suitable EOR methods for this kind of lithology is very difficult. There is evident where gas and water-based recovery methods are applicable for carbonate reservoirs (E. Manrique *et al.*, 2010). WAG is the common interest EOR in carbonate reservoirs. Based on E. Manrique *et al.* (2004), polymer flooding is the only proven EOR chemical of EOR methods in carbonate formation. A thermal method is not suitable in carbonate reservoirs because the structured of carbonate reservoirs which highly fractured can cause early breakthrough of the steam. So the use of thermal methods in not popular in carbonate reservoirs.

In order to find the best method of EOR for carbonate reservoirs, a set of screening test has been developed (David and Michael, 1981) and also the set of screening criteria based on the primary and thousands of field projects have been recorded (J.J Taber *et al*, 1996). The screening process will be conducted using two methods which are (1) manual screening based on the screening criteria and (2) a screening programming. Before the screening test take place, all the screening criteria data should be take into account. The screening criteria are based on the oil properties and reservoir characteristics (J.J Taber *et al*, 1996).

1.2 Problem Statement

1.2.1 Problem Identification

Carbonate reservoirs contributes almost half in oil reserves and many of these reservoirs are naturally fractured (Roehl and Choqueete, 1985). Carbonates rock texture has spatial variations in permeability and capillary bound water volumes. It also has different types of porosity and variations of permeability which make this lithology has heterogeneity manner.

Fractured carbonate reservoirs which has high porosity but low permeability (Allan and Sun, 2003) could use EOR processes to optimize the oil production. The oil recovery from this type of reservoir is very low by conventional waterflooding and because it is fractured about 80% being originally less water-wet (Yongfu *et al.*, 2006).

Complex characteristics of carbonates reservoirs produce complex interrelationships between porosity, permeability, Swi, Sor, wettability, and capillarity. When pursuing the EOR processes, the injected fluids will likely flow through the fractured network and bypass the oil in rock matrix. Therefore, the choosing of EOR processes in this lithology is also complex and difficult since the understanding of reservoir behaviour when certain EOR process is conducted is very important in order to choose which EOR process can provide high production in carbonate reservoirs.

Based on J.J Taber *et al.* (1996), screening test using all the screening criteria on oil properties and reservoir characteristics can help to choose the best EOR method for carbonate reservoirs.

Initially, this project was proposed to use PRIze™ software, the renowned EOR screening software in the oil and gas industry. But since the software cannot be run in UTP, the author needs to create a program almost similar to PRIze™ in order to make the screening easier. Therefore, two ways to do the screening in this project which are (1) manual screening based on the screening criteria and (2) a screening programming. The screening program is developed using the Excel VBA Code and Excel Macro. The properties in this program are based on the PRIze™ manual's screening criteria.

There is only technical screening provided in this project, economic screening on the specific method might as well be done if the further study is continued.

1.2.2 Significant of the Project

This project is very important in order to find the best EOR method for carbonate reservoir. In this project, suitable EOR method is chosen using (1) manual screening based on the screening criteria and (2) a screening programming which evaluating and screening all the properties of the reservoirs. Screening criteria on the reservoir data should be taken into account to conduct the screening. The criteria are based on oil-displacement mechanisms and the result of EOR field projects (J.J Taber *et al.*, 1996). Further study in this topic will help in improving the EOR technique for carbonate reservoir and also choosing the best method economically.

1.2 Objectives

The ultimate objective of this project is to screen the criteria of carbonate oil reservoirs and EOR processes using (1) manual screening based on the screening criteria and (2) a screening programming in order to choose the best EOR process for that lithology.

The other objective that has been recognized in this project is the optimizing study on carbonate reservoirs and EOR processes to choose the satisfying EOR process this lithology.

1.3 Scope of Study

For this project, the scope of study covered about the all the types of EOR processes and its criteria. There are two types of EOR processes which are non-thermal and thermal methods. The suitability of each kind of this EOR processes should be studied to find the best solution for carbonate reservoirs.

The reservoirs characteristic which is carbonate reservoirs also should be taken into account for this project. In addition, an extensive research on both context which are EOR methods and carbonate oil reservoirs are very important to make sure there is no bad effect happen during the EOR processes taking place in that lithology. The report on the EOR field projects for carbonate reservoirs also can give the overview on the trend of common EOR process in carbonates reservoirs.

1.4 The Relevancy of the Project

This project is definitely relevance in order to choose and consider all the EOR methods that are suitable for carbonate reservoirs before further experiment is conducted and pilot project is implemented. After considering the methods by the screening criteria, the suitable methods will be experimental in order to make sure the ability of the process to the carbonate reservoirs. From that, the production of oil in carbonate reservoir will be increasing.

1.5 Feasibility of the Project

This project is feasible to be implemented and study since the time given is definitely enough and the tool to conduct the project is available. The time given to make the raw screening process is satisfying but to do more analysis on the reservoirs need much more time.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Declining in oil production making the oil companies and authorities sought-after the new technologies to overcome this problem. Enhanced Oil Recovery (EOR) technology widely use nowadays in increasing the economic value of existing oil fields by increased oil recovery and extending the field life (E.Manrique and J.Wright, 2005)

2.2 Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) technology is trusted by oil companies and authorities can help to play the key role to meet energy demand for years to come. There are several EOR methods that has been recognized can help to improve and increase oil recovery. Based on Sarma (1999), EOR methods are divided by two categories which are non-thermal and thermal. Non-thermal methods consist of chemical flood, waterflood, and gas drives while thermal methods consist of steam injection, hot waterflood, and in-situ combustion.

2.3 EOR Screening

EOR screening is the test required to find the best EOR method for carbonate reservoirs. Each EOR methods have their own criteria. The criteria are based on the oil properties and reservoir characteristics. These criteria are called as screening criteria for EOR methods. The criteria for oil properties are gravity (^{0}API), viscosity (cp), and composition while the reservoir characteristics are formation type, net thickness (ft), average permeability (md), depth (ft), and temperature (^{0}F) (J.J Taber *et al*, 1996). All this data should take into account in order to do the EOR screening. By doing the screening, the exact method is suitable for carbonate reservoirs can be determined.

In order to do the screening, two ways are develop which are (1) manual screening based on the screening criteria and (2) a screening programming. The screening program is using Excel VBA Code and Excel Macro. The properties in this program are based on the PRIze™ manual and screening criteria by J.J Taber *et al.*, (1997).

TABLE 3—SUMMARY OF SCREENING CRITERIA FOR EOR METHODS

		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.

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

2.4 Carbonate Reservoirs

For this project, it is focusing on the EOR method for carbonate reservoirs. Carbonates are divided into reefs, clastic limestone, and dolomite. The reservoirs in this lithology will trap in that formation. Not all EOR methods are suitable for carbonate reservoirs since carbonate reservoirs has heterogeneous porosity and permeability. It is also highly fractured and oil-wet type reservoirs. As the carbonate reservoirs fractured, during the EOR process, the injected fluids will likely flow through the fracture network and bypass the oil in the rock matrix. The high permeability in fracture network and the low porous volume will result in early breakthrough of the injected fluid. It shows that it is very difficult to pursue EOR techniques in this kind of lithology. Therefore, deeply study and test is needed to find the best EOR method for this lithology.

2.5 Thermal Method

Thermal method is generally preferred for shallow oil reservoirs containing viscous crude oil. The heat will reduce the viscosity of oil and mobilization will be easier. But for this project, since it is focusing on light oil reservoirs, thermal method will be not preferable in this project. This method is not popular in carbonate reservoirs because the fractured carbonate reservoirs will cause the uneven sweeping and irregular steam can lead to early breakthrough of steam, resulting in low recovery factor (Vladimir and Eduardo, 2010).

Air Injection or High Pressure Air injection (HPAI) shows an effective recovery method in deep light crude oil reservoirs (E. Manrique, 2004). Air injection is considered when there is no access to CO_2 sources at onshore or offshore reservoirs. HPAI or air injection is not preferable because there will be some additional cost elements for air injection process and also some significant risk and uncertainty might be occurring during the process (T.B Jensen *et al.*, 2000). The other advantages for air injection are well corrosion, oil oxidisation, and risk of explosion (Marcel Latil, 1980).

2.6 Non-Thermal Method

Non-thermal method consists of chemical flooding, waterflooding, and gas flooding (After Sama, 1999). Waterflooding is the process when injection water pushes the oil towards the producing well. Chemical flooding is a process to increase the mobility of oil in order to enhance oil recovery. Additives or chemicals are added in displacing fluid or to the residual oil to control viscosity and interfacial tension. While gas flooding is divided into immiscible and miscible gas injection. In miscible gas injection, gas is injected at or above MMP for the gas to miscible in the oil whereas in immiscible gas injection, the process is below MMP. Chemical flooding and gas injection are processes to be considered in carbonate reservoirs.

2.6.1 Chemical Flooding

Chemical flooding EOR is subjected to increase the capillary number (Nc) to mobilize residual oil, decrease the mobility ratio (M) for better sweep efficiency, and to improve conformance in heterogeneous reservoirs for better sweep efficiency (Mayank and Quoc, 2010). Altering wettability of carbonate reservoirs which originally in oil wet by surfactants has been intensively studied and many research papers have been published (Spinler and Baldwin, 2000).

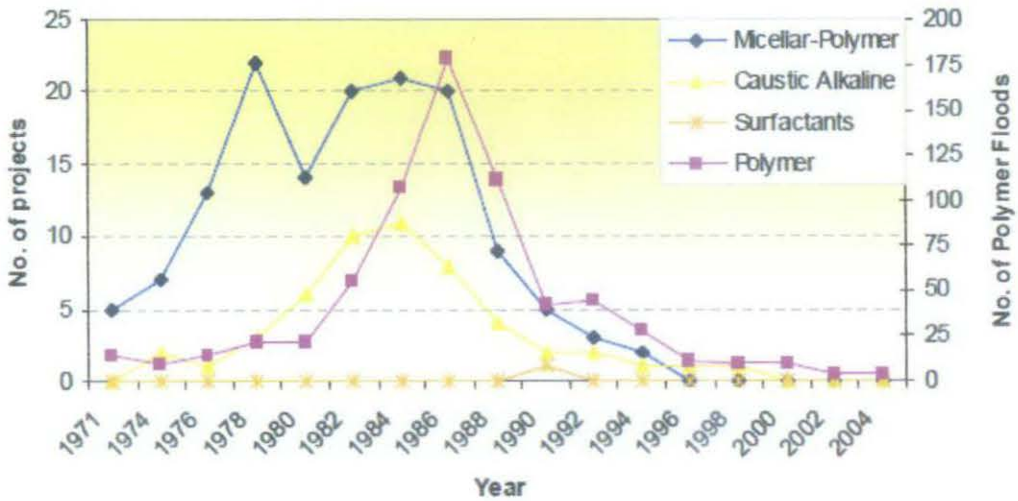


Figure 1: Evolution of EOR projects by chemical methods in US (Moritis, 2004).

Based on the report above, polymer flooding is the most important chemical method of EOR. More than 290 polymers field projects have been reported in the literature. Nevertheless, polymer flooding shows its ability as the proven EOR technology in carbonate light oil reservoirs.

2.6.1.1 Polymer Flooding

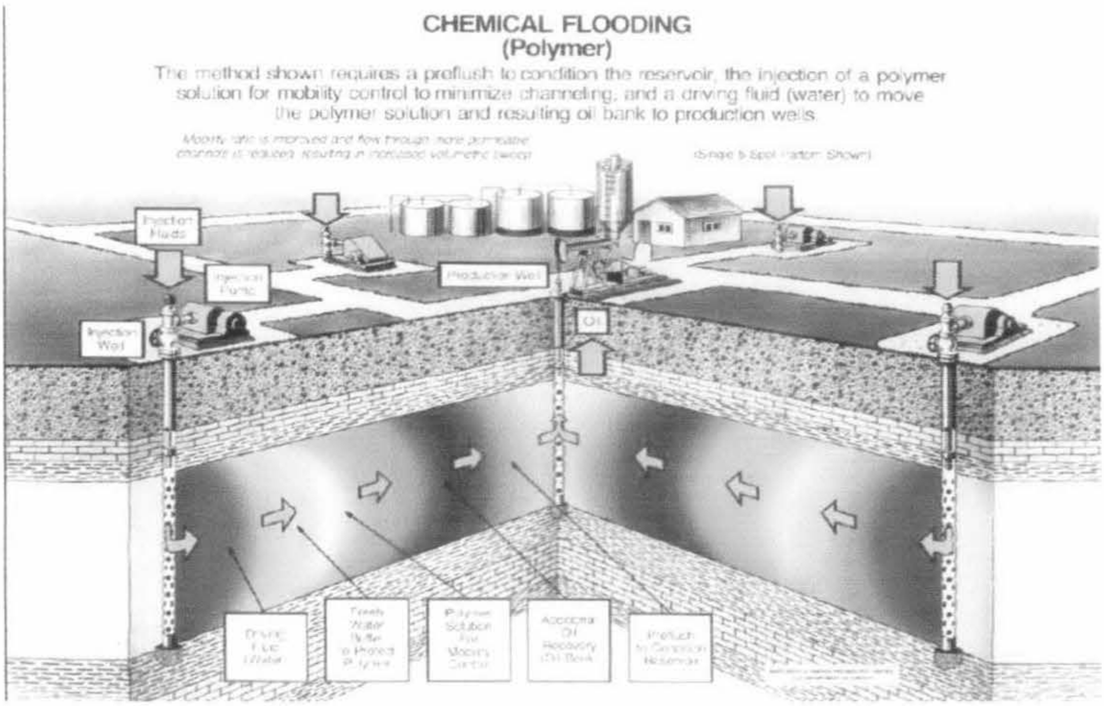


Figure 2: Polymer injection diagram (www.netl.doe.gov)

This method introduces polymers injected into the reservoir to increase the efficiency of waterflooding or to boost the effectiveness of surfactants, which are cleansers that help lower surface tension that inhibits the flow of oil through the reservoir

Polymer flooding is the feasible EOR process in carbonate reservoirs. Polymers that injected into reservoirs can increase the efficiency of waterflooding using the polyacrylamides in the early stage of waterflooding for mobility control strategy and improve sweep efficiency (David and Michael, 1981). Moreover, it can also help to boost the effectiveness of surfactants and reducing the surface tension that inhibits the flow of oil through the reservoir. Other than that, polymer also can alter the wettability of the carbonate reservoirs which originally oil-wet to water-wet.

2.6.1.2 Surfactant-Polymer Flooding (SP)

It is the second most used EOR chemical method in light and medium crude oil reservoirs and the fewer projects reported in this method compare to polymer floods. The need in high concentrations and cost of surfactants limited the use of this method although it is considered as the most promising EOR process (Matheny, 1980).

One of the field projects using SP was at Bob Slaughter Block (BSBL). It is a San Andres dolomite reservoir (Noran, 1978). SP system clearly showed that it capable to mobilize and displace tertiary oil.

2.6.1.3 Alkali-Surfactant-Polymer Flooding (ASP)

The functions of alkaline are promote crude oil emulsification and increase ionic strength decreasing interfacial tension (IFT) and modifiable phase behaviour. The alkaline additives also help to reduce the adsorption of anionic chemical additives by increasing the negative charge density of mineral rocks and make the rock more water-wet.

The alkaline agents will contribute to reduce the surfactant concentrations which making ASP formulations less costly than SP formulations. The surfactant uses are petroleum surfonates. Its ability is to reduce IFT between the oil and injected aqueous formulations and finally can help the existence of miscible formations. ASP is widely conducted in sandstone reservoir and no project reported in carbonate reservoir but recent laboratory test shows that commercial anionic surfactants can change the wettability of calcite surface to intermediate or water-wet condition with a West Texas crude oil in the presence of Na_2CO_3 (Seethepalli *et al*, 2004).

2.6.1 Gas Flooding

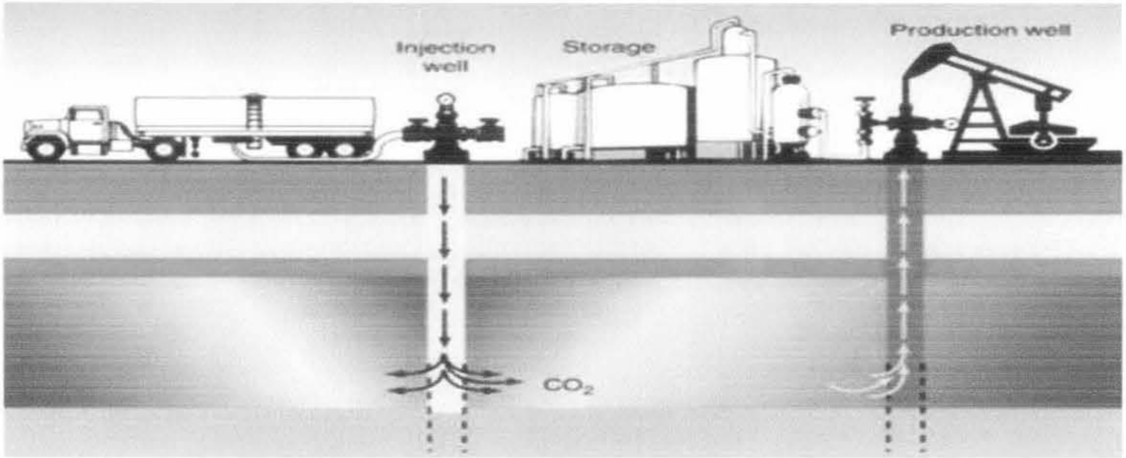


Figure 3: Gas flooding diagram (www.netl.doe.gov)

When the gas is injected, it will either expand and push gases through the reservoir, or mix with or dissolve within the oil, decreasing viscosity and increasing flow

Gas injection is the popular EOR method in carbonate reservoirs over the last decades. The considerable gas injection in carbonate light oil reservoirs is from N_2 gas injection and CO_2 injection. The injection of gas at or above MMP is called as miscible gas injection while injection of gas below MMP is known as immiscible gas injection.

2.6.2.1 N_2 Flooding

For deep, high-pressure and light oil reservoirs, N_2 flooding has been practiced successfully reported in carbonate reservoirs in U.S for last four decades. N_2 injection is under miscible gas injection displacement. It is also widely use in oil field operations for gas cycling, reservoir pressure maintenance, and gas lift. The using of N_2 is also related to the usually cheaper cost than CO_2 whilst the ability of being non-corrosive (Duraya, 2007). N_2 has less solubility in oil with high molecular weight. Therefore, N_2 injection is recommended for miscible displacement in light oil reservoirs.

Although high pressure N_2 injection is preferable for naturally fractured carbonate light oil reservoirs, there is no increment project using this process since the increased availability of CO_2 (E.J Manrique *et al.*, 2006).

2.6.2.2 CO_2 Flooding

The characteristics of CO_2 that can make it effective in removing oil from the formation are, (1) it promotes oil swelling, (2) it reduces oil viscosity, (3) it increases oil density, (4) it is highly soluble in water, (5) it exerts an acidic effect on the rock, (6) it can vaporize or extract portions of the crude oil and (7) it is transported chromatographically through porous rock. CO_2 on the other hand can give the displacement as miscible or immiscible type of EOR (S.M Farouq Ali, 1977).

The chosen of CO_2 instead N_2 is because CO_2 is more viscous than N_2 at reservoir condition. So sweep efficiency is stronger than N_2. It is good for immiscible gas injection displacement. MMP CO_2 is lower than N_2 is good characteristic for miscible gas injection displacement. The availability of natural sources of CO_2 and CO_2 transporting pipelines relatively close to the oilfields, especially in Permian Basin make the increment number of CO_2 projects (E. Manrique, 2004).

The injection of CO_2 also successfully implemented in carbonate reservoirs. However, the injection of gas can cause fingering due to the viscosity different between the oil and the gas injected. During the miscible displacement, some asphaltenes precipitation may occur during the flood and causing the permeability reduction (S.M Farouq Ali, 1977).

2.6.2.3 Applications of Gas Injection

Other EOR gas method to be mention is injection hydrocarbon gases in water or Water Alternating Gas (WAG). WAG is the most common EOR method in carbonate reservoirs (Vladimir and Eduardo, 2010). During WAG, the hydrocarbon gas will be injected in the reservoir which has been filling with water. By injecting the gas, the gas will push the water and finally producing the oil at the production well.

Based on the EOR screening for Ekofisk field by T.B Jensen *et al.* (2000), the selected EOR processes on the gas injection are from HC WAG, N_2 WAG, and CO_2 WAG. Incremental oil recovery forecasts for the processes at Ekofisk were as follow:

- HC WAG : 3.3 % OOIP
- N_2 WAG : -2.2 % OOIP
- CO_2 WAG : 5.6 % OOIP

Results showed that N_2 WAG injection was already eliminated from further consideration. CO_2 WAG could give large reserves potential if the source is available while HC WAG gave the significant reserves potential. The development project using HC WAG should be implemented since it is an economically technique.

The use of gas is also an option to substitute polymer in conditions where its application is not feasible. As the carbonates reservoirs has low permeability and contain vugs and fractures, when the polymer process is conducted, it may result in loss of permeability and chemical conformance control. In order to overcome this problem, gas is a good source since the direct dispersed gas mobility reduces the gas plugging oil-rich low permeable rock matrix in carbonate reservoirs (Mayank and Quoc, 2010).

When the gas is injected in the chemical solutions, simultaneous flow of two phases results in the mobility reduction of each phase. This can produce to high sweep efficiency in immiscible EOR. Gas and chemical surfactant injection can cause formation of foam. The formation of foam in the reservoirs can reduces the mobility of chemical slug and improves mobility control in the process. Foam can reduce the gas mobility in high permeable media and resulting in the improvement of volumetric sweep efficiency or conformance control (Nguyen et al., 2005).

FAWAG technology moreover has the potential for plugging selected zones or layers with foam while the reservoir remains under WAG flood. By this, more gas can be forced to less permeable or unswept areas and finally increase the sweep efficiency of the gas (F.E Suffridge *et al*, 1989).

2.7 Conclusion

Based on the technical reading and also report journal, probably the most suitable EOR method for carbonate reservoir in producing oil is polymer flooding or the combination of gas injection and polymer. Han Dakuang (1998) reported the result research achievement in onshore oilfields in China by using polymer flooding exhibits the most prospective application in light oil reservoirs.

Besides, laboratory experimental by T.Babadagli (2001) on naturally fractured reservoirs using four different fluids for EOR techniques which are brine, surfactant, polymer and hot water showed that surfactant provides the fastest recovery but polymer provides the highest recovery for oil.

Therefore, in order to prove the possibility, a screening test will be conducted. The EOR screening using those two methods and further analysis will give the best selection of EOR method for carbonate reservoirs.

CHAPTER 3
METHODOLOGY

Project methodology is one of the important aspects in this project to make sure the project is done smoothly and successfully. Figure 4 below showed the process and activities involve in this project.

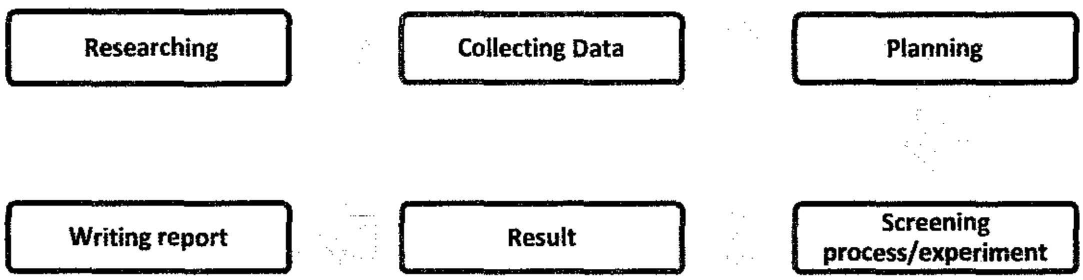


Figure 4: Methodology

I) **Researching**: The researching process is the continuing processes since FYP I. From the research, all about the projects and how the screening process taking place has been identified.

II) **Collecting Data**: During the researching process, all the data that gained by the literature review and based on the field cases and EOR projects are collected.

III) **Planning:** At this point, how the screening process will take place need to be planned and what to do after that.

IV) **Screening Process:** After considering all the screening criteria and all the methods, the screening process will take place. For the screening process, two methods use, which are :

1) **Manual screening**: Based on the screening criteria properties. Data from the selected fields are compared to the properties of screening criteria for each EOR method. The most suitable EOR method for the field will be chosen based on people's judgement.

2) **Programming:** By using this method, I create a program that automatically showed the result of the exact method for the field selected when the user key in the properties of the field. The name for this program is EORscreening.

V) **Result:** The result gained from the screening by both methods will be analyzed and compared. By analyzing the result, the most suitable EOR method for the selected fields can be identified.

VI) **Writing Report:** The result will be compiled in the report and the suitable EOR method for the selected fields will be proposed.

3.1 Tool

The main highlight in this project is to find the best method for the carbonates reservoirs. In order to find the solution, a screening process should be taking place and for the screening process to be done, a set of screening criteria has been developed by J.J Taber *et al.* (1997) which based on statistics on successful commercial IOR operations.

By using the properties in the properties on the table below which are from PRIze™ manual, a manual screening will be conducted.

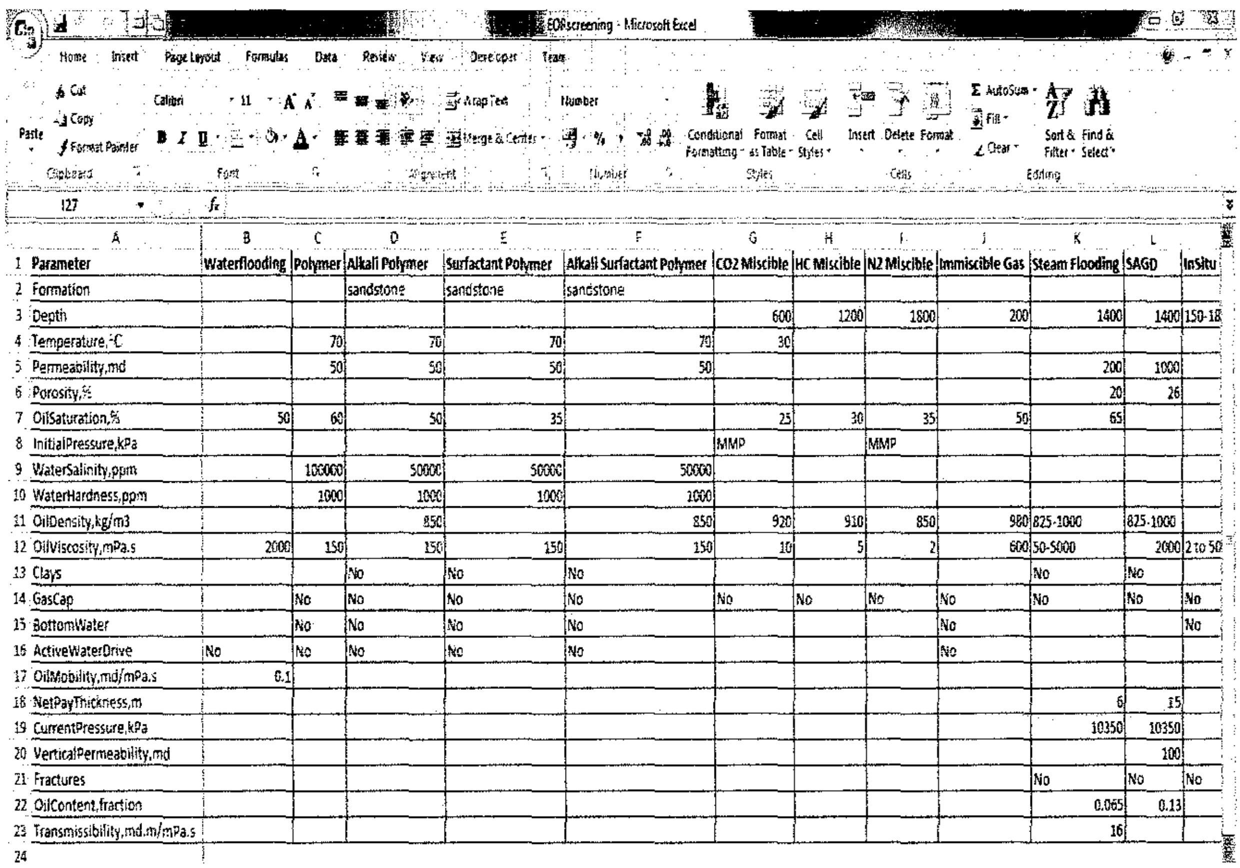
Parameter	Waterflooding	Polymer	AP	SP	ASP	CO2 Miscible	HC Miscible	N2 Miscible	Immiscible Gas	Steam Flooding	SAGD	InSitu Combustion
Formation			SS	SS	SS							
Depth						>600	>1200	>1800	>200	<1400	<1400	150-1800
Temperature,°C		<70	<70	<70	<70	>30						
Permeability,md		>50	>50	>50	>50					>200	>1000	>50
Porosity,%										>20	>26	>18
OilSaturation,%	>50	>60	>50	>35		>25	>30	>35	>50	>65		
InitialPressure,kPa						MMP		>MMP				
WaterSalinity,ppm		<100000	<50000	<50000	<50000							
WaterHardness,ppm		<1000	<1000	<1000	<1000							
OilDensity,kg/m3			>850		>850	<920	<910	<850	<980	825-1000	825-1000	
OilViscosity,mPa.s	<2000	<150	<150	<150	<150	<10	<5	<2	<600	50-5000	>2000	2 to 5000
Clays			No	No	No					No	No	
GasCap		No	No	No	No	No	No	No	No	No	No	No
BottomWater		No	No	No	No				No			No
ActiveWaterDrive	No	No	No	No	No				No			
OilMobility,md/mPa.s	>0.1											
NetPayThickness,m										>6	>15	>3
CurrentPressure,kPa										<10350	<10350	
VerticalPermeability,md											>100	
Fractures										No	No	No
OilContent,fraction										>0.065	>0.13	>0.065
Transmissibility,md.m/mPa.s										>16		>16

Table 2: Screening Criteria

The result can be obtained by comparing the properties in table and the properties of the fields selected.

The other method is by using programming. A set of program is created in order to make an easier way to make the screening process. The program is using Excel VBA Code and Excel Macro. Following below are the screen shots on how the program is working.

1) Key in all the screening criteria. Set as database in the Microsoft Excel.



Parameter	Waterflooding	Polymer	Alkali Polymer	Surfactant Polymer	Alkali Surfactant Polymer	CO2 Miscible	HC Miscible	N2 Miscible	Immiscible Gas	Steam Flooding	SAGD	InSitu
Formation			sandstone	sandstone	sandstone							
Depth						600	1200	1800	200	1400	1400	150-18
Temperature,°C		70	70	70	70	30						
Permeability,md		50	50	50	50					200	1000	
Porosity,%										20	26	
OilSaturation,%	50	60	50	35		25	30	35	50	65		
InitialPressure,kPa						MMP		MMP				
WaterSalinity,ppm		100000	50000	50000	50000							
WaterHardness,ppm		1000	1000	1000	1000							
OilDensity,kg/m3			850		850	920	910	850	980	825-1000	825-1000	
OilViscosity,mPa.s	2000	150	150	150	150	10	5	2	600	50-5000	2000	2 to 50
Clays			No	No	No					No	No	
GasCap		No	No	No	No	No	No	No	No	No	No	No
BottomWater		No	No	No	No				No			No
ActiveWaterDrive	No	No	No	No	No				No			
OilMobility,md/mPa.s	0.1											
NetPayThickness,m										6	15	
CurrentPressure,kPa										10350	10350	
VerticalPermeability,md											100	
Fractures										No	No	No
OilContent,fraction										0.065	0.13	
Transmissibility,md.m/mPa.s										16		

Figure 5: Database of screening criteria

2) Coding the program using VBA-Excel Macro

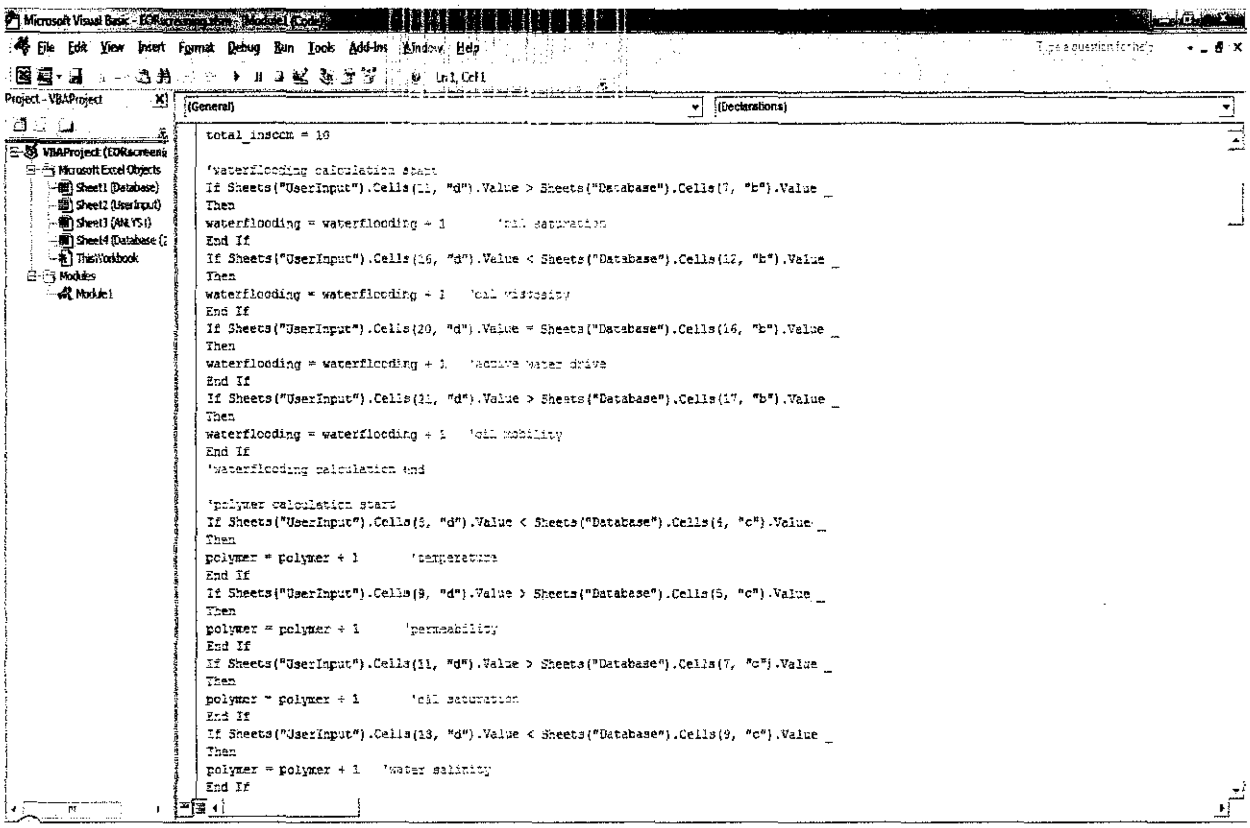


Figure 6: VBA Coding

3) Create the user input interface and result area.

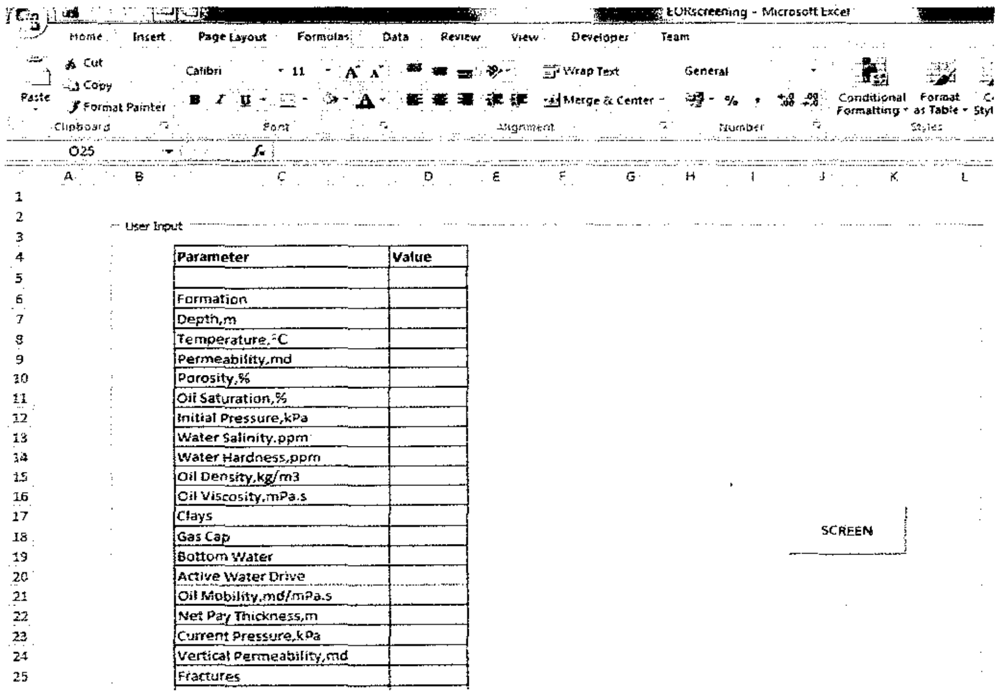


Figure 7: User input

For example, dolomite reservoir at San Andres is tested using this program. After the user key in all the data in the value column, click the screen button and the result will show.

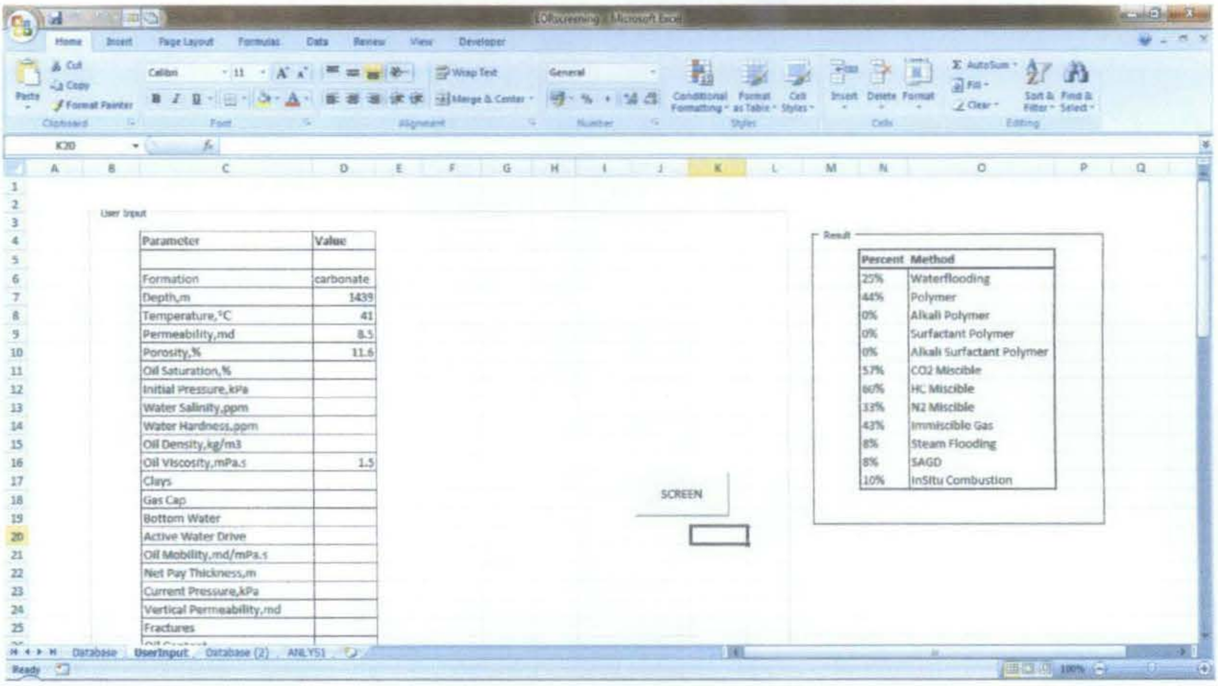


Figure 8: User input and result

The example result above shows the suitability percentage for each method. From the result, a feasible method for the field can be predicted.

From the technical screening above, a bar chart can be developed for each field to analyze the percentage suitability of each method. Figure 9 below shows the result for the test.

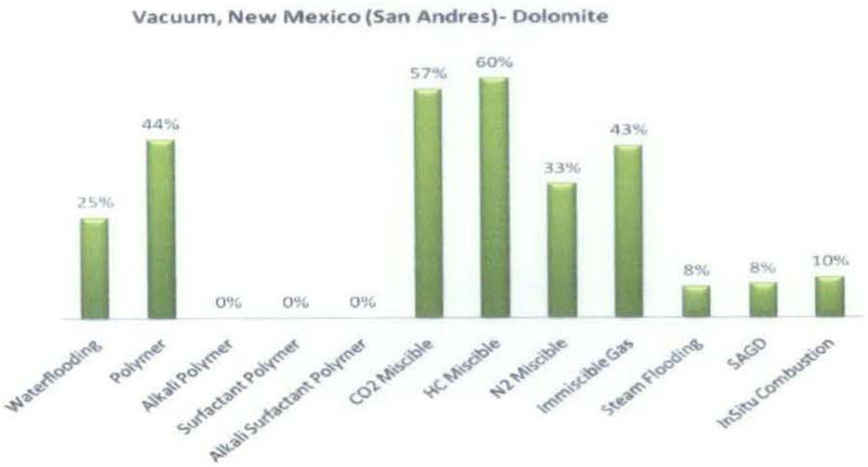


Figure 9: Vacuum, New Mexico (San Andres) - Dolomite

After each field is tested, a trending for example for dolomite reservoir can be figured out and ready to analyze as discussed in result and discussion chapter.

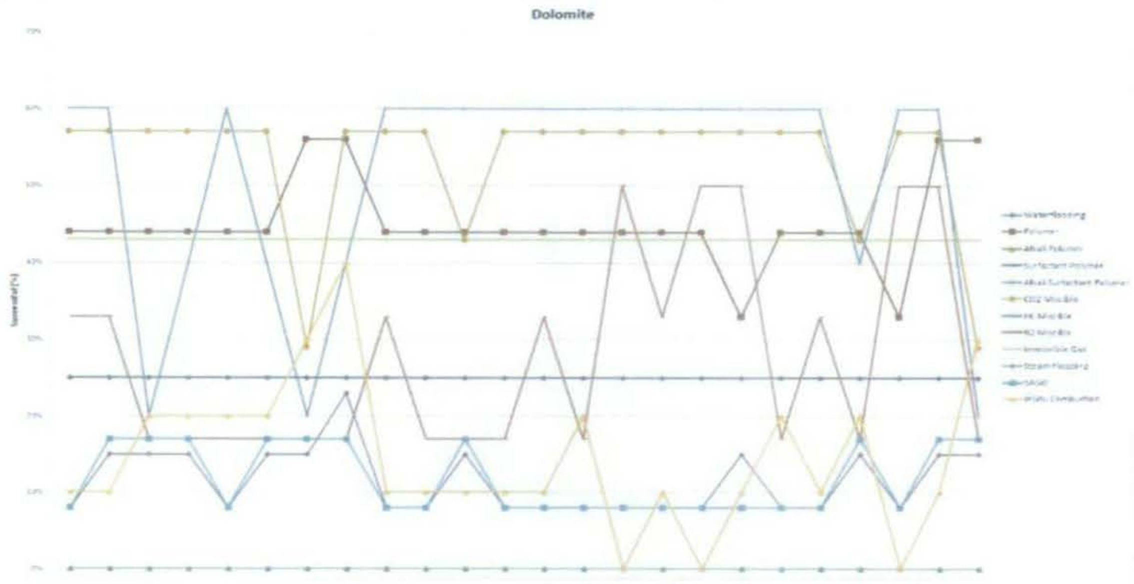


Figure 10: Percentage methods for dolomite

3.3 Gantt Chart

The key milestone and propose planning throughout this semester activities are as follow:

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues	■	■	■	■	■	■	■	Mid-Semester Break								
2	Submission of Progress Report									●							
3	Project Work Continues									■	■	■	■	■			
4	Pre-EDX												●				
5	Submission of Draft Report													●			
6	Submission of Dissertation (soft bound)														●		
7	Submission of Technical Paper														●		
8	Oral Presentation															●	
9	Submission of Project Dissertation (Hard Bound)																●

● Suggested milestone

■ Process

Table 3: Gantt chart

CHAPTER 4
RESULT AND DISCUSSION

After doing the technical screening for several types of fields, the results gained are discussed as follow. Since there are three types of carbonate reservoirs which are calcium carbonates, dolomite, and limestones, the results are divided into three section.

The technical screening that have been done are basically divided into four methods based on the project fields data. They are CO_2 floods, HC floods, N_2 floods, and chemical methods. For gas injection, the fields projects are based on continous injection or WAG while the chemical method includes surfactants or polymer floods.

The EOR fields projects that are from carbonate reservoirs in US and one from the North Sea which is Ekofisk Field.

Calcium Carbonates

Table 5 below shows the field and reservoir for calcium carbonates lithology that have been tested.

Field/Reservoir	Lith
Old Lisbon (Pettit)	Car
Fitts (Viola,Cromwell,Hunton)	Car
Stanley (Burbank)	Car
Garza (San Andres)	Car
Wasson (San Andres)	Car
Wasson South (San Andres)	Car
Blackjack Creek (Smackover)	Car

Table 4: Calcium carbonates reservoirs

From the technical screening, the result for each field and methods are recorded in percentage and is ilustrated in the graphs below.

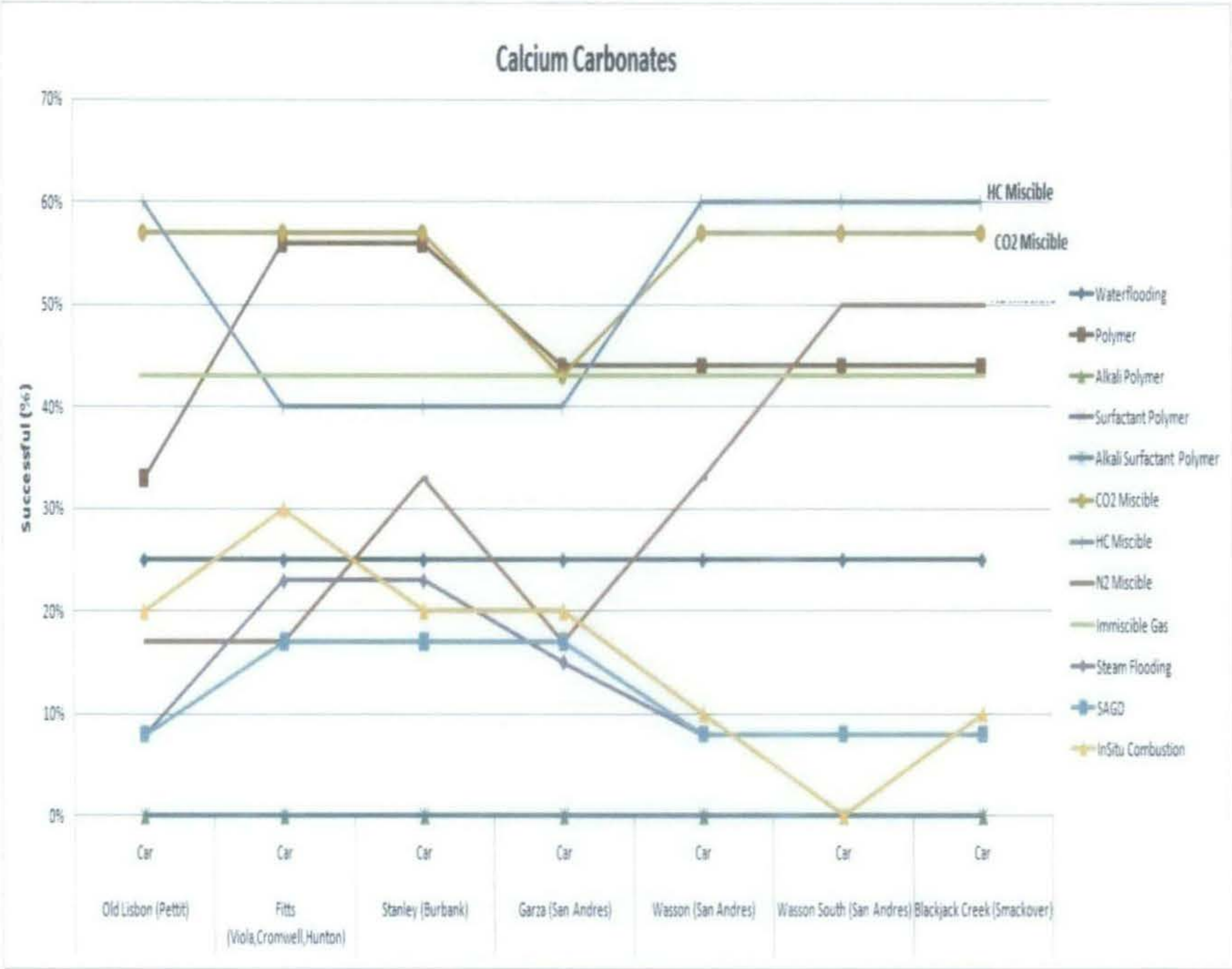


Figure 11: Percantage methods for calcium carbonates

Dolomite

No	Field/Reservoir	Lith
1	Vacuum (San Andres)	Dol
2	Vacuum (Grayburg/San Andres)	Dol
3	C-Bar (San Andres)	Dol
4	Dune (San Andres)	Dol
5	Goldsmith 5600 (Clearfork)	Dol
6	McElroy (Grayburg)	Dol
7	Yates(San Andres)	Dol
8	Handford (San Andres)	Dol
9	Handford East (San Andres)	Dol
10	West Brahaney Unit (San Andres)	Dol
11	East Penwell (San Andres)	Dol
12	Welch (San Andres)	Dol
13	Slaughter Sundown (San Andres)	Dol
14	Mabee (San Andres)	Dol
15	Dollarhide (Clearfork)	Dol

16	Sable (San Andres)	Dol
17	T-Star (Abo)	Dol
18	Chatom (Smackover Lime)	Dol
19	Levelland (San Andres)	Dol
20	Slaughter (San Andres)	Dol
21	McElroy (San Andres)	Dol
22	Chunchula Field Unit (Smackover)	Dol
23	Andector (Ellenburger)	Dol
24	Yates (Grayburg/San Andres)	Dol

Table 5: Dolomite reservoirs

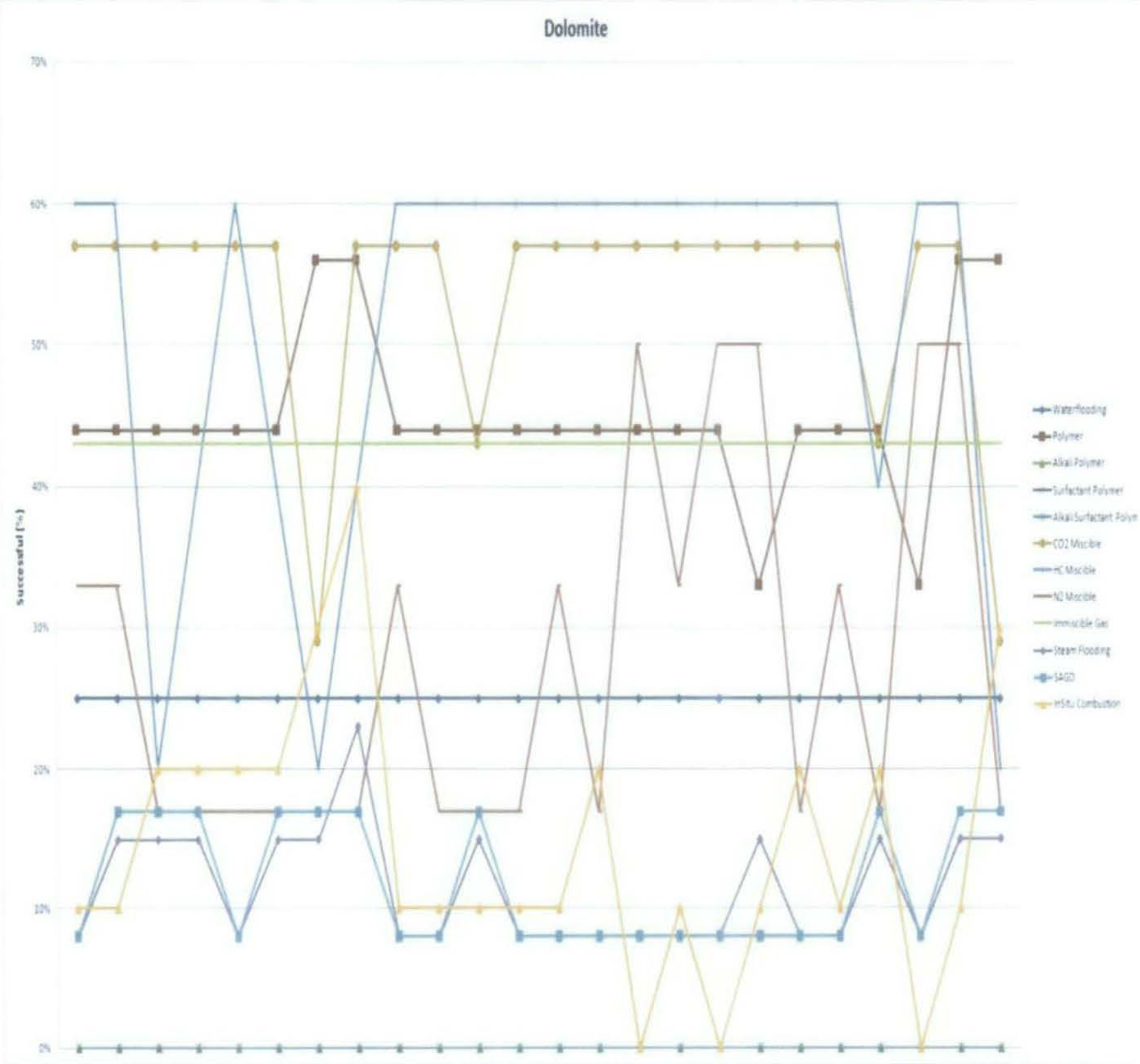


Figure 12: Percantage methods for dolomite

Limestone

No	Field/Reservoir	Lith
1	Phosphoria (Wesgum A)	LS
2	Tonti (Renoist Auxvases McClusky)	LS
3	Trapp (Lansing/Kansas City)	LS
4	Bates Unit (Mississippi)	LS
5	Harmony Hill (Lansing/Kansas City)	LS
6	Dry Creek (Lansing/Kansas City)	LS
7	Blue Buttes (Madison)	LS
8	Fitts (Viola)	LS
9	Balko South (Kansas City)	LS
10	Garza (San Andres)	LS
11	Cottonwood Creek (Phosporia)	LS
12	Corossett (Devonian)	LS
13	Wellman (Wolfcamp)	LS
14	Codgell (Canyon Reef)	LS
15	Aneth (Ismay Desert Creek)	LS
16	Ekofisk (Norwegian Sector)	LS
17	Carlson (Madison)	LS
18	Red Wing Creek (Mission Canyon)	LS
19	Fairway (San Andres)	LS
20	Wolfcamp Univ Block ((Wolfcamp)	LS
21	Block 31 (Devonian)	LS
22	Jay-Little Escambia Creek (Smackover)	LS

Table 6: Limestones reservoirs

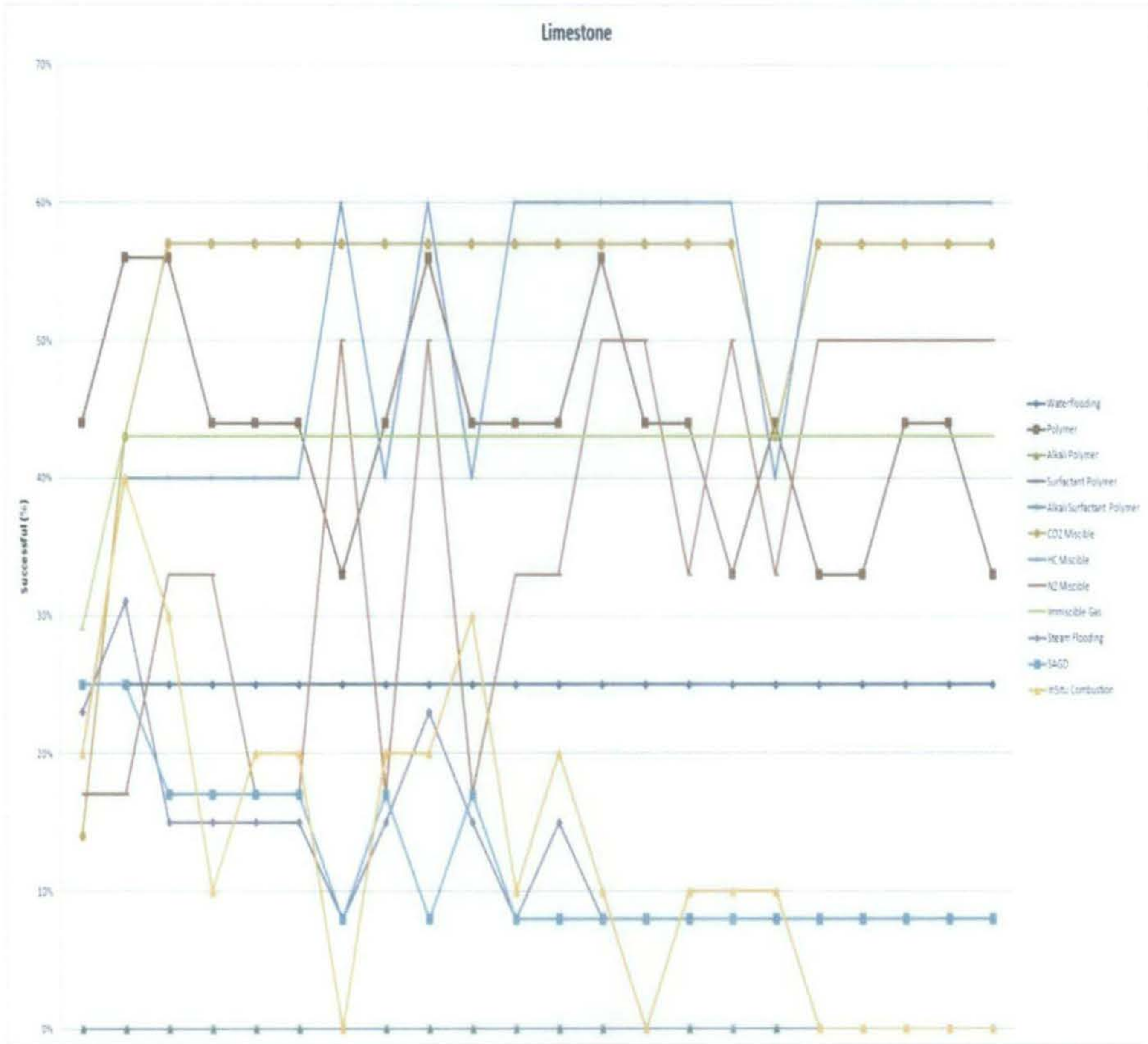


Figure 13: Percantage methods for limestone

Limestone/Dolomite

No	Field/Reservoir	Lith
1	Reinecke (Cisco Canyon Reef)	LS/Dol
2	Hilly Upland (Greenbrier)	LS/Dol

Table 7: Limestone/ Dolomite reservoirs

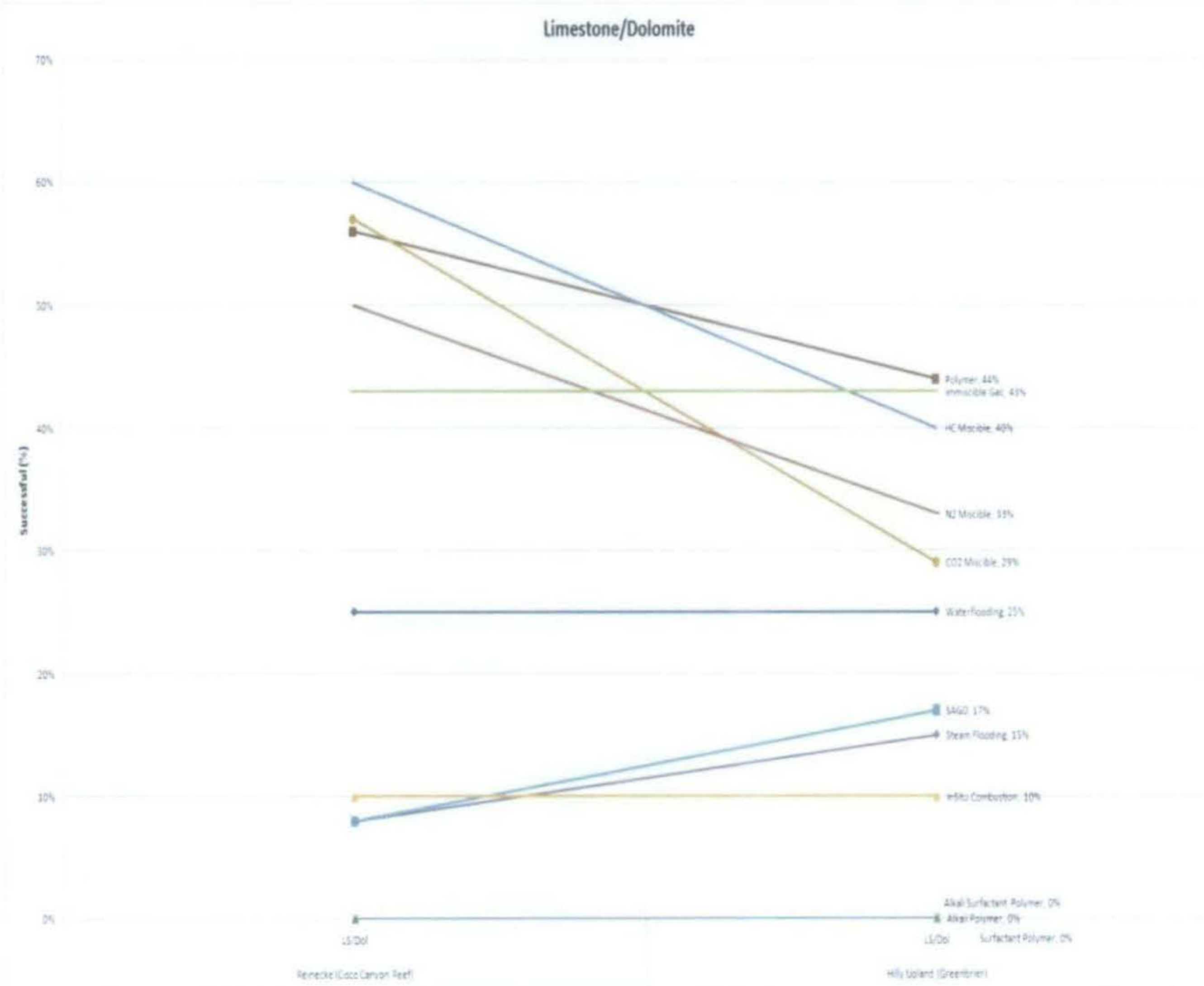


Figure 14: Percantage methods for Limestone/Dolomite

Based on the result shows above, on the technical screening using the EORscreening, the programming software which developed using the visual basic Microsoft Excel 2007 Macro and the data gained from E.E Manrique *et al.* (2007), the most suitable methods for calcium carbonates, dolomite, and limestones are HC Miscible, CO_2 Miscible, Polymer and N_2 Miscible. Comparing with the research made by E.J Manrique *et al.* (2007), CO_2 flooding has been successful in the both mature and waterflooded carbonate reservoirs. The use of CO_2 is definitely popular among the oil companies because of the affordability and availability of CO_2 rather than the other methods (E.J Manrique *et al.*, 2007). Although the HC Miscible is showing the most suitable for the reservoirs, but for the economic purposes, it is more profitable to sell the gas immediately. HC gas is the better choice when it is available in sufficient quantities and non economical to export (A.R Awan *et al.*, 2008).

For Alkali Polymer, Surfactant Polymer, and Alkali Surfactant Polymer, they show 0% for each test based on the EOR screening database as they are not suitable for carbonate reservoirs but for sandstone only. It is because the use of surfactant in chemical methods needs co surfactant, mostly alcohol. Alkali in carbonates makes will increase the chemical absorption within the rocks because of the different charges. In other cases, polymer are widely use because it uses the water-soluble polyacramides in other to control the mobility of water during waterflooding (E.J Manrique *et al.*, 2007).

Waterflooding shows 25% for each as the fields at first will initiated to improve the recovery by injecting water. After certain time, the water will bypass the oil since the highly fractured of carbonate reservoirs. Therefore, another method needs to be implemented to overcome the problem. Injecting gas or polymer is proven as the best solution to control the mobility of oil.

CO_2 flooding, either continuous or WAG is the dominant EOR process used in the US while in chemical method, polymer flooding is highly tested in the US (E.J Manrique *et al.*, 2007). The use of CO_2 is also the first step taken by the oil companies towards the viable geological carbon storage and sequestration. Furthermore, with the current focus on CO_2 emissions, EOR by CO_2 injection is considered attractive and will be the main focus for future research programs. WAG can be used when the gas is available in sufficient quantities and non economical to export while SWAG can be considered when the injected gas is available in limited quantities. With the current oil price, the use of polymers also could be possible in carbonate reservoirs (A.R Awan *et al.*, 2006).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Recommendation

The results that gained from this project and data that has been used can produce the new criteria for screening criteria. This means that the screening criteria for carbonate reservoirs can be improved. The continuing study on this project can produce a good database system in choosing the suitable EOR method for carbonate reservoirs.

Based on the discussion above, the most probably suitable EOR methods that can implemented in carbonate reservoirs are HC Miscible, CO_2 Miscible, Polymer Flooding, and N_2 Miscible. But, there are certain limitations for each method. Waterflooding is always the best secondary type of recovery since the economical value and the process is easier to be implemented. Tertiary recovery or EOR will come after that since the waterflooding alone will sooner create to more residual oil in the carbonate reservoirs. Therefore, gas injection and chemical injection can help to reduce the residual oil and increase the mobility of oil in the reservoirs. Then, to choose the suitable methods, screening criteria on the properties and economic value must be conducted.

As per discussion above, the recommendation for suitable methods for carbonate reservoirs can be made. Based on the technical screening and history on successful project, the most preferable method for carbonate reservoirs is CO_2 flooding either miscible, continuous, or in WAG. CO_2 is proven as the dominant method in carbonate reservoirs in US because the availability and low cost (E.J Manrique *et al.*, 2007). Other than that, the use of CO_2 also can reduce the excessiveness of the gas to the atmosphere, and then prevent the global warming.

5.2 Conclusion

As for the conclusion, this project helps to determine the best solution of EOR process in carbonate reservoirs. All the data on the specific reservoirs has been screened and the EOR process applicable for that reservoir can be selected as the most promising EOR process that can improve the production of carbonate reservoirs recovery. The screening test has been conducted by using manual screening and also the programming based database on previous successful project.

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APPENDIX

Field/Reservoir	Lith	Waterflooding	Polymer	Alkali Polymer	Surfactant Polymer	Alkali Surfactant Polymer	CO2 Miscible	HC Miscible	N2 Miscib	Immiscible Gas	Steam Floodi	SAGD	InSitu Combusti
Phosphoria (Wesgum A)	LS	25%	44%	0%	0%	0%	14%	20%	17%	29%	23%	15%	30%
Tonti (Renoist Auxvases McClusky)	LS	25%	56%	0%	0%	0%	43%	40%	17%	43%	31%	25%	40%
Trapp (Lansing/Kansas City)	LS	25%	56%	0%	0%	0%	57%	40%	33%	43%	15%	17%	30%
Bates Unit (Mississippi)	LS	25%	44%	0%	0%	0%	57%	40%	33%	43%	15%	17%	10%
Harmony Hill (Lansing/Kansas City)	LS	25%	44%	0%	0%	0%	57%	40%	17%	43%	15%	17%	20%
Old Lisbon (Pettit)	Car	25%	33%	0%	0%	0%	57%	60%	17%	43%	8%	8%	20%
Dry Creek (Lansing/Kansas City)	LS	25%	44%	0%	0%	0%	57%	40%	17%	43%	15%	17%	20%
Vacuum (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
Vacuum (Grayburg/San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	33%	43%	15%	17%	10%
Blue Buttes (Madison)	LS	25%	33%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Fitts (Viola)	LS	25%	44%	0%	0%	0%	57%	40%	17%	43%	15%	17%	20%
Balko South (Kansas City)	LS	25%	56%	0%	0%	0%	57%	60%	50%	43%	23%	8%	20%
Fitts (Viola,Cromwell,Hunton)	Car	25%	56%	0%	0%	0%	57%	40%	17%	43%	23%	17%	30%
Stanley (Burbank)	Car	25%	56%	0%	0%	0%	57%	40%	33%	43%	23%	17%	20%
C-Bar (San Andres)	Dol	25%	44%	0%	0%	0%	57%	20%	17%	43%	15%	17%	20%
Dune (San Andres)	Dol	25%	44%	0%	0%	0%	57%	40%	17%	43%	15%	17%	20%
Goldsmith 5600 (Clearfork)	Dol	25%	44%	0%	0%	0%	57%	60%	17%	43%	8%	8%	20%
McElroy (Grayburg)	Dol	25%	44%	0%	0%	0%	57%	40%	17%	43%	15%	17%	20%
Garza (San Andres)	LS	25%	44%	0%	0%	0%	57%	40%	17%	43%	15%	17%	30%
Yates(San Andres)	Dol	25%	56%	0%	0%	0%	29%	20%	17%	43%	15%	17%	30%
Cottonwood Creek (Phosporia)	LS	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
Handford (San Andres)	Dol	25%	56%	0%	0%	0%	57%	40%	17%	43%	23%	17%	40%
Handford East (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
West Brahaney Unit (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	17%	43%	8%	8%	10%
East Penwell (San Andres)	Dol	25%	44%	0%	0%	0%	43%	60%	17%	43%	15%	17%	10%
Garza (San Andres)	Car	25%	44%	0%	0%	0%	43%	40%	17%	43%	15%	17%	20%
Welch (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	17%	43%	8%	8%	10%
Corossett (Devonian)	LS	25%	44%	0%	0%	0%	57%	60%	33%	43%	15%	8%	20%
Wasson (San Andres)	Car	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
Wasson South (San Andres)	Car	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Reinecke (Cisco Canyon Reef)	LS/Dol	25%	56%	0%	0%	0%	57%	60%	50%	43%	8%	8%	10%
Slaughter Sundown (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
Mabee (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	17%	43%	8%	8%	20%
Wellman (Wolfcamp)	LS	25%	56%	0%	0%	0%	57%	60%	50%	43%	8%	8%	10%
Dollarhide (Clearfork)	Dol	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Sable (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
Codgell (Canyon Reef)	LS	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
T-Star (Abo)	Dol	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Aneth (Ismay Desert Creek)	LS	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
Hilly Upland (Greenbrier)	LS/Dol	25%	44%	0%	0%	0%	29%	40%	33%	43%	15%	17%	10%
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Chatom (Smackover Lime)	Dol	25%	33%	0%	0%	0%	57%	60%	50%	43%	15%	8%	10%
Carlson (Madison)	LS	25%	44%	0%	0%	0%	43%	40%	33%	43%	8%	8%	10%
Red Wing Creek (Mission Canyon)	LS	25%	33%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Levelland (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	17%	43%	8%	8%	20%
Slaughter (San Andres)	Dol	25%	44%	0%	0%	0%	57%	60%	33%	43%	8%	8%	10%
McElroy (San Andres)	Dol	25%	44%	0%	0%	0%	43%	40%	17%	43%	15%	17%	20%
Fairway (San Andres)	LS	25%	33%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Wolfcamp Univ Block ((Wolfcamp)	LS	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Block 31 (Devonian)	LS	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Chunchula Field Unit (Smackover)	Dol	25%	33%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Blackjack Creek (Smackover)	Car	25%	44%	0%	0%	0%	57%	60%	50%	43%	8%	8%	10%
Andector (Ellenburger)	Dol	25%	56%	0%	0%	0%	57%	60%	50%	43%	15%	17%	10%
Jay-Little Escambia Creek (Smackover)	LS	25%	33%	0%	0%	0%	57%	60%	50%	43%	8%	8%	0%
Yates (Grayburg/San Andres)	Dol	25%	56%	0%	0%	0%	29%	20%	17%	43%	15%	17%	30%

Colour	Legend
Green	Chemical
Orange	CO2
Dark blue	HC
Blue	N2