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Study on Potentials of Light Oil Air Injection (LOAI) in Malaysian Oil Fields

submitted by

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for the fulfillment of the requirements for the degree of

Masters of Science in Mechanical Engineering

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UNIVERSITI TEKNOLOGI PETRONAS

Study on Potentials of Light Oil Air Injection (LOAI) in Malaysian Oil Fields

By

Zeeshan Mohiuddin

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

AS A REQUIREMENT FOR THE

DEGREE OF MASTERS OF SCIENCE IN MECHANICAL

ENGINEERING

BANDAR SERI ISKANDAR,

PERAK

JULY , 2007

1) secondary recovery of oil

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Signature :

Name : Zeeshan Mohiuddin

Date : July 6, 2007

ACKNOWLEDGEMENT

After thanking the Almighty Allah, the author would like to express his heartfelt gratitude to his honorable supervisors, Assoc. Prof. Dr D.M Anwar Raja and Dr Ismail Mohd Saaid for their advices and constant guidance during the course of this research. They have always been eager to listen and discuss various aspects of the project. Furthermore, their comments on the drafts of this thesis have improved its quality of presentation considerably.

The author also would like to express his deep appreciation to the staff of Postgraduate Studies Programme. Special thanks for those people who has offered their advices which was of great assistance in completing the study. It includes Dr Nasir Haji Darman (PMU, PETRONAS), Mr. Nurisman Maroop (PETONAS Carigali Sdn. Bhd), Mr. Nor Aidil B Anua (PETRONAS Research Group), Mr Brundaban Tripathy (ExxonMobil Malaysia), Professor Dr M. Greaves (University of Bath), Professor Dr G. Moore (University of Calgary), Dr Myron Khulman (M.K. Tech Solutions), Dr Ashok Singhal (Alberta Research Council), Dr. Janusz Grabowski (Alberta Research Council), Dr Tianxiang Xia (Total E&P, UK), Mr. Darrell Davis (Petroleum Development Oman) , and Mr. Bharath Rao (Bhavya Tech. Solutions).

Finally, the author would like to take this opportunity to thank his parents for the love and support they had given to him during the entire life and in the period of this research. Especially, author would like to thank his mother who despite of her health, support him to complete his research study. Author also wants to thank all good friends and colleagues who have helped the author many times during his stay in the university.

ABSTRACT

Air injection has been used as one of the enhanced oil recovery (EOR) techniques especially to extract the heavy oil. In light oil reservoirs, the thermal EOR method is known as light oil air injection (LOAI). The present research work has been carried out to assess the potentials of LOAI in Malaysian light oil reservoirs. The research project begins with the development of reservoir screening criteria by evaluating the worldwide successful LOAI projects and consultation with the industry experts. In principle, the reservoir screening criteria embeds major reservoir properties such as the reservoir temperature, reservoir pressure, oil viscosity, formation depth and reservoir permeability. Based on the developed screening criteria, Dulang E12/13 and Dulang E14 reservoirs were screened out for further study. Selection of these reservoirs was further verified using PRIze screening software. PRIze screening indicated incremental recovery at the cost of high gas production. Black oil simulations were carried out using eight different configurations of injection and production wells to further investigate the potential of LOAI for Dulang E12/13 and E14 reservoirs.

The present research assumes that the combustion occurs in the low temperature oxidation range and the combustion mixture remains immiscible. Besides, nitrogen was used in place of air as an injecting fluid to simplify the LOAI process. Thus, oil swelling, viscosity reduction by CO_2 dissolution and thermal effects were not accounted in the research study. Based on these assumptions, black oil simulation was used to identify the potential of LOAI in terms of oil, water and gas production. This eliminates the need for the experimental work for estimating the early potential of LOAI. Results of the black oil simulations seemed to suggest that the LOAI could significantly increase the oil recovery factor in Dulang E12/13 and E14 reservoirs by 35%. The high incremental recovery however is accompanied with high GOR which might impose safety hazards and corrosion related problems.

ABSTRAK

Pancitan udara, satu bentuk perolehan minyak secara haba, telah lama digunakan sebagai satu daripada teknik-teknik perolehan minyak tertingkat (EOR). Dalam reserbor minyak ringan, teknik ini dikenali sebagai pancitan udara minyak ringan (LOAI). Penyelidikan yang dijalankan ini adalah untuk menaksir potensi teknik LOAI bagi reserbor minyak ringan di Malaysia. Penyelidikan ini dimulakan dengan membangunkan kriteria penapisan reserbor melalui penilaian projek-projek LOAI yang telah berjaya diseluruh dunia serta perundingan dengan orang-orang industri. Secara prinsip, kriteria penapisan reserbor mengambilkira sifat-sifat reserbor yang asas seperti suhu, tekanan, kelikatan minyak, kedalaman formasi dan kebolehtelapan. Bersandarkan kriteria ini, reserbor Dulang E12/13 dan Dulang E14 telah dikenalpasti untuk penyelidikan seterusnya. Pemilihan reserbor-reserbor ini telah disahkan lagi melalui penggunaan perisian penapisan PRIze, sejenis perisian penapisan reserbor komersil. Penapisan melalui PRIze ini juga telah menunjukkan perolehan tokokan, tetapi ianya melibatkan pengeluaran gas yang tinggi. Penyelakuan minyak hitam telah dijalankan dengan menggunakan lapan tatarajah berbeza untuk telaga pengeluaran dan pancitan. Penyelakuan ini adalah untuk mengkaji dengan lebih mendalam potensi LOAI untuk reserbor Dulang E12/13 dan E14.

Pengkajian terkini menganggap bahawa pembakaran setempat berlaku di kawasan pengoksidaan suhu rendah, sesaran nitrogen meninggalkan kesan besar dan campuran pembakaran kekal tak boleh campur. Pembengkakan minyak, pengurangan kelikatan melalui pelarutan CO_2 dan kesan-kesan haba tidak diambilkira dalam penyelakuan minyak hitam. Dengan anggapan-anggapan ini, penyelakuan minyak hitam telah digunakan untuk mengenalpasti potensi LOAI dari segi pengeluaran minyak, air dan gas. Pengecualian-pengecualian ini menamatkan keperluan ujikaji makmal dalam menganggarkan potensi LOAI. Hasil-hasil penyelakuan minyak hitam mencadangkan bahawa LOAI boleh menambahkan faktor perolehan minyak dari reserbor Dulang 12-14 sehingga mencapai 35%. Namun perolehan yang tinggi ini diiringi dengan kadar nisbah minyak gas (GOR) yang tinggi. Ini tentunya memberikan ancaman keselamatan dan masalah- masalah berkaitan karat.

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CHAPTER 1
INTRODUCTION

1.1) Background

Oil has become a vital part of industry, agriculture, and the fabric of society at large. The use of oil has changed world economies, social and political structures, and lifestyles beyond the effect of any other substance in such a short time. Presently, the production of vehicles worldwide is increasing approximately 5% per year (Gottschalk, 2006). These vehicles are using oil and its derivatives like gasoline, kerosene and naphtha as fuel. In the first half of year 2006, 35.4 million vehicles worldwide were manufactured (Gottschalk, 2006). According to Energy Information Administration (EIA), the world used around 84020 thousand barrels per day in 2005. However, oil is a finite resource, and its consumption is at an exponentially high rate (BBC News, June 20, 2006). This great challenge needs to increase the recovery factor from the current average levels of about 30% (Schulte *et al.*, 2005). On the demand side, the developing world's rapid economic growth is the major contributor of oil consumption which is evidenced by Figure 1.1. A dramatic rise of over seven times in Asia over the last four decades has occurred because of high population growth and improving standard of living (Oil Consumption, 2006)

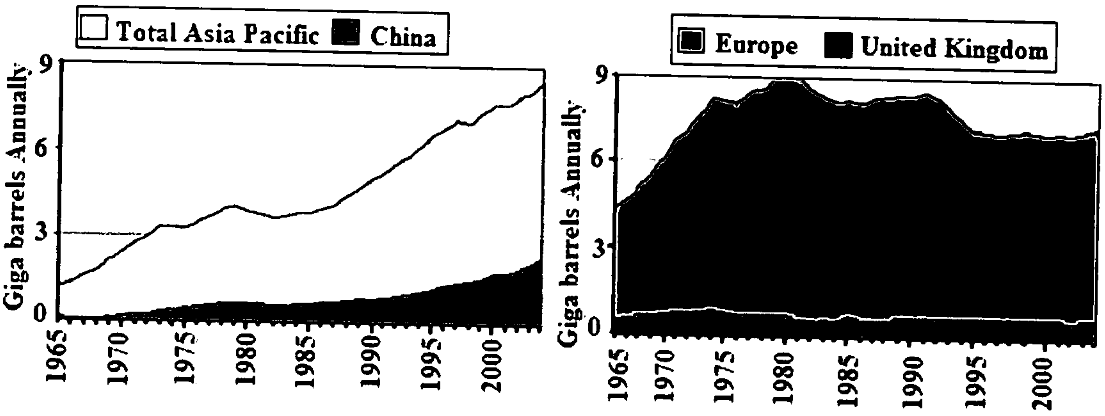


Figure 1.1 Consumption of Oil in Asia Pacific and Europe (Oil Consumption, 2006)

Oil consumption in Asian Pacific countries has reached the level of the Europe, but at a much higher rate as shown by Figure 1.1. The trend suggests that oil consumption in

Asian Pacific countries will increase dramatically in the next few decades. Figure 1.2 represents the change in oil consumption in different parts of the world from 1965 to 2005. It indicates that the increment of oil consumption in Asia pacific region is 636% which is very high.

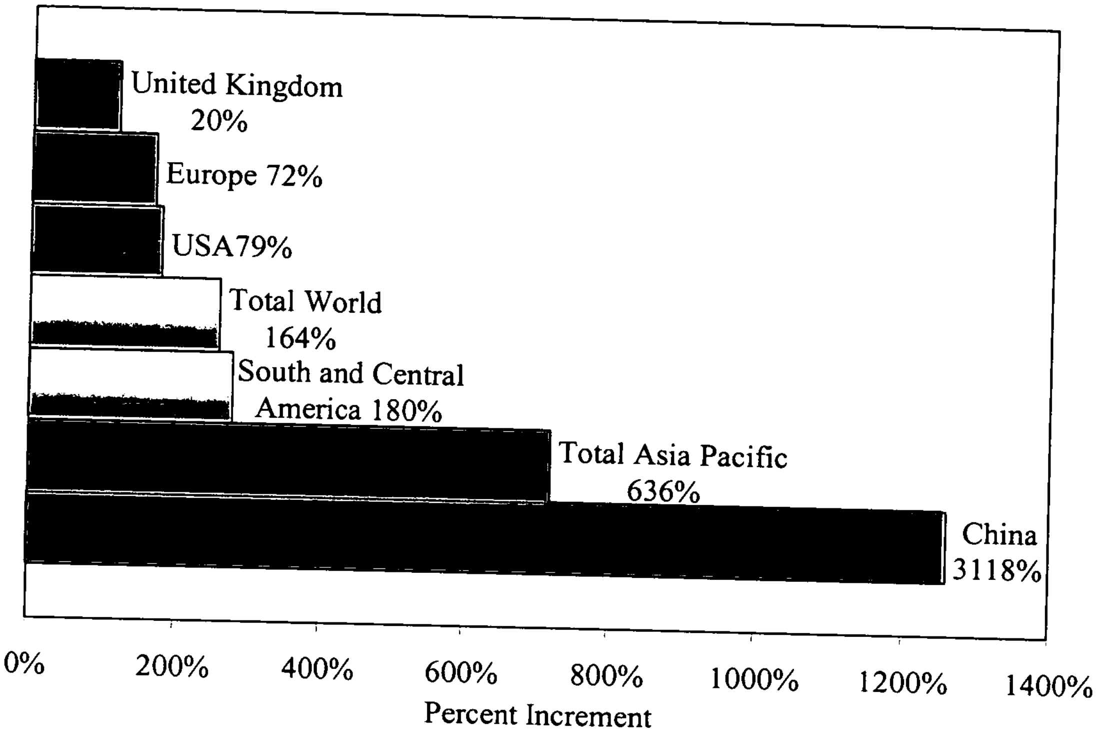


Figure 1.2 Changes in Oil Consumption from Year 1965 to 2005 (Oil Consumption, 2006)

On the supply side, the increasing difficulty of finding new large reservoirs has put pressure on major oil producing countries (Peak Oil, 2006). For this reason, the price of crude oil and its derivatives has experienced a massive increase in excess of inflation. Figure 1.3 shows the increase in the price of Brent oil per unit barrel from 2005 to 2006.

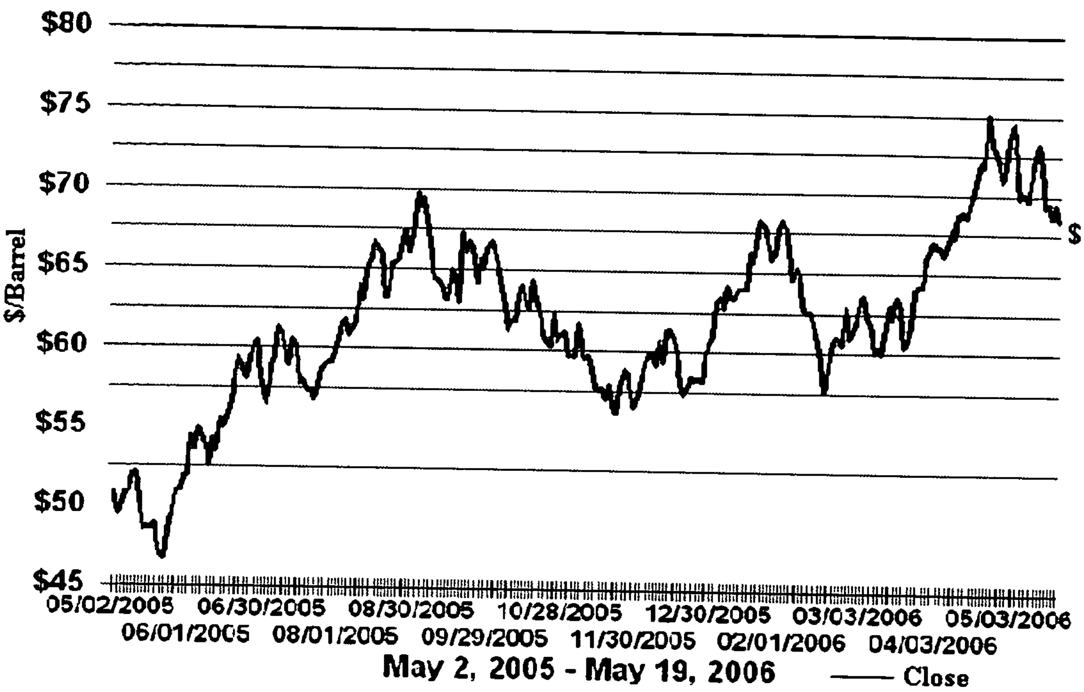


Figure 1.3 Brent Oil Price Inflation (Williams, 2006)

According to National Economic Action Council (NEAC), the existence of a world wide tight market is due to the small margin between production (83.0 million barrels per day) and demand (82.5 million barrels per day) of oil (National Economic Action Council, 2006). Figure 1.4 shows the OPEC spare production capacity of petroleum reserves. It shows that the spare production capacity of petroleum reserves had reached more than 10Mbd in mid 80's which was reduced to a value of 0.5 Mbd in year 2003 (Rehaag,2004).

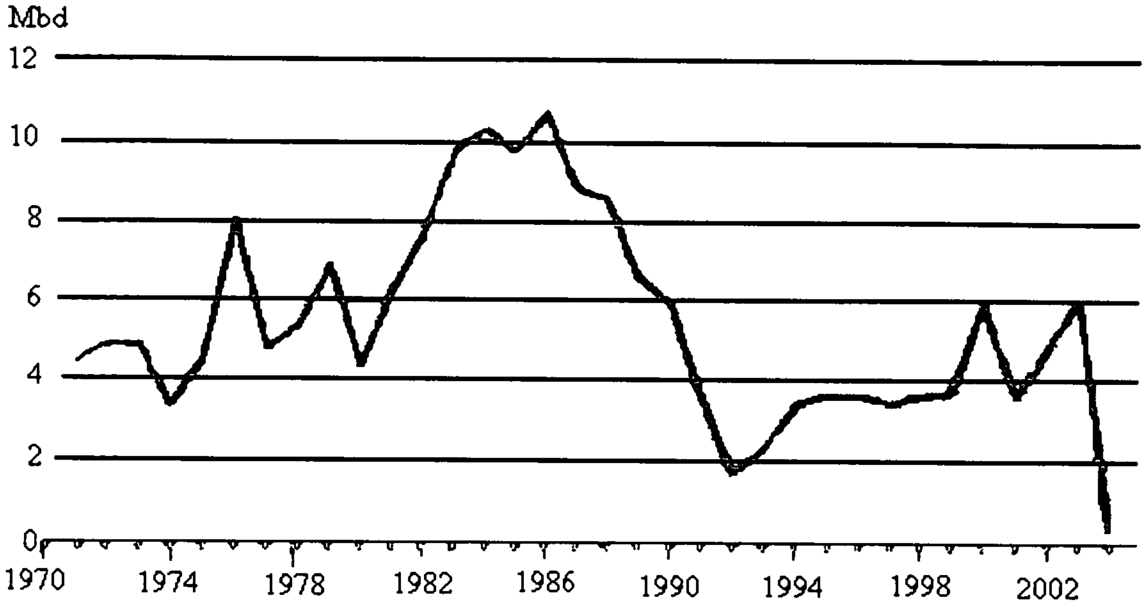


Figure 1.4 Historical OPEC Spare Production Capacity (Rehaag, 2004)

The present world energy problem due to small margin in production and demand is different from the temporary political and social problems which world experienced in 1973-74, 1979-86, 1990-91 and 2000 (Maxwell, 2004). In the light of above facts, Enhanced Oil Recovery (EOR) technologies provide a unique opportunity to increase a sizeable contribution to additional reserves by increasing production from the existing reservoirs.

1.2 Malaysian Oil Industry

Malaysia is important to world energy markets. Today, the Malaysian oil and gas industry has extended to approximately 500,000 km^2 of acreage contained in 52 offshore blocks which are demarcated for exploration and production. A total of eight major operators currently operate thirty-one of the production sharing contract (PSC) blocks, engaging in exploration, development and production. This also includes nine deepwater blocks, located in offshore Sabah and Sarawak (Hamdan *et al.*, 2005).

1.2.1 Current Status of Malaysian Oil Reserves

As of January 2005, the estimated oil-in-place from producing fields in Malaysia stood at about 17.0 Bstb, with estimated ultimate recovery (EUR) of 5.62 Bstb. The reserves in 2005 translate to an average oil recovery factor of 33% for producing fields in Malaysia. The remaining oil-in-place of 11.38 Bstb still remain in the oil reservoirs to be recovered (Samsudin *et al.*, 2005). On the other side, the demand of oil and gas is increasing per year in Malaysia which is chiefly due to the growth of industrial sector and improving living standard. Figure 1.5 represents the growing trend of yearly oil consumption in Malaysia from year 1980 to 2004. The trend shows that the energy consumption in Malaysia exceeds the value of 1×10^5 BTU in year 2004. This situation necessitates the need of increasing oil production from the existing petroleum reserves in Malaysia to meet the energy requirements.

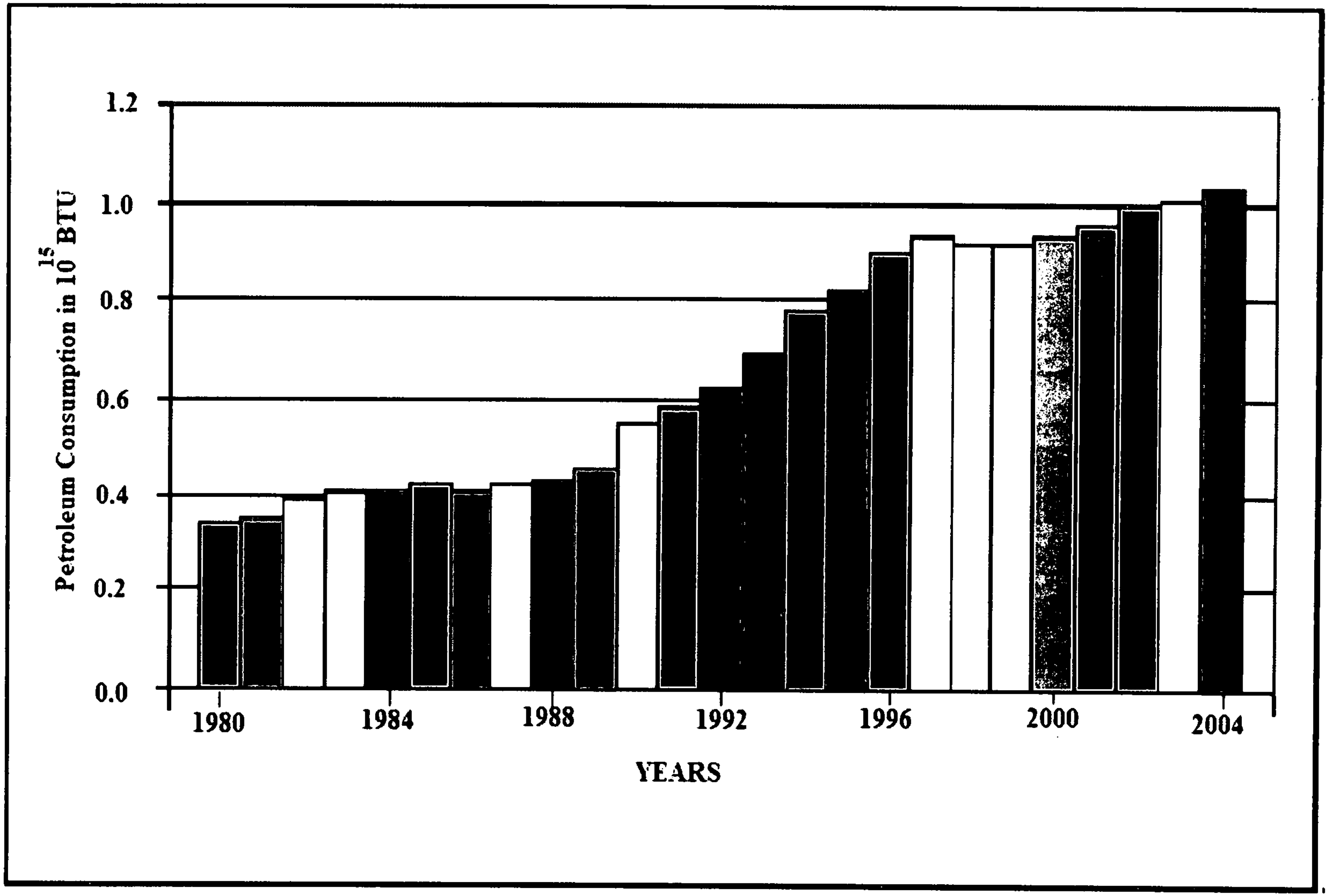


Figure 1.5 Malaysian Historical Trend for Oil Consumption (Energy Information Administration, 2006)

Malaysian forecast of oil production is expected to decline from 2007, and projections of domestic consumption indicate that the country could become a net importer of oil by the end of this decade (Chadwick *et al.*, 2003). Proven oil reserves are set to decline gradually through lack of drilling success. Most of the current producing fields in Malaysia are at maturing stage with declining pressure and oil production rates and increasing water-cut and GOR trend. A number of fields are already under secondary recovery, i.e. pressure maintenance either by gas or water injection, to supplement the production (Hamdan *et al.*, 2005). Nevertheless exploration activities are still active with a number of recent discoveries. These discoveries have added to the national's reserves, while existing reservoirs contain large volumes of remaining oil that is not being effectively recovered. These oil reserves constitute a huge target for the development and application of modern, cost-effective technologies for producing oil. Therefore, special attention should be given to Enhanced Oil Recovery (EOR) to recover the remaining oil. The term EOR is usually applied to processes that augment the recovery of oil from a reservoir by injection of materials not normally present in that reservoir. Steam and hot waterflooding, insitu combustion, micellar and surfactant floods, miscible and immiscible solvent injection methods, and mobility control polymers all fall under the category of EOR. Several reservoir characteristics usually determine the type of EOR that will be successful in a given oil field.

Till year 2005, there has been no full-field application of EOR in Malaysia (Hamdan *et al.*, 2005). Nadeson (2004) suggested that to prolong the declining production and diminishing reserves of the country, timely implementation of EOR applications is required. This scenario necessitates the need to implement successful EOR projects to extend the production, beyond the primary and secondary techniques. A successful practice of EOR in Malaysia requires a number of long- term commitment in human and capital resources, R&D and technology deployment. If the EOR projects are to be carried out, they need to be planned, studied and implemented in the near future rather than much later in the field life, where higher cost of maintenance and development is envisaged.

1.3 Problem Statement

Screening study by PETRONAS in year 2000 identified that almost a billion barrels of additional reserves can be achieved through EOR processes (Hamdan *et al.*, 2005 and Turta *et al.*, 2000). Despite the higher recovery potential through EOR processes and the availability of proven technologies, the application of EOR process carries challenges and difficulties on both technical and commercial level (Hamdan *et al.*, 2005). Some of the problems associated with conventional EOR processes are as follows:

1.3.1 Injecting Fluids Cost

Most often, expensive injecting fluids are used in EOR which might be not available in sufficiently large quantity during operation. Majority of the surfactants used in chemical EOR process are very expensive. When CO_2 is used as an injecting fluid, the cost of facilities development such as corrosion resistant pipelines and CO_2 storage tank disturbs the economics of the EOR project.

1.3.2 Injecting Fluids Availability

Most often the injecting fluids are not available on site. If the required volume of the injecting fluid is large, then the availability of injecting fluid is an important consideration.

1.3.3 Changes in Chemical Composition of Injecting Fluids

Most of the injecting surfactants and polymers used in chemical EOR are non-stable at elevated temperatures which may change their chemical composition. Chemical losses or changes in composition of injecting fluids during chemical EOR processes suggest that the injected fluid slug size must be large enough to sustain the losses or changes.

1.3.4 Toxic or Corrosive Injecting Fluids

Use of toxic injectants in micellar-polymer and caustic floods EOR processes might cause health and safety hazards for workers who are exposed to these irritating, toxic and caustic chemicals.

1.3.5 Offshore Challenges

Offshore environment holds additional challenges and difficulties both on technical and commercial level (Hamdan *et al.*, 2005). In offshore environment, chemical injection could be dangerous for marine life. Thus, it requires adopting best-management practices to prevent runoff, drainage, or spills of certain chemicals. Surface spills of these toxic injecting chemicals, leakage from storage tanks and leakage from pipelines will therefore be sources of contamination (Kaplan, 1984). Age of platform in offshore environment is also a concern in constructing new facilities which are required to implement EOR process.

In the present situation, the need of unconventional EOR method is required to address to recover the remaining Malaysian oil reserves. In this context, Light oil air injection (LOAI) may be regarded as a new alternate EOR method. Air is the most convenient to use as an injecting fluid since it is abundantly available. Therefore air injection could be an economical alternative for pressure maintenance. Air injection in high temperature, high pressure and deep reservoirs could lead to unique economic and technical opportunities for improved oil recovery in many candidate reservoirs. This method can offer unique economic and technical opportunities such as (Fassihi *et al*, 1997, Sakthikumar *et al.*, 1995, Clara *et al.*, 1999):

- Excellent displacement efficiency and mobilization of extra combustion oil.
- Rapid reservoir pressurization
- Oil swelling
- Injection gas substitution
- Operation above critical point of water, with possible superextraction benefits.
- Freely available in large amount hence economical.

- Flue gas striping of the reservoir oil.
- High oil recovery via gravity-stabilized immiscible gas displacement.

Nevertheless, Light Oil Air Injection (LOAI) also carries inherent disadvantages over other enhanced oil recovery methods such as chemical reactions occurring within the reservoir, and/or chemical reactions taking place in the tubing and casing of the injection or producing well. Corrosion could be one of the problems as flue gas with high sulfur content creates corrosion related problems in the production well (Gillham *et al.*, 1998). Air compressor reliability is also a factor to take into account; if a compressor trips or shut down occurs by any means, no air will be injected and the combustion front will eventually die.

1.4 Research Objectives

The present research project attempts to assess the feasibility of light oil air injection to improve oil recovery for Malaysian oil fields. The basic objectives of this research are as follows:

- To develop screening criteria for LOAI based on worldwide successful projects.
- To identify candidate reservoir for LOAI based on the developed criteria.
- To apply the reservoir simulation tool over the selected reservoir.
- To predict the potential or success level of LOAI in Malaysian oil reservoirs.

The technique of LOAI has been implemented successfully in some parts of the world. Therefore, the purpose of this research study is to determine technically, the potential or success level of LOAI in Malaysia utilizing optimal recourses. In the past, early potential of LOAI was determined by performing expensive experimental studies followed by the complex numerical simulations (Ren *et al.*, 2002). Significance of this research work is to find a method of testing the early success level of the LOAI project by simple numerical simulation studies with relevant assumptions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

After primary and secondary recovery, more than 50% of original oil in place (OOIP) still remains in the reservoir (Greaves *et al.*, 1998, Cogeneration Technologies, 1999). This significant amount necessitates the need for finding ways of increasing the recovery. Globally, the average oil recovery factor is in the order of 30% (Schulte *et al.*, 2005). Nevertheless, increment in recovery factor could be achieved through more cost effective and better execution of EOR processes. Due to limitation and challenges described in Section 1.3 of Chapter 1, some alternative and effective EOR processes need to be investigated to recover the remaining oil from Malaysian reservoirs.

2.2 Selection of Appropriate EOR Method for Malaysian Reservoirs

Any EOR method is considered significant, if it can increase the expected oil production economically from existing oil fields. In Malaysia, need for efficient and promising EOR techniques exist. Air injection could be one of the EOR techniques which utilizes the freely available air together with the potential economic incentives.

The technique of air injection is extending its realm from heavy oils to lighter oils. Air injection in light oil reservoirs does not contribute only to viscosity reduction as in the case of heavy oils; it also provides additional driving mechanisms for oil production (Turta *et al.*, 1998 and Sakthikumar *et al.*, 1995). Air injection in light oil is known as Light Oil Air Injection (LOAI) which could serve multiple functions. These include reservoir pressurization, mobilization of reacted oil, nitrogen stripping of remaining oil and steam or thermal effects (Ren *et al.*, 2002). In reservoirs of high temperature, high pressure and high depth, LOAI could lead to unique economic and technical opportunities for improved oil recovery in many candidate reservoirs, beyond the traditional combustion applications (Sakthikumar *et al.*, 1995). LOAI had also been shown technically feasible in light oil reservoir following waterflooding (Stokka *et al.*, 2005).

LOAI offers a unique alternative as compared with other conventional EOR processes. Air is a low cost injectant which is freely available. It does not suffer any constraint on supply, as in the case of hydrocarbon, nitrogen, or carbon dioxide gases. In the past, LOAI has been applied successfully to produce significant oil recovery in many offshore light oil fields like Maureen and West Hackberry. Additional oil recovery of 26.3 MMstb and 24MMstb was obtained through air injection in these reservoirs respectively (Stokka *et al.*, 2005, Fraim *et al.*, 1997). In addition, Ren (2002) reported that till year 2002, majority of the air injection projects for light oil reservoirs had been reported as successful and a number of projects had been operated for more than 12 years continuously.

2.3 Light Oil Air Injection (LOAI)

LOAI is an EOR process in which compressed air is injected into low oil density and high pressure reservoir. As a result, oxygen in the injected air reacts with a fraction of the reservoir oil at an elevated temperature of approximately 100°C to produce carbon dioxide (Moore *et al.*, 2004). The resulting flue gas mixture, which is primarily nitrogen and carbon dioxide, mobilize the oil to the downstream of the reaction region, sweeping it to production wells. The gas-oil mixture downstream of the reaction region might be in one of the three forms (Moore *et al.*, 2002):

1) Immiscible mixture. Miscibility of combustion gases will not be achieved due to very high miscibility pressure of reservoir.
2) Partly miscible mixture. Partial miscibility of CO_2 might be achieved.
3) Completely miscible mixture. All combustion gases will be completely miscible with the oil at reservoir conditions

General process of LOAI is illustrated in Figure 2.1. The process is initiated by injecting the air, which will ignite the oil. As shown in Figure 2.1, air is injected from the left side. Combustion will then take place that consumes 5-10% of the in-place oil due to the high temperature and pressure conditions in the reservoir (Stokka *et al.*, 2005, Moore *et al.*, 2004). Behind the combustion zone there is a burned zone, and ahead of it is an evaporation zone which contains steam, nitrogen, hydrocarbon gases and combustion gases. Ahead of the evaporation zone is the condensation zone and then followed by the water bank, oil bank and the unswept zone (Stokka *et al.*, 2005).

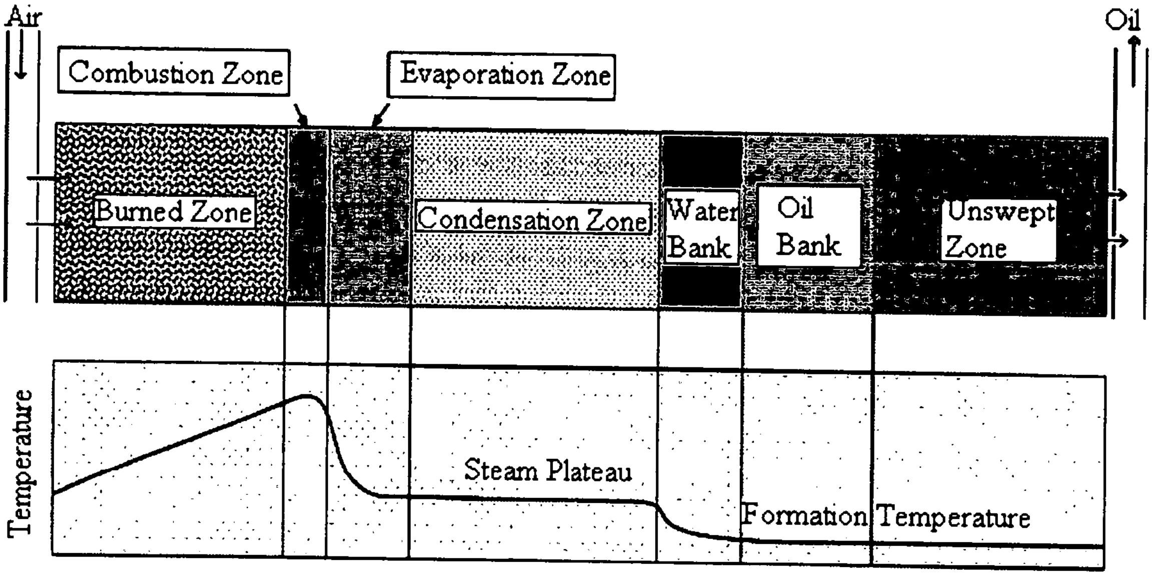


Figure 2.1 Air Injection Process Schematic Diagram with Temperature Profile (Stokka *et al.*, 2005).

The injected air warms into the reservoir due to the spontaneous ignition. Fraim (1997) reported that the oxygen of the injected air is consumed in a confined zone known as oxidation or combustion zone. The size of this zone depended on the air injection rate, the characteristics of the oil, and the reservoir formation (Clara *et al.*, 1999). When the hot air enters the oxidation zone, the oxygen of the injected air reacts with in-place oil to generate heat and carbon dioxide. The generated heat after combustion will help to produce superheated steam. Produced superheated steam reacts with tars and waxes to convert them into coke and light hydrocarbons. The gravity of oil will slightly increase (2^{o} to 4^{o} API gravity) due to the removal of tars and waxes by superheated steam (Fraim *et al.*, 1997). The carbon dioxide produced after combustion, helps to vaporize the heavy oil components. The resulting emulsion steam was then mobilized to the producing well by nitrogen, present in the injected air.

2.3.1 Low Temperature Oxidation and High Temperature Oxidation

When air is injected into an oil reservoir, combustion occurs in small percentage of reservoir oil which consumes oxygen in the injected air. Crude oil combustion is made-up of two reactions, the low temperature oxidation (LTO) and high temperature oxidation (HTO). In heavy oil reservoirs, the LTO process extends from the ignition temperature to approximately 350°C. The LTO is then followed by HTO reaction that extends up to 450°C (Moore *et al.*, 2002). However, in light oil reservoirs, LTO extends from the ignition temperature to approximately 150°C. The LTO is then followed by HTO reaction that extends up to 300°C (Moore *et al.*, 2004).

2.3.2 Light Oil Air Injection Vs Heavy Oil In-situ Combustion

The air injection technique applied in light oil reservoirs is different from the one applied in heavy oil reservoirs. In heavy oil this technique is known as in-situ combustion (ISC) process. The principle of ISC is to burn part of the oil and to mobilize the remaining oil. Heat production, steam generation and subsequent viscosity reduction are the primary oil displacement mechanisms in the ISC (Fassihi *et al.*, 1996). Thermal effect plays an important part in ISC for heavy oils. ISC in heavy oil reservoirs occurs in the vigorous HTO reaction regime with a temperature range of 350-450°C, which needs to be maintained by using sufficiently high air flux. Combustion is started by an artificial ignition device or by spontaneous ignition, which significantly raises the temperature of the zone around the injection well. If artificial means of ignition is used, it would be time consuming and expensive procedure (Ren *et al.*, 2002).

Unlike heavy oil ISC, LOAI can be viewed as a conventional gas injection process. For deep light-oil reservoirs, oxygen might be consumed in the LTO range of temperature. LTO in light oil reservoir can be sufficient at reservoir temperature of 80-130°C to consume all of the oxygen in the injecting air, without the need to generate higher temperatures. Gillham (1997) also reported that LTO temperature regime is sufficient for light and medium gravity crude to consume all oxygen in air after combustion takes place. The air flux used for LTO of light oils is very low, compared with ISC. Therefore the LTO reaction rate is relatively low (Ren *et al.*, 2002). Turta (2001) reported that if the reservoir temperature is higher than 70-80°C, ignition could take place within hours. If oxygen is completely consumed in LTO, then it is considered to be a more safe process because less heat will be generated. Thus, if the combustion occurred in LTO range of temperature, the heat generated after combustion is of secondary value and displacement of oil through flue gas is considered as the primary mechanism of oil recovery (Fassihi *et al.*, 1996 and Glandt *et al.*, 1998). Turta (1998) reported that an increase in volumetric sweep efficiency seemed to be the main mechanism of air injection for light oil reservoirs rather than viscosity reduction.

2.4 Effect of Different Factors in LOAI Process

To find early potentials of LOAI, different factors were studied in the present research study which influences the LOAI process. Thus, based on the findings of literature review, effects of the following factors on LOAI were separately studied:

1. Thermal effects.
2. Miscibility effects.
3. Behavior of nitrogen and air.

2.4.1 Thermal Effects in LOAI

Glandt (1998) reported that air injection in light oil reservoir is considered as a displacement process which does not require thermal effects for oil mobilization. Stokka(2005) suggested that in the Ekofisk case the contribution to oil recovery by oxidation itself i.e. recovery through heat and steam generation was insignificant. Most of the reservoir was outside the oxidation region and the recovery mechanisms was identical as that of flue gas injection i.e. gravity segregation and stripping of light components (C1-C4) by nitrogen.

Ren (2002) performed a simulation study for sensitivity analysis of air injection rates in the reservoir. Table 2.1 shows the results of that study which demonstrate the velocity and distance traveled by the thermal and gas front after half year of air injection for three different air injection rates. Table 2.1 shows that the gas displacement front advances at a much higher rate than the thermal front. The escalating separation between the two fronts indicates that recovery of oil is due to the gas displacement and not because of the effect of thermal front. It further shows that effect of gas injection was more significant than that of thermal effects. Since the velocity of the thermal front was much less than that of the leading gas nitrogen front therefore oxygen breakthrough would be impossible, even after injecting several pore volumes (PVs) of air injection.

Table 2.1 Influence of Injected Air Rate on Reaction Zone (Ren *et al.*, 2002)

Air Injection Rate (PV/year)	Thermal Front, Distance From Injection Well at 184 Days, m	Gas Front, Distance From Injection Well at 184 Days, m	Thermal Front Velocity (m/day)	Gas Front Velocity (m/day)
0.4	21	74	0.15	0.63
0.8	39	145	0.22	1.24
1.6	62	245	0.47	2.24

Based on the available literature and reported LOAI experience, thermal effects might be considered as negligible for the present preliminary studies because the combustion is assumed to occur in the LTO range of reaction.

2.4.2 Miscibility Effects

Miscibility of the gaseous mixture i.e. CO_2 and N_2 after combustion in LOAI is required to determine that whether these gases are miscible with oil or not. Miscibility is defined as that physical condition between two or more fluids that permits them to mix in all proportions without the existence of an interface (Holm, 1986). It means that when miscibility is achieved, the interface between the fluid phases will be absent, and the value of interfacial tension between the two phases will be zero. Therefore, two fluids are miscible when they can be mixed together in all proportions and all mixtures remain in a single phase (Fred *et al.*, 1983).

Miscible flooding involves the injection of a solvent that is miscible with the in-place oil and capable of mobilizing the residual oil. Miscibility of the injected gas with oil can be achieved either by first contact or by multiple contacts of gas with oil. Usually, for all gases the first contact miscibility requires higher levels of pressure, as compared with the multiple contact miscibility (Turta *et al.*, 1998). The multiple contact miscibility is also called dynamic miscibility and it is realized after considerable mass transfer between oil and gas, during immiscible displacement of oil by gas. N_2, which is present in higher amount in the combustion mixture, can be either first contact miscible or multiple contact miscible with the oil. N_2 becomes miscible by vaporizing light end hydrocarbons, mainly some of the C_2-C_5 components from the oil at high pressure (Turta *et al.*, 1998).

2.4.2.1 Minimum Miscibility Pressure

For a fixed gas composition, the lowest pressure at which dynamic miscibility or multi component miscibility can be achieved is called Minimum Miscibility Pressure (MMP) (Turta *et al.*, 1998). If the gas is injected in the reservoir, below its MMP then it results in immiscible displacement of oil by that injected gas. The MMP is determined in the laboratory by carrying out a series of tests at different pressures. The MMP of CO_2 can be determined by slim tube experiments and rising bubble method (Turta *et al.*, 2001).

2.4.2.2 Firoozabadi *et al.* Correlation

The percentage of N_2 in the combustion mixture produced after combustion in LOAI process varies from 85% to 90% (Myron, *et al.*, 2000, Turta *et al.*,, 1998). An approximate value of nitrogen gas MMP can be determined using a simple correlation proposed by Firoozabadi (1986) which is expressed in equation 2.1. Three parameters account the effect of multiple-contact miscibility of a reservoir fluid under N_2 flooding: the concentration of intermediates, the volatility, and the temperature. The correlating parameter includes the ratio of the intermediates (mole percent) divided by molecular weight of the C_7^+ fraction. Intermediates contents of a reservoir fluid are usually attributed to the presence of C_2 through C_6, CO_2, and H_2S. Firoozabadi (1986) observed that exclusion of C_6 from intermediates could improve the correlation of the MMP. Intermediates in this study are defined by C_2 through C_5 and CO_2 components. The heptane plus molecular weight provides an indication of the oil volatility. The equation is as follows:

$$P_m = 9433 - 188\times10^3\left(\frac{C_{C2}-C_{C5}}{M_{C7_+}T^{0.25}}\right) + 1430\times10^3\left(\frac{C_{C2}-C_{C5}}{M_{C7_+}T^{0.25}}\right)^2 \qquad (2.1)$$

Where,

P_m = MMP in psia

T= Temperature in °F

$C_{C2} - C_{C5}$ = Concentration of intermediate in mol %

MC_7^+ = Molecular weight of heptane plus

2.4.2.3 MMP of the Resulting Mixture after Combustion

In both HTO and LTO air injection processes, the produced flue gas comprises of 10% to 14% CO_2, with the rest being mainly N_2 (Ren *et al.*, 2002). At approximately 120°C reservoir temperature, the MMP for pure CO_2 is approximately 200 bar (Yellig *et al.*, 1980). However, this value of MMP will not be very significant for a flue gas containing only 10% to 14% CO_2 and the rest is N_2 (Turta *et al.*, 1998). Turta (1998) reported that when the N_2 occurred as an impurity in the CO_2 stream, small percentages of N_2 could substantially increase the MMP of the mixture. Therefore, MMP of the combustion mixture in oil is mainly controlled by the N_2 content in it. As the temperature and pressure increase, solubility of N_2 in oil increases. Nevertheless, Turta (1998, 2001) suggested that unlike MMP for CO_2, MMP for N_2 would not be influenced considerably by the temperature. MMP of N_2 at a reservoir temperature of 100°C is predicted to be over 400 bar which is considerably high (Ren *et al.*, 2002). Selim (1986) found that the MMP of the mixture of N_2 and CO_2, containing 14% CO_2, was equal to the MMP for pure N_2. However, a significant decrease of MMP due to the presence of CO_2 is believed to exist only when the percentage of CO_2 is relatively high. Turta (2001) illustrated qualitatively, the effect on miscibility due to the presence of N_2 in a gaseous mixture of N_2 and CO_2 as shown in Figure 2.2. It shows that if the percentage of CO_2 in the gaseous mixture (N_2 and CO_2) is less than 30%, then its MMP will be equal to the MMP of N_2.

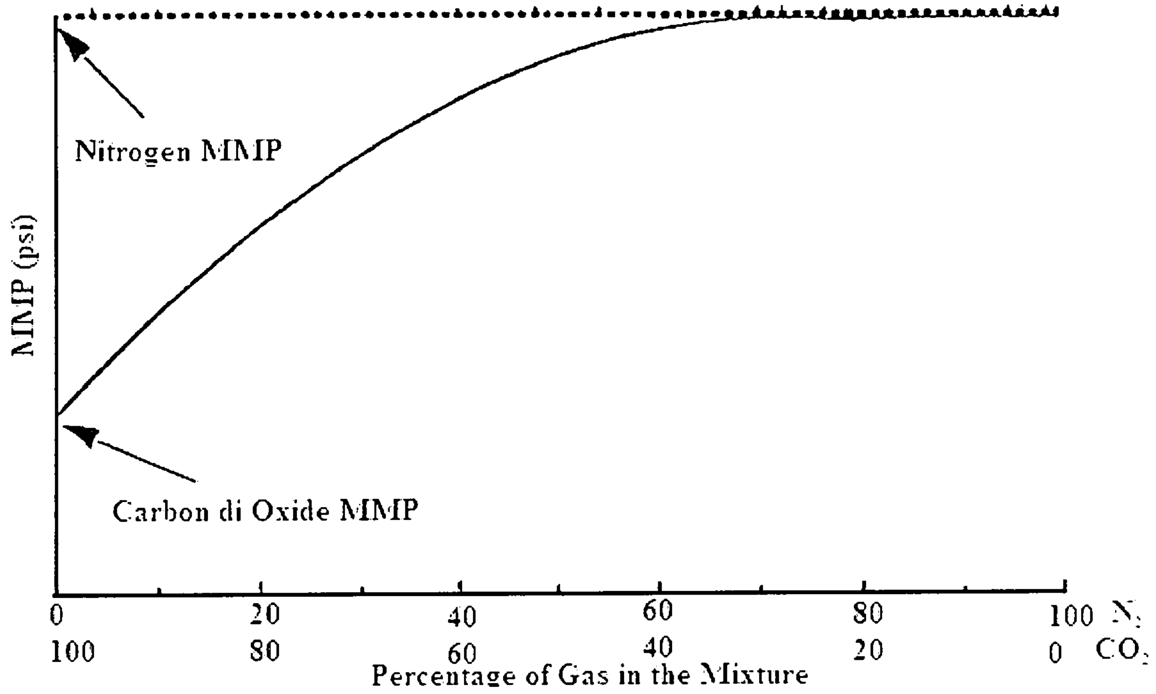


Figure 2.2 Illustration of MMP Variation for a N_2- CO_2 Mixture (Turta *et al.*, 2001)

If the reservoir formation pressure is less than the MMP and miscible flooding is required, the injection pressure must be increased more than the MMP of the reservoir so that miscible oil displacement can occur. However, increasing the pressure of the injected gas into the reservoir increases the risks of undesirable formation fracturing and creates additional hazards for personnel (Mihcakan *et al.*, 1996). Alternate way of achieving miscibility is to enrich oxygen in the injected air. However, it must be make sure that oxygen should be completely consumed during combustion. If oxygen is not consumed completely, the un-burnt oxygen might create safety hazards on the gas break through at the oil producing wells (Moore, 2004). Thus, oxygen enrichment in the injected air is not considered a good method to achieve miscibility as it holds additional safety risks.

2.4.2.4 Miscibility Effects in Malaysian Reservoirs

As shown in Figure 2.2, it is very difficult to get the miscibility of the mixture after combustion if it contains N_2 gas in high percentage. In majority of Malaysian reservoirs, the present reservoir pressure is very low (1200-1600 psi) as compared with the MMP (3500-4500 psi) of the gaseous mixture of N_2 and CO_2 (Zahidah *et al.*, 2001). Thus, miscibility in Malaysian reservoirs is very difficult to achieve. Several studies reported that in those cases of LOAI when it is not possible to pressurize the reservoirs to the acceptable minimum miscibility pressures, immiscible air flooding could be considered (Sakthikumar *et al.*, 1995, Ren *et al.*, 2002, Turta *et al.*, 1998, Turta *et al.*, 2001). The application of air injection as an immiscible gas flood represents a gas injection process that might have small additional beneficial effects associated with the propagation of the heat wave. Immiscible air flooding process might increase the ultimate oil recovery by at least as much as the immiscible gas injection using nitrogen, flue gas or hydrocarbon gas injection (Turta *et al.*, 1998).

2.4.3 Comparison between Air and Nitrogen

Air is a mixture of gases, in which nitrogen varies from 78% to 80 % of its composition. The general distribution of gases in air is shown in the Table 2.2. Table 2.2 shows that nitrogen has the major contribution of 78% among all the gases in air. Because of this, the properties of air and nitrogen are very similar to each other. Table 2.3 compares physical properties of air and nitrogen at atmospheric conditions which also shows that the physical properties of nitrogen and air are almost similar due to dominant presence of nitrogen in air.

Table 2.2 Constituent Analysis of Air (Wikipedia, 2006)

Component	Volume
Nitrogen(N_2)	78.08%
Oxygen(O_2)	20.95%
Argon(Ar)	0.93%
Carbon dioxide (CO_2)	0.03%
Neon (Ne)	18.2 PPM
Helium (He)	5.2 PPM
Krypton (Kr)	1.1 PPM
Sulfur dioxide (SO_2)	1 PPM
Methane (CH_4)	2 PPM
Hydrogen (H_2)	0.5 PPM
Nitrous Oxide (N_2O)	0.5 PPM
Xenon (Xe)	0.09 PPM
Ozone (O_3)	0.07 PPM
Nitrogen dioxide (NO_2)	0.02 PPM
Iodine (I_2)	0.01 PPM
Carbon monoxide (CO_2)	Trace
Ammonia (NH_3)	Trace

Table 2.3 Comparison of Physical Properties between Air and Nitrogen (Fluidprops1.1 software of Bhavya-Tech)

Property	Air	Nitrogen
Molecular Weight	28.9625	28.0134
Boiling Point (°F)	-317.8	-320
Freezing Point °F	-353.1	-346
Critical Pressure psi	534	478
Critical Temperature °F	-221.3	-232.5
Critical Volume ft^3/lbm	0.0517	0.051
Acentric Factor	-0.00187	0.0372
Specific Gravity	1	0.9672

Table 2.4 shows the effect of varying pressure on the compressibility factor of air and nitrogen at a fixed temperature of 150 °C (approximate temperature after combustion in LTO range). It also shows that the difference of compressibility factors between air and nitrogen is very small even at higher pressure of 2000 psi.

Table 2.4 Comparison of Compressibility Factor at 150 °C between Air and Nitrogen (Fluidprops1.1 software of Bhavya-Tech)

Pressure psi	Compressibility Factor (Air)	Compressibility Factor (Nitrogen)	Difference
0	1.000054	1.000194	0.00014
200	1.001016	1.003058	0.002042
400	1.002406	1.006315	0.003909
600	1.004203	1.009945	0.005742
800	1.006391	1.013926	0.007535
1000	1.008949	1.018237	0.009288
1200	1.011862	1.022858	0.010996
1400	1.01511	1.027772	0.012662
1600	1.018677	1.03296	0.014283
1800	1.022546	1.038405	0.015859
2000	1.026701	1.044091	0.01739

2.4.3.1 LTO Air Injection Vs Nitrogen Injection

Sakthikumar (1995) performed a series of tests on crushed sandstone core, saturated with stock tank oil. These tests were performed to acquire a better understanding of the mechanism involved in an air injection process. One of the tests was consisted of two nitrogen injection cases and one LTO air injection case. The air injection yielded 46.4 % recovery whereas the N_2 injection cases yielded 43.2% and 42.3 % OOIP respectively as shown in Figure 2.3. A difference of about 3% to 4% OOIP was therefore observed when comparing the air injection and nitrogen injection processes. Since the difference of 3% to 4% OOIP oil recovery obtained after air and nitrogen injection cases is very small, it indicates that air injection process is quite similar to that of N_2 injection process. Additional recovery of 3% to 4% OOIP in air injection case was due to the additional thermal effects which cannot be observed in nitrogen injection. However, thermal effect produces less impact over the oil production as indicated by the experimental study of Sakthikumar (1995).

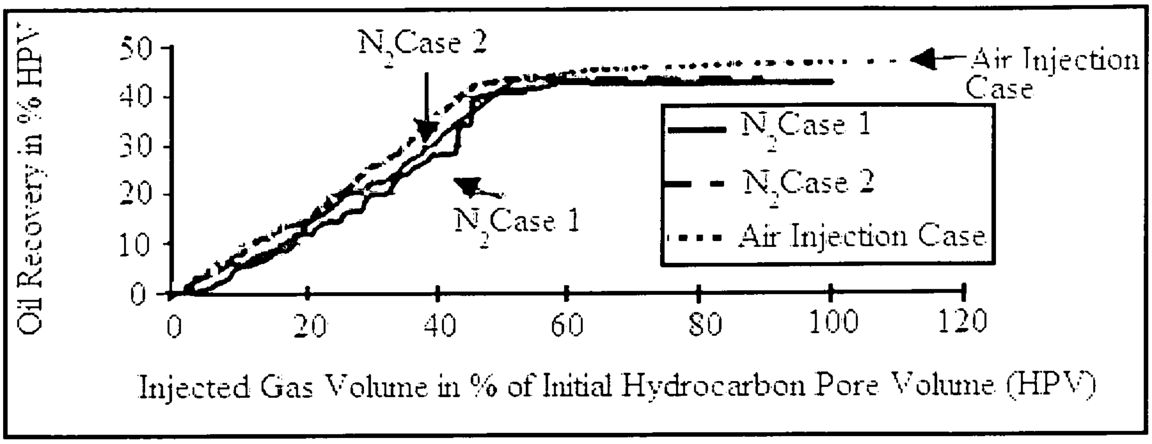


Figure 2.3 Experimental Result of Nitrogen Vs Air Injection (Sakthikumar *et al.*, 1995)

2.5 Selection of Simulation Type to Find Potentials of LOAI

Based on the literature review in Section 2.4.1 and Section 2.4.2, the present research study presumed that the oil swelling, oil miscibility, viscosity reduction by CO_2 dissolution and thermal effects were not taken into consideration. Thus, using thermal and compositional simulation for the present research work was not recommended because a non thermal and non miscible system was under consideration. Moreover, if nitrogen was assumed to be injected in the reservoir in place of air as mentioned in Section 2.4.3, the black oil simulation could be used to find the early potentials of LOAI method (Sakthikumar *et al.*, 1995).

The use of black oil simulation in the research work eliminates the need of laboratory experiments to find kinetic parameters such as activation energies and ignition temperatures which are required in thermal simulations (Stokka *et al*, 2005). Furthermore, thermal simulations require a complete reaction scheme of combustion reactions which are complex and involved hundred of intermediate products (Sakthikumar *et al.*, 1995). Combustion tube experiments might also be required in thermal simulations to study propagation of the combustion front through porous media. (Stokka *et al.*, 2005). Ren (2002) reported that in order to validate the thermal type of numerical simulations, oxidation tube experiments are required which physically simulates the dynamics of the air injection process. These types of experiments provide the information on the oxygen consumption, CO_2 formation, and oil/water production rates. Ren (2002) also reported that the oxidation tube experiments were used for history-matching to verify the reaction kinetics, PVT, and the relative permeability models. Stokka (2005) reported that in thermal simulation study for Ekofisk filed, parameters to be used in computer simulation of the air injection process were measured through experiments. Oxidation kinetics of Ekofisk crude oil in Ekofisk core was investigated by conducting different experiments. Sakthikumar (1995) reported that in the simulation study for air injection, nitrogen was simulated instead of air. Calculated performances were therefore considered as conservative because the thermal effects were not taken into consideration. Therefore, use of black oil simulation simplifies the process of finding potential of an air injection method and the complex mechanism of combustion will not be considered.

2.6 Case Studies of LOAI Projects

LOAI was applied successfully in many oil reservoirs worldwide which includes both carbonate and sandstone reservoirs (Fassihi *et al.*, 1997). The present research study focuses on Malaysian oil reservoirs, which are mainly sandstone reservoirs. Therefore LOAI case studies of three fields having sandstone reservoirs were reviewed i.e. Maureen Field, Brrancas Field and West Hackberry. The purpose of these case studies is to develop screening criteria which can be used to identify suitable Malaysian reservoir for the present research project.

2.6.1 Maureen Field

The Maureen field is a light oil reservoir in the UK sector of the North Sea (Fraim, 1997). It consists of a simple anticline over a salt dome. The primary reservoir layers were massive sandstones resulting from tutrbidite flows. The reservoir had very good lateral and vertical conductivity except where calcite cementation was extensive. A large aquifer existed to the west of the oil reservoir that provided extensive pressure support. The waterflood utilized peripheral water supplement the natural water drive. A very favorable sweep efficiency was attained, with the ultimate volumetric sweep efficiency reportedly in the range of 90% (Fraim *et al.*, 1997) .After 53% of OOIP was recovered from waterflooding, the field was considered to be at the end of its life but if abandonment was performed in that state, this field would leave 175 MMstb in place as unrecoverable oil. Since the residual oil saturation to water is in the range of 23% and air injection is one economic way to reduce the remaining oil saturation left after waterflooding. Fraim (1997) reported that after simulation studies, the expected incremental oil recovery due to air injection could be in range of 17.8 to 26.3 MMstb (approx 7% OOIP). Reservoir and fluid properties are shown in Table 2.5.

Table2.5 Maureen Field Reservoir and Fluid Properties (Fraim *et al.*, 1997)

Parameters	Value
Depth m	2530
Permeability md	100-500
Porosity %	20-25
Dip degree	9
Reservoir temperature ^oC	117
Initial pressure psia	3792
Average reservoir pressure psi	3000
Bubble point pressure psi	1786
Initial oil saturation (S_{oi})	0.56
Viscosity cp	0.7
Oil specific gravity ^{o}API	36
OOIP MMstb	398
Formation volume factor for oil (B_{oi}) rb/stb	1.26
Ultimate oil production under waterflooding MMstb	222 (55.7%OOIP)
Incremental recovery through air injection MMstb	26.3 (7%OOIP)

Table 2.5 shows that the reservoir of Maureen field was relatively deep, hot and high pressure. Values of permeability and porosity were also relatively high, which encourages the recovery from air injection process. The oil in porous medium was relatively light as shown by the gravity value. Table 2.5 also shows that air injection could produce additional 7% OOIP recovery after the primary and secondary recovery of 55.7% OOIP. Thus, cumulative production of 62.7% OOIP from Maureen reservoir was expected to obtain which is quite substantial amount.

2.6.2 Brrancas Field

Brrancas field is located in Argentina in the north-east portion of the Cuyana Basin, Mendoza (Pascual *et al.*, 2005). The reservoir dips from north to south with an average of 6.5°. The origin of the reservoir is fluvial, consistent of quartz sandstone of medium and coarse grain and a small relative proportion of argillaceous matrix. The mean porosity and shale volumes are 15% and 30% respectively. The hydrocarbon bearing formation can be divided into four vertical sequences with good lateral continuity. The upper layer called Red has the greatest permeability which ranges between 24 mD and 1100 mD, with a mean of 100mD. The rest of the layers are called Blue, Violet and Green, with a mean permeability of 14, 42 and 60 mD (Pascual *et al.*, 2005).

A zone was selected for the pilot test of LOAI in the upper most part of the anticline, of 1 km long and 1.3 km wide. It contains 6 oil producer wells surrounded by several water injectors. Laboratory results by Pascual (2005) suggested dry air injection could produce additional oil recovery of 12% OOIP. Reservoir and fluid properties are shown in Table 2.6. Table 2.6 shows that the reservoir of Brrancas field was relatively deep. However, temperature and pressure values were not as higher as in case of Maureen field. Values of permeability and porosity were high which encourages the recovery from air injection process. In comparison with Maureen field, the oil in porous medium was not much light as shown by the gravity value in Table 2.6. Table 2.6 also shows that air injection could produce additional 12% OOIP recovery after the primary and secondary oil recovery.

Table 2.6 Brrancas Field Reservoir and Fluid Properties (Pascual *et al.*, 2005)

Parameters	Value
Formation depth m	2300
Permeability, md	60
Porosity %	15
Dip degree	6.5
Reservoir Temperature °C	85
Pressure psi	2275.74
Bubble Point Pressure psi	526.264
Viscosity cp	4.6
Oil Specific Gravity °API	31
Water Oil Contact depth m	1750
Gas Oil Ratio m^3/m^3	20
Formation Volume Factor for Oil (Bo) rb/stb	1.17
Water Saturation %	58
Net Pay m	10
Incremental recovery through Air Injection %	12

2.6.3 West Hackberry

West Hackberry is located in Cameron Parish, in southwestern Louisiana (Fassihi *et al.*, 1996). The West Hackberry Tertiary Project was a field test of the concept that air injection could generate tertiary oil recovery through the Double Displacement Process (DDP). The DDP is the gas displacement of a water invaded oil column for the purpose of recovering tertiary oil through gravity drainage. This project shows the application of LOAI as a gas displacement process in which thermal effects are rarely considered. Complete oxygen utilization was made certain to avoid production of emulsions, corrosion and explosions in the production well (Fossil Energy, 2006). The concept was field tested in low pressure reservoirs of pressure range from 300 to 700 psi on the north flank of the field and high pressure reservoirs of pressure range from 2500 to 3300 psi on the west flank of the field. Air injection commenced in the low pressure reservoirs on the North Flank of the field in 1996. The low pressure reservoirs are characterized by low pressure gas caps, slow water encroachment and steep bed dips. This case study shows that air injection could be implemented in low pressure reservoirs as a gas displacement process. Gillham (1998) reported that for the past 16 months, air injection had generated

70,000 barrels of incremental oil production in two low pressure North Flank reservoirs. Reservoir and fluid properties of high pressure reservoir are shown in Table 2.7.

Table 2.7 West Hackberry Reservoir and Fluid Properties (Fassihi *et al.*, 1996)

Parameters	Value
Depth m	2287-2743 (avg 2622)
Average Permeability md	1000
Average Porosity %	26
Reservoir Temperature °C	94.45
Initial Reservoir Pressure, psi	4227
Bubble Point Pressure, psi	4227
Initial Oil Saturation,(Soi)	0.79
Oil Viscosity at Bubble Point Pressure, cp	0.72
Oil specific gravity, °API	33
Solution Gas Oil Ratio, scf/stb	680
Formation volume factor for oil (Boi) rb/stb	1.35
Average Net Pay, m	21
OOIP, MMstb	24

The three LOAI case studies indicate that a candidate light oil reservoir should have high depth, high pay thickness and high temperature. Moreover, high permeability and porosity values are good for the process. These parameters help to develop good screening criteria.

2.7 Screening Criteria Development for LOAI

Selection and implementation of EOR methods requires several steps. Initially, technical screening criteria should be developed to select a number of reservoirs for further study. Screening criteria is based on a set of reservoir parameters such as depth, temperature, pressures, permeability, oil saturation, heterogeneity of reservoir and viscosity. The values of these parameters were generally obtained from either experience of successes and failures or from an understanding of the characteristics and physics of a particular EOR process. It provides the initial determination of possible applicability of the EOR method on the selected reservoir. Exact matching of the reservoir is barely possible in actual cases.

In the development of screening criteria for LOAI, reservoir engineering aspects of selection and implementation of LOAI method in Malaysian sandstone reservoirs were discussed. The developed criteria considers major important reservoir parameters which may help the process of LOAI. The parameters which were considered during development of screening criteria are described below.

2.7.1 Pressure

Usually LOAI could produce higher oil recovery from high pressure light oil reservoir than that of low pressure reservoir. This is due to the fact that high pressure reservoir could support spontaneous combustion of air in the reservoir in which oxygen is consumed by the combustion front (Moore, 2004). However, high pressure reservoir requires injection of the compressed air more than the current reservoir pressure to ignite the oil. It might require compressors of high capacity which disturbs the economics of the project. Also injection of high pressured air may fracture the formation of the reservoir. Nevertheless, in West Hackberry, LOAI was implemented in low pressure reservoir as gas displacement process (Fassihi *et al.*, 1996). Therefore, reservoirs in the pressure range of 1200-2500psi have been cited to have spontaneous combustion (Greaves, 2006).

2.7.2 Temperature

A relatively high initial reservoir temperature (~100°C) promotes spontaneous ignition in LOAI. Moore (2004) suggested a rule of thumb which states that reservoir temperature greater than 85°C is desirable for the application of spontaneous ignition. Ren (2002) reported that in the simulation study for sensitivity analysis of reservoir temperature, the model was modified to simulate a reservoir with different temperatures. Two cases were tested: a low initial reservoir temperature of 80°C and high reservoir temperature of 120°C. Results of these two simulated cases showed that there was little difference in the oil production profile. As compared to case with reservoir temperature of 120°C, case with reservoir temperature of 80°C delayed the time at which a thermal zone was formed during the earlier stages of air injection. However, the delay in formation of thermal zone had very little effect on the consumption of oxygen. As time increased, the temperature in the reaction zone rose to a level close to that developed in the case with 120°C. This case study clarifies that light oil reservoir(s) has very little effect on oxygen consumption in air due to low temperature. Moreover, Literature review in Section 2.3.2 highlights that temperature range of 80- 130°C could be sufficient to consume all oxygen in the injecting air without the need to generate the higher temperatures. Experience in Brrancas field and West Hackberry shows that combustion and complete oxygen utilization was obtained at the reservoir temperature of 85°C and 95°C respectively (Fassihi *et al.*, 1996 and Pascual *et al.*, 2005). Hence Malaysian reservoirs having temperature greater than 100°C could be potential candidates for application of LOAI.

2.7.3 Formation Depth

Formation depth has been considered as one of the important parameters in the selection of an appropriate reservoir for LOAI (Myron, 2000). When the depth of the reservoir increases, increase in temperature occurs. This temperature gradient would ensure that the oxygen in the air will be consumed. Furthermore, increasing depth sometimes helps solubility of flue gas in the oil, which will promote increased recovery. However, increasing depth may increase the cost of air compression. Therefore, depth of reservoir must be chosen to that economically feasible value upon which the combustion could occur easily. Usually for air injection processes, the least depth considered was approximately 800m (Greaves, 2006 and Myron, 2006).

2.7.4 Pay Thickness

Pay thickness plays an important role to ensure the success of LOAI project especially in low vertical permeability reservoirs (Myron, 2006). High pay thickness could decrease the heat losses and therefore the energy released by combustion becomes steam. This heat preheats the reservoir and causes water to dissolve in the oil in the hot zone.

Myron (2006) performed experiments to find out the sensitivity of temperature, porosity and pay thickness of reservoir during air injection process. The study as shown in Figure 2.4 shows that production increases almost linearly with thickness. The study suggested that deeper, hotter and thicker fields are excellent candidates for Light Oil Air Injection.

In the screening study, the least pay thickness considered was approximately 10m as in case of Brrancas Field (Pascual *et al.*, 2005).

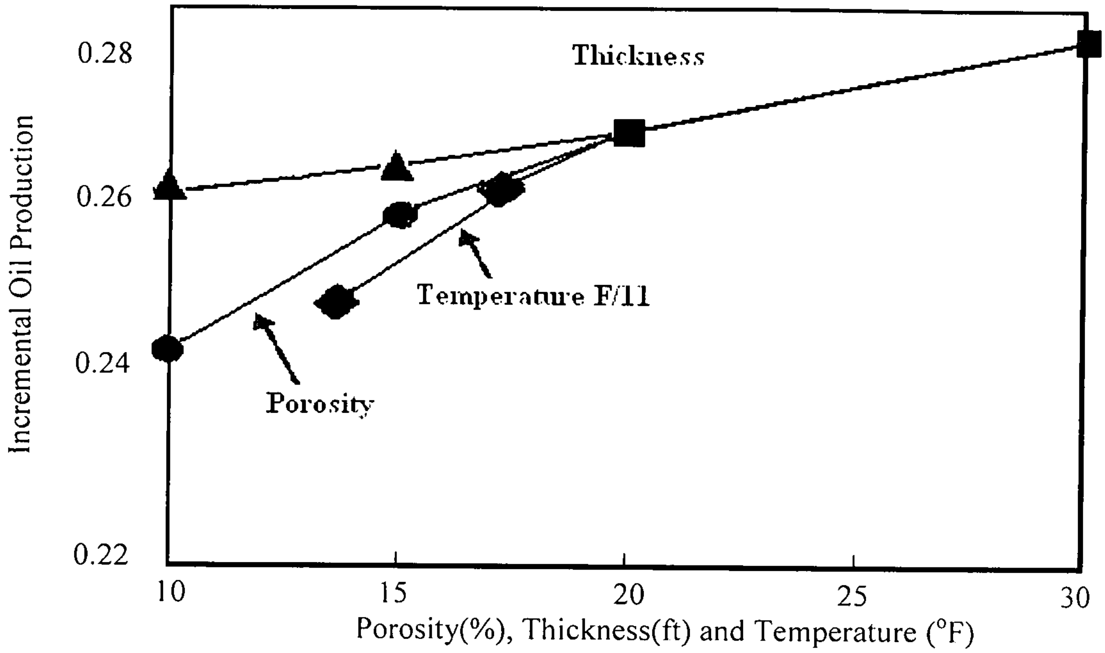


Figure 2.4 Effects of Porosity, Temperature and Pay Thickness on Incremental Oil Production by LOAI (MK Tech Solutions, 2006)

2.7.5 Rock Properties

2.7.5.1 Oil Saturation

For any EOR process to be implemented, the remaining hydrocarbon in place must be of considerable amount. This is because if the candidate reservoir has higher amount of oil which has not been effectively removed by either primary or secondary method, EOR method has higher chances to recover more oil from it. In the LOAI process, approximately 5% of oil is consumed during combustion process after injection of compressed air into the reservoir (Fassihi *et al.*, 1997). Oil saturation in case of Maureen field and West Hackberry was 56% and 79% respectively (Fassihi *et al.*, 1996 and Fraim *et al.*, 1997). Greaves (2006) and Myron (2006) suggested that reservoirs having minimum oil saturation level of approximately 30% could be considered for possible LOAI project.

2.7.5.2 Porosity

Porosity is the fundamental contributor to the reservoir oil storage capacity. Porosity values of a reservoir vary widely for different depositional systems, but these values generally are in the range between 11 and 30% (Beike *et al.*, 1996). Reduced porosity in thermal methods has a large negative effect since the heat produced by combustion is retained by more reservoir rock (Myron, 2006). This could reduce the maximum temperature and thermal expansion of gas and vaporization of water. Therefore, the minimum value of porosity suggested for the LOAI candidate reservoir was approximately 20% (Greaves, 2006). This value is the mean of range of porosity values for the general rock mentioned by Beike (2006).

2.7.5.3 Permeability

Permeability is the ease at which fluid flows through a rock. It determines the fluid dynamics of the reservoir. High permeability will allow high volumes of air to be injected into a single well. High horizontal permeability will allow combustion mixture after combustion to move quickly into the reservoir. However, large permeability variation could be a potential contributor to unsuccessful combustion mixture flood. Nevertheless, reservoir having low vertical permeability value was considered as good candidate to achieve good sweep efficiency (Myron, 2006). For this reason, the maximum kv/kh value considered in the screening is approximately 0.4.

2.7.5.4 Water Saturation

Initial water saturation is another important parameter in the development of screening criteria for LOAI. Since small amount of heat is generated in LTO mode of combustion, low value of initial water saturation would be favorable. For high water saturation, more heat is required to displace larger volume of water. Water saturation in case of Brrancas field was 58% (Pascual *et al.*, 2005). Therefore, the maximum value of water saturation, suggested in screening study for the LOAI candidate reservoir is approximately 60%. This consideration is also in favor with Greaves (2006).

2.7.5.5 Homogeneity/ Heterogeneity of Reservoir

The permeability of a field is said to be heterogeneous if it is spatially varying (Onur, 2003). One simple representation of heterogeneity is to collect a set of continuous layers, each with different value of permeability and porosity. An accurate complete description of the reservoir permeability is almost impossible. Therefore, geostatistical techniques are used to create a possible description of the reservoir based on the knowledge observed at the wells. These methods create a random selection (sample) from a field (population) of infinite extent with the exact Dykstra Parsons coefficient and correlation lengths desired.

Reservoir rocks are seldom homogeneous and variation in permeability occurs on a variety of length scale (Gharbi *et al.*, 1996). Unfavorable heterogeneity of the porous medium results in bypassing of oil. Furthermore, at low displacement rates, gravity forces which would segregate the less dense fluid from the more dense fluid, can dominate the other forces. This may lead to gravity override or underride of the oil by the injected fluid, and thus poor sweep efficiency. The large scale geological heterogeneities could reduce the recovery. However, perfect homogeneous reservoirs are rarely found. Therefore the homogeneity of reservoir is preferred. The heterogeneity condition may be compromised if reservoir could satisfy other parameters of screening criteria.

2.7.5.6 Other Parameters

Irreducible water saturation (Swi), the immovable water held in the rock by capillary forces and interfacial tension, fills part of the pore volume. Low values are preferred because more oil is contained in the rock to be produced by a LOAI process (Myron, 2006). For LOAI process dip of reservoir may be considered when the injection of air is taken place in updip of reservoir. However, this effect may be neglected in case of updip air injection. Minimum dip angle value suggested in screening study for the LOAI candidate reservoir is approximately 7° which is closer to the dip angle of 6.5° as in case of Brrancas field. Oil Gravity in the screening criteria is considered greater than 30°API because the scope of the research study is confined to the light oil reservoirs of Malaysia. Appendix A shows the parameters upon which the reservoir was screened out.

2.8 Selection of Candidate Reservoir for LOAI in Malaysia

Based on the developed screening criteria mentioned in Section 2.7, the selection of candidate reservoir was performed in the research study. In reservoir selection, twenty-two Malaysian light oil reservoirs were evaluated in the present research study. Details of reservoirs are mentioned in Appendix A. Most of the reservoirs are moderate pressure (1200-4000 psi), high temperature (90-130°C) and deep. Porosity values of most of the reservoirs lies in the range of 15% to 25%. Values of some parameters were unknown due to the unavailability of data. Reservoirs of three fields were short listed. Short listing of reservoirs was performed using the developed screening criteria. The short-listed reservoirs include Tabu (Upper/Lower I), Tapis (Upper/Lower J) and Dulang (E12/13 and E14). Details of the properties of these short listed reservoirs are mentioned in Appendix B. Due to unavailability of detailed data for the other two fields, the research work is confined to Dulang E12/13 and E14 reservoirs of Fault S Block.

Dulang field is located at about 130 km from Terengganu Crude Oil Terminal (TCOT) in about 76 meter water depth (Figure 2.5). Dulang structures are East West trending anticline with an area size of about 11 km by 3.5 km. The field is dissected by numerous normal faults with assumption that they are sealing. In its development, the field was divided into three major areas namely Dulang Unit, Dulang Western and Dulang Eastern.

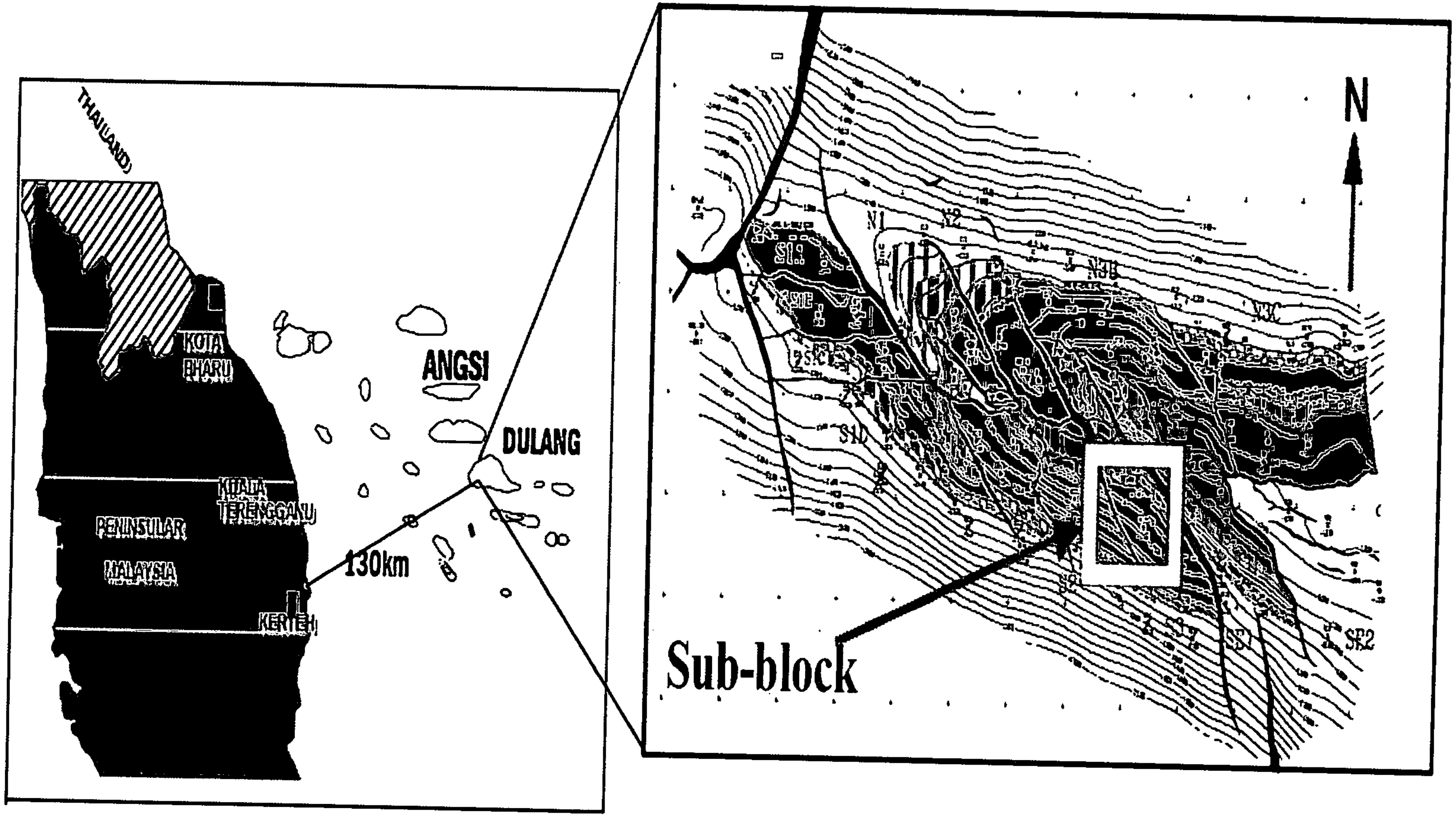


Figure 2.5 Dulang Oil Field, 130 km Offshore Trengganue, South China Sea (Nadeson *et al.*, 2004)

The Dulang S3 fault block was developed with a total of 6 wells, including two down-dip water injectors i.e. A29L and A31L. The first production from the block started in March 1991. The initial depletion strategy for Dulang S3 block was by natural depletion. Subsequently, falling reservoir pressures coupled with decreasing production rates have led to the implementation of a peripheral water injection scheme through down-dip wells in 1996. Later, feasibility studies identified re-injection of the produced gas as an EOR option. For this reason, pilot project was initiated in November 2002 with an attempt to improve recovery from the E12/13 and E14 reservoirs in S3 fault block. The main contributing mechanisms of the proposed water alternating gas (WAG) injection are expected to be drainage of 'attic oil' up-dip of the existing producers and more efficient sweep of water flooded regions.

Permeability of Dulang reservoirs rock is generally much larger in the horizontal direction than in the vertical direction, because of the tidal environment of deposition in the E14 and fluvial/ deltaic fan in the E12/13 sediments. Permeability in the E14 interval is generally much larger than in the E12/13 interval but the net thickness is comparable. The relationship between horizontal and vertical permeability for Dulang has been studied previously as part of the data preparation for the Dulang Unit Area Simulation Study. Core data from wells A17, B20 and B21, were examined and it was concluded that the Kv/Kh ratio for all reservoirs in Dulang is around 0.3 (Neve, 2004). Dulang E12/13 and E14 are light oil reservoirs in which average gravity of oil found to be 37 °API. Detail oil compositional analysis of the reservoirs is given in Appendix C.

Miscibility studies in Dulang indicates that at the reservoir temperature of 102°C, CO_2 will not be miscible with the crude oil at the current reservoir pressure, or even if the pressure is increased to the initial reservoir pressure (Zahidah *et al.*, 2001). By Equation-of- State (EOS) modeling, it was determined that the Multiple Contact Miscibility Pressure (MCMP) for CO_2 and produced hydrocarbon gas are 3230 psig and 3340 psig respectively (Zahidah *et al.*, 2001). These pressures are significantly higher than the initial reservoir pressure of 1800 psig and current reservoir pressure of 1400 psia. Since MMP of N_2 is more than that of CO_2, therefore immiscible flooding must be considered for Dulang E12-14 reservoirs. This result verifies the literature review in Section 2.4.2.4 that miscibility in Malaysian reservoirs is very difficult to achieve.

2.8.1 Previous Simulation Studies on Dulang E12/13 and E14

A detailed reservoir simulation study was conducted in year 1999 and later in year 2001 to re-assess the various WAG injection options in E12/13/14 reservoirs in South-3 block (Neve, 2004). These studies were the starting points for the design and development of field (pilot) testing of immiscible water alternating gas (WAG) in South-3 block in Dulang field. In August 2003, a revised geological model was constructed (Neve, 2004). The model was built on a regular 25m by 25m grid oriented in a North South direction. There were a total of 24 layers used to model the E12/13/14 leading to a model with a total of 433680 cells. The layering within the model is set out as mentioned in Table 2.8. Figure 2.6 shows the top and side view of the model.

Table 2.8 Formation Distribution in the Dulang E12-E14 Reservoir Simulation Model

Formation	Sub-Grid	Layers
E12/13A	1	1 to 3
E12/13B	2	4 to 8
E12/13C	3	9 to 13
E12/13 Shale	4	14
E14	5	15 to 24

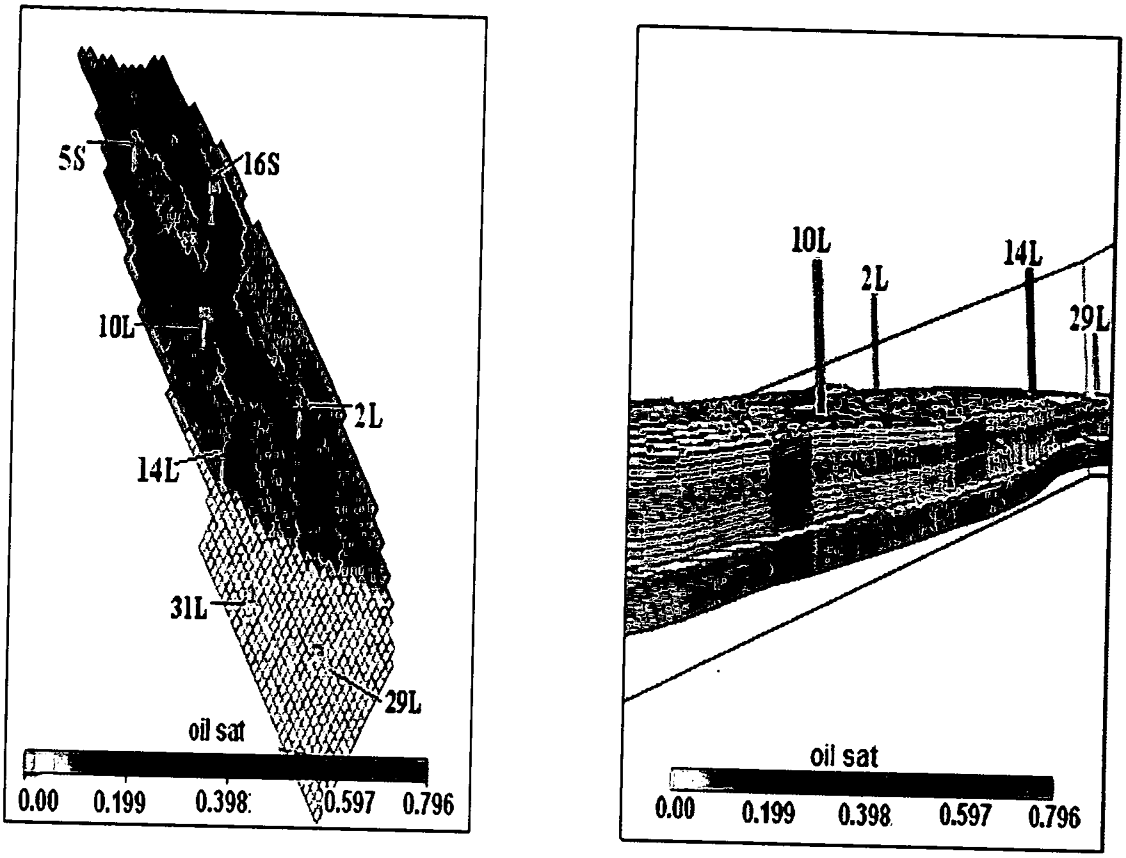


Figure 2.6 Top and Side View of the Simulation Model of Dulang E12-14 Reservoirs with Locations of Wells

In March 2004, the study was made to produce a history matched reservoir simulation model of the S3 fault block, incorporating the new geological model of year 2003, which can be used to evaluate the impact of the WAG scheme and for future reservoir management purposes. The history match which had been obtained was regarded as good having sufficient amount of reservoir surveillance data.

2.9 Summary

Literature findings show that LOAI could offer an effective EOR process for deep, high-pressure-high-temperature (HPHT) light oil reservoirs. Heat generation in this process is of secondary value and displacement of oil through gases is considered as conventional gas injection process. If complete utilization of oxygen in air is achieved after combustion in LTO mode, it could be a safe EOR process. Moreover, low air flux might be required for combustion. Hence thermal effects will not be considered in the research study because the combustion and complete oxygen utilization in light oil is considered to occur in the LTO range of temperature.

Gaseous mixture after combustion mainly comprises of carbon oxides and nitrogen. Percentage of nitrogen in the combustion mixture is high because nitrogen percentage in the injected air varies from 78% to 80%. Therefore, miscibility is difficult to achieve in the gaseous mixture. In fact, miscibility effects are hardly come across in the actual process. Nitrogen is the major component of air and physical properties of nitrogen are very similar to air. So, potentials of LOAI could be determined by studying nitrogen injection in place of LAOI. Using nitrogen injection, the early potentials of LOAI can be identified without performing experimental studies and without considering complex reaction mechanisms of combustion. Tingas (1996) also reported that isothermal nitrogen injection could be used to appraise the minimum of air injection requirement. By utilizing these considerations, black oil simulation could be used in the research study to assess the potential application of the LOAI technique for depleting Malaysian light oil reservoirs. Experimental studies may need to be carried out if simulation results show significant amount of incremental oil.

To identify the candidate reservoir, screening criteria was developed after evaluating successful LOAI projects around the world and consulting industry experts. The developed screening criteria embeds major reservoir properties such as the reservoir temperature, oil gravity and reservoir permeability. The purpose of developing the criteria is to identify potential reservoirs of LOAI in Malaysian oil fields. Based on the developed screening criteria, Dulang E12/13 and E14 reservoirs were selected as potential candidates for possible LOAI application.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

Methodology used for the present research study is described in Figure 3.1. Figure 3.1 describes that the research activities started with the literature review. It includes basic information regarding discrepancies in the currently used EOR methods and basic information regarding LOAI process which is mentioned in Section 1.3 of Chapter 1 and Section 2.3 and 2.4 of Chapter 2. Case histories of LOAI process were also studied which are mentioned in Section 2.6 of Chapter 2. By utilizing information about these case studies and consultation with industry experts, screening criteria was developed to identify the candidate reservoir(s). This screening criteria embeds major important parameters, like reservoir pressure, temperature, porosity and permeability, which might influence the process of LOAI. Based on this criteria, required screening parameters of different Malaysian reservoirs were collected. Reservoirs which match closely to the screening criteria were then short listed. To verify the selection of the final short listed reservoir, PRIze software was used. PRIze is the screening software which is widely used in industry to screen a reservoir for different EOR processes. During PRIze screening, N_2 was used in place of air due to its similar physical properties with air as described in Section 2.4.3 of Chapter 2. Simulation studies were conducted to predict the future performances of LOAI process. Black oil simulation was used in the research study because thermal and miscibility effects were not considered as mentioned in Section 2.5 of Chapter 2. Moreover, nitrogen was used instead of air to simulate the effect of LOAI. Thus, black oil simulator, Eclipse 100 was used in the simulation work to estimate the incremental recovery from gas injection. To optimize the simulation results, different configurations of injection and production were tested.

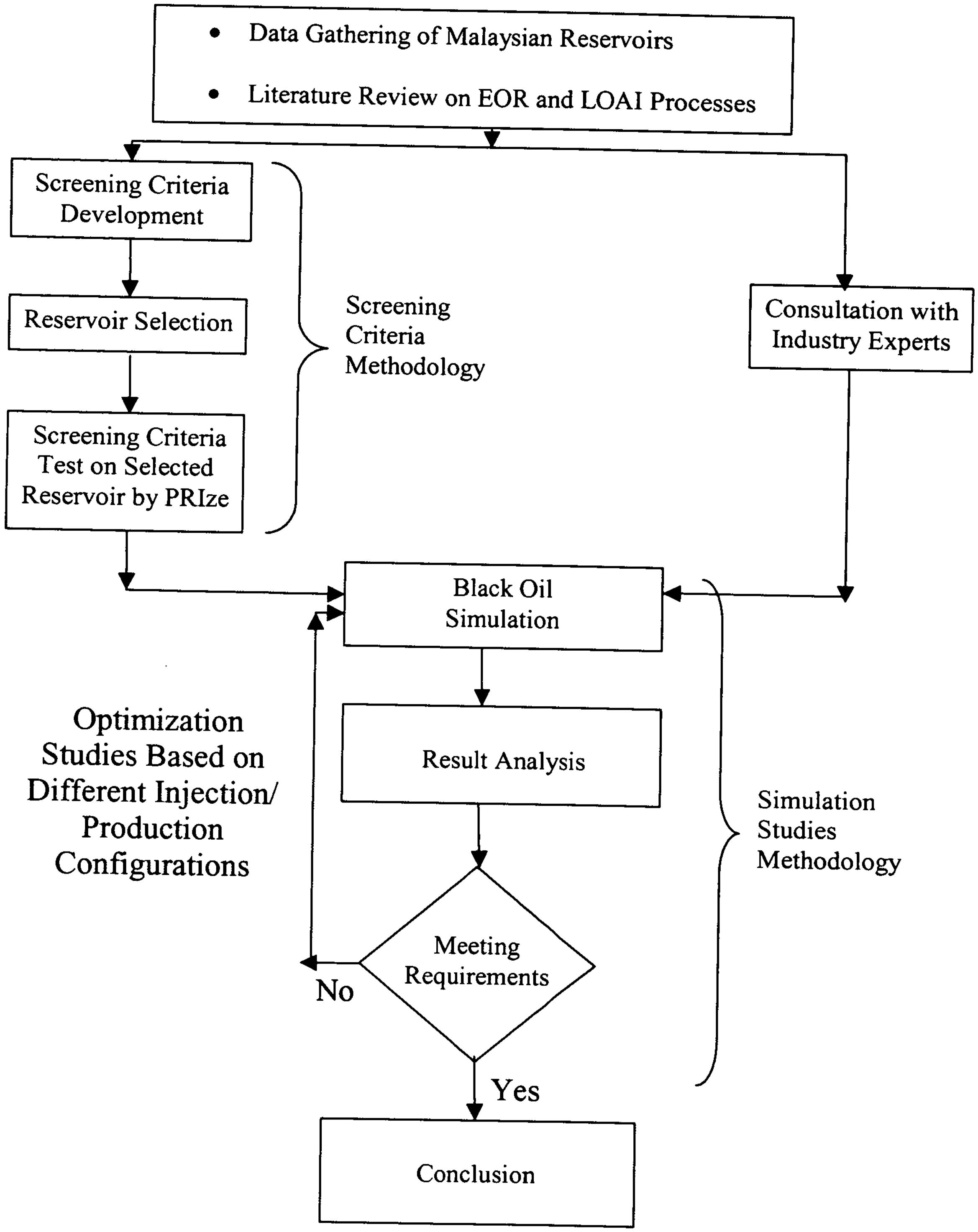


Figure 3.1 Methodology of the Research Project

3.2 Reservoir Screening Methodology

Methodology involved in the reservoir screening study is mentioned in Figure 3.2.

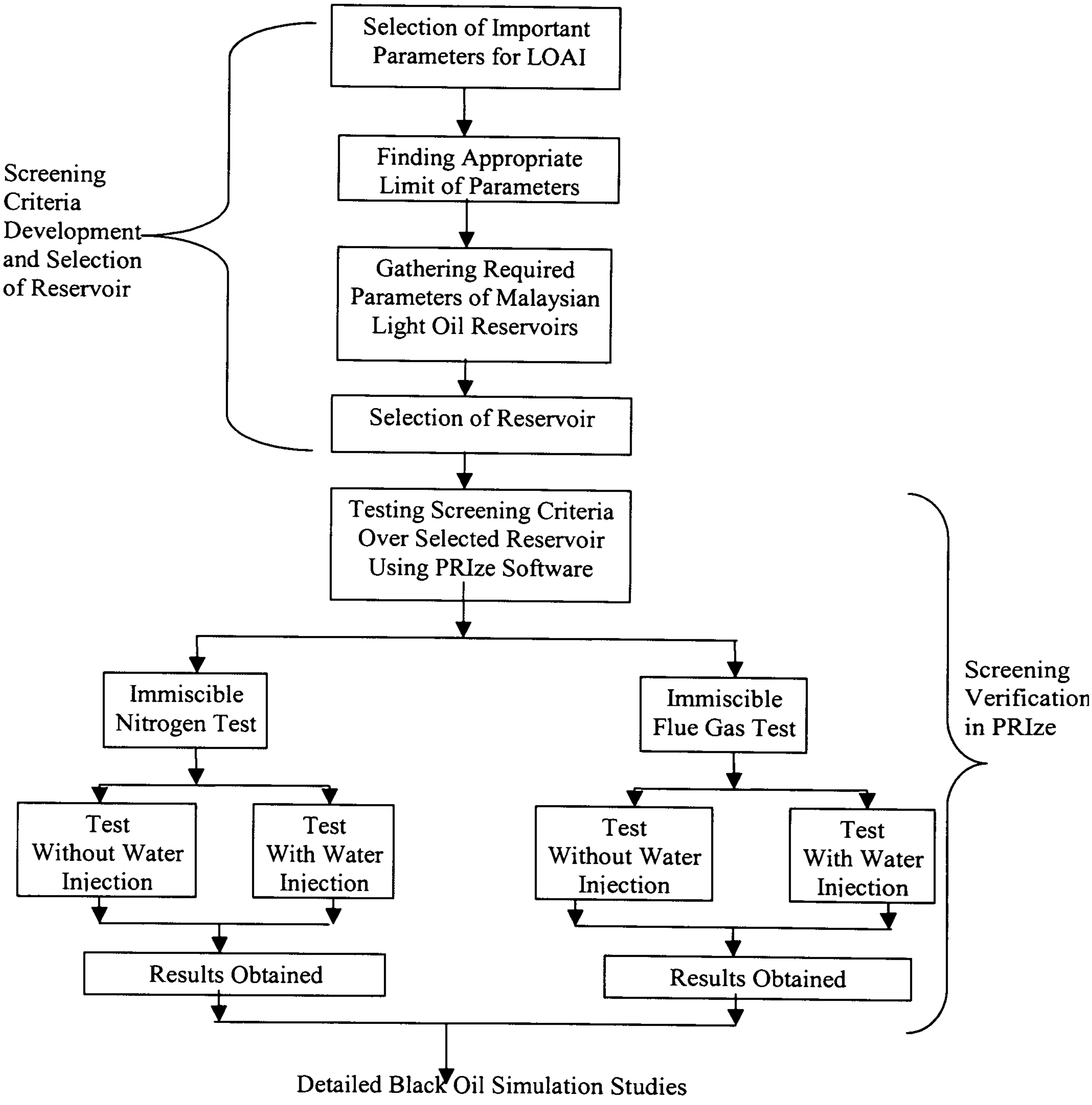


Figure 3.2 Process Flow in the Reservoir Screening Study

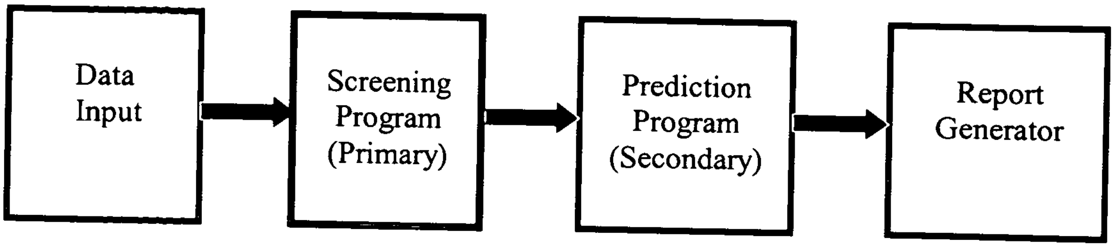


Figure 3.3 Screening Methodology of PRIze Software

In the present research study two different modes were tested in PRIze secondary screening, for the LOAI process performance forecasting. These two modes were: immiscible nitrogen gas injection and immiscible flue gas injection. The two modes were studied due to the non availability of test option in PRIze for air injection using light oil. In both of the cases, immiscible nature of flood was tested in view of the fact that the miscibility studies mentioned in Section 2.4.2 of Chapter 2 suggests that the miscibility is very difficult to achieve in Malaysian reservoirs due to their high MMP and low current pressure. Immiscible nitrogen gas injection option was tested because of the significant role of nitrogen in the resulting combustion mixture as discussed in Section 2.4.3 of Chapter 2. Immiscible flue gas injection was tested because after combustion in the reservoir, the composition of gaseous mixture is close to flue gas. The reason to test immiscible flue injection in PRIze is to confirm the results which were obtained using nitrogen test. Each of the two modes of injection cases was tested with and without water injection to check the requirement of water injection through downdip wells.

3.3 Simulation Studies Methodology

After selection of the candidate reservoir was verified through PRIze. The next step was to perform detailed simulation studies and sensitivity studies. Based on the literature survey mentioned in Section 2.5 of Chapter 2, black oil simulation was considered to be used in the research work. Black oil simulation avoids complex thermal scheme and does not require experimental data. Therefore, black oil simulator, Eclipse 100 was used in the simulation work to estimate the incremental recovery from gas injection.

3.3.1 Sensitivity Analysis of Injecting Gas Density in the Selected Reservoir

In view of the fact that black oil simulations were used in the present research work, the sensitivity study of injecting gas density was required to confirm that selected reservoir is not sensitive with injecting gas density. It is because of the fact that black oil simulators are usually designed to simulate hydrocarbon gas (methane) as an injectant, but nitrogen is desired to be simulated in the present research work. Black oil simulators differentiate the injection gases with respect to their density. Nevertheless, the difference between hydrocarbon (methane) and nitrogen gas density is significantly small of about 0.00243 lb/ft^3. By simulating following two cases with increased number of layers in the simulation model, the effect of density variation of the injecting gas can be determined on oil, water and gas production.

1. Simulation with injection of gas with hydrocarbon gas density.
2. Simulation with injection of gas with nitrogen gas density.

Results of the above mentioned cases were then compared. If the difference of results between these cases is negligibly small so that profiles of oil, gas and water production overlapping each other , the reservoir is believed to be independent of density change of the injecting gases. Moreover, black oil simulation can be used for further study.

3.3.2 Base Case for the Simulation Studies

To estimate the performance of the simulated process, a base case is required so that the performance of the simulated process will be compared with it. Usually the base case in simulation studies is considered as the existing running production scenario upon which the reservoir is operating. The present research study also aims to set the present production scenario as the base case for the simulation study.

3.3.3 Optimization Simulation Studies

Different optimization studies of production and injection schemes were intended to be performed so that best possible configuration will be obtained. The configuration results were compared with that of the base case so that performance can be judged. The configuration which gives expected simulated result to produce significant amount of oil along with low gas oil ratio (GOR) can be considered as a potential configuration for that candidate reservoir.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter describes the findings obtained from the research study in achieving the research objective to find the potentials of LOAI in Malaysian oil fields. It describes the studies which were carried out to: 1) select the candidate Malaysian reservoir for LOAI using developed screening criteria, 2) verify the selection of reservoir using PRIze software and 3) obtain the results after detailed simulation studies on the selected reservoir to predict potentials of LOAI. The analysis of the results obtained in the research study will help to assess the success level of LOAI in Malaysian oil fields.

4.1 Screening Criteria Development

To select the candidate reservoir(s) for LOAI in Malaysia, screening criteria was constructed. Details of development of screening criteria is mentioned in Section 2.7 of Chapter 2 which shows that the values of screening parameters, like reservoir pressure, temperature, depth and porosity, were obtained from case studies and suggestions from experts. Table 4.1 summarizes the developed criteria for the selection of candidate reservoir for LOAI.

Table 4.1 Screening Criteria for Selection of Reservoir to Implement LOAI

Required Parameters	**Criteria**
Current Reservoir Pressure	Moderate (1200-2500 psi)
Present Reservoir Temperature	> 100 °C
Oil Saturation (S_o)	> 30%
Water Saturation (S_w)	< 60%
Pay Thickness(t)	> 10m
Porosity (ϕ)	> 20%
Horizontal Permeability (k_h)	$(k_v/k_h)_{maximum} = 0.4$
Vertical Permeability (k_v)	
Dip Angle	> 7°
Formation Depth (d)	> 800 m
Homogeneity	Preferred
Oil Gravity	> 30°API

4.2 Reservoir Selection for LOAI

Based on the developed screening criteria for LOAI, the selection of the Malaysian light oil reservoir was performed. Detail of reservoir selection is mentioned in Section 2.8 of Chapter 2, Appendix A and Appendix B. Dulang E12/13 and E14 reservoirs were selected as the candidate reservoirs of LOAI in Malaysia.

4.3 Verification of the Reservoir Selection

The aim of this part of research project was to analyze and verify the selection of Dulang E12/13 and E14 reservoirs for the LOAI method. The screening verification study consists of calculating the projections for incremental oil recovery and oil production profile for the nitrogen injection/LOAI processes on selected Dulang E12/13 and E14 reservoirs.

4.3.1 PRIze Model Development

The model in PRIze was created by inputting detailed information of different required reservoir parameters. Details of the input parameters in the model generation of Dulang reservoirs in PRIze are given in Appendix D. Since Dulang E12/13 reservoirs shows the heterogeneous behavior due to their permeability variation. Therefore, the value of Dykstra-Parson Coefficient inputted in PRIze was 0.72 which is shown in Appendix D. This value of Dykstra Parson Coefficient represents a very heterogeneous reservoir and therefore it was selected so that reservoir was tested at its maximum heterogeneity.

4.3.2 PRIze Primary Screening

Primary screening option in PRIze is based on go-nogo logic. Due to non availability of test option in PRIze for air injection using light oil, immiscible nitrogen gas injection option was tested. Details of the results obtained after primary screening in PRIze is given in Table 4.2. The primary screening results shows that all conditions except current oil saturation met the criteria for immiscible gas injection. Suggested minimum value of S_o in PRIze was 0.5, however, the calculated vales of S_o by PRIze for Dulang E12-14 reservoirs were 0.4. Since these two values were close to each other and rest of the conditions was also passed the criteria, therefore this parameter can be compromised.

Table 4.2 Results of Primary Screening in PRIze

Screening Criteria of PRIze		**Value of Parameters for Dulang Reservoirs**	**Result**
Parameter	**Value**		
Depth in meters	> 200.000	1290	Pass
Oil Density (surface) in kg/m3	< 980.000	840	Pass
Live Oil Visc. (at BPP)	< 600.000	0.98	Pass
Active Water Drive	NO	NO	Pass
Bottom Water	Local	Local	Pass
Gas Cap	Local	None	Pass
Current Oil Saturation in fraction	> 0.500	0.4	**FAIL**

4.3.3 PRIze Secondary Screening

After primary screening studies, screening prediction was done in PRIze. Two different modes were examined in PRIze: injection of immiscible gas with and without water injection. Immiscible gas injection was recommended because of the high MMP of Dulang E12/13 and E14 reservoirs, as discussed in Section 2.8 of Chapter 2. Due to the unavailability of option in PRIze for the simultaneous water injection with the injected gas, WAG option was used in PRIze to model the effect of water injection. Two different immiscible injection gases were tested in the screening study i.e. pure nitrogen and flue gases (85% N_2, 14% CO_2, and 1% CO). Nitrogen was used to model air due to the fact that the percentage of nitrogen in air is very high and its physical properties are almost similar to that of air. Flue gas was also examined because in the process of LOAI, when air is injected in the reservoir, combustion takes place and the composition of the produced gases after combustion is close to the composition of flue gas. Therefore, the cases of nitrogen and flue gas show the relatively closer picture with the process of LOAI. The following four cases were executed in PRIze.

1. Immiscible nitrogen injection with WAG.
2. Immiscible nitrogen injection without WAG.

3. Immiscible flue gas injection with WAG.
4. Immiscible flue gas without WAG.

4.3.3.1 Estimated Injection Rate and Estimated Project Duration

Secondary screening study in PRIze for Dulang E12/13 and E14 reservoirs predicts the estimated injection rate and estimated life of project for the four cases which is shown in Table 4.3.

Table 4.3 Estimated Injection Rate and Project Duration for E12/3 and E14 Reservoirs

IOR Process	Estimated Injection Rate – Surface conditions, (Mscf/day)	Estimated Duration of IOR project (years)
Immiscible Nitrogen Flood with WAG	4512	15
Immiscible Nitrogen Flood without WAG	37257	3
Immiscible Flue Gas Flood with WAG	4512	15
Immiscible Flue Gas Flood without WAG	37257	3

Table 4.3 shows that for the cases with immiscible nitrogen flooding with WAG, the project could last for 15 years if the injected nitrogen gas rate is maintained at the rate of 4500 Mscf/day. Table 4.3 also shows that the case of immiscible flue gas flooding with WAG have the same calculated values of injection rate and project duration as that of immiscible nitrogen injection with WAG. This is due to the fact that the flue gas, which is produced after combustion of air, contains high amount of nitrogen (80-90%). This result proves the use of nitrogen in place of air as described in Section 2.4.3 of Chapter2. Results in Table 4.3 shows that this project could last for 15 years if the injected rate is maintained at the rate of around 4500 Mscf/d.

Table 4.3 also shows that for immiscible nitrogen flooding without WAG, the estimated gas injection rate of 37257 Mscf/day is very high. The project could last for only 3 years if this injection rate is maintained. The reason of short life time of the project might be due to higher flux of injected nitrogen gas. Moreover, the gas breakthrough at surface might occur in a very short time due to higher mobility of the injected gas and heterogeneity of the reservoir. Table 4.3 shows that immiscible flue gas injection without

WAG have the same calculated values as in the case for the immiscible nitrogen injection without WAG. This also might be due to the same reason that the flue gas contains significant amount of nitrogen in it. Table 4.3 shows that the estimated gas injection rate is very high for immiscible flue gas flooding without WAG. This project could also last for only 3 years if the injected rate will be maintained at the rate of 37257 Mscf/day. It might be due to the higher mobility of flue gas and higher injecting flux into the reservoir. The estimated injection and production values calculated by PRIze are not precisely accurate as described in Section 3.2.1 of Chapter 3. The reason of this screening is to roughly investigate the performance of the EOR process.

4.3.3.2 Calculation of Different Parameters

PRIze calculates values of different parameters for the four cases which are given in Table E1, Table E2, Table E3 and Table E4 of Appendix E. Table E1 and Table E3 indicate that the use of nitrogen or flue gas in immiscible mode along with WAG can produce the total recovery of approximately 39.3% OOIP. It shows that the additional recovery through nitrogen or flue gas injection will be approximately 17.5% OOIP at the end of 15 years operation. This amount of oil recovery shows significant amount which might be due to the high mobility of oil bank as shown in Table E1 and Table E3. Tables also show that water injection rate which is estimated by is 1510 m^3/day or 9500 bbl/day. It is to be noted that the values calculated by PRIze for nitrogen and flue gas given in Table E1 and Table E3 are exactly similar. It might be due to the single cell model of PRIze which could not differentiate between nitrogen and flue gas because of the high percentage of nitrogen (80-90%) in flue gas. This result also proves the use of nitrogen in place of air in the research work as described in Section 2.4.3 of Chapter2.

Table E2 and Table E4 of Appendix E shows that the use of nitrogen or flue gas in immiscible mode without water can produce a total recovery of 29.5 % OOIP at the end of 3 years operation. This value is comparatively small as compared to the immiscible nitrogen or flue gas injection with WAG case. It might be due to high injection rate and early breakthrough of nitrogen. The total additional recovery through nitrogen or flue gas injection without WAG will obtain 7.7% OOIP. Figure 4.1 represents the additional recovery estimated by PRIze in the four screening cases.

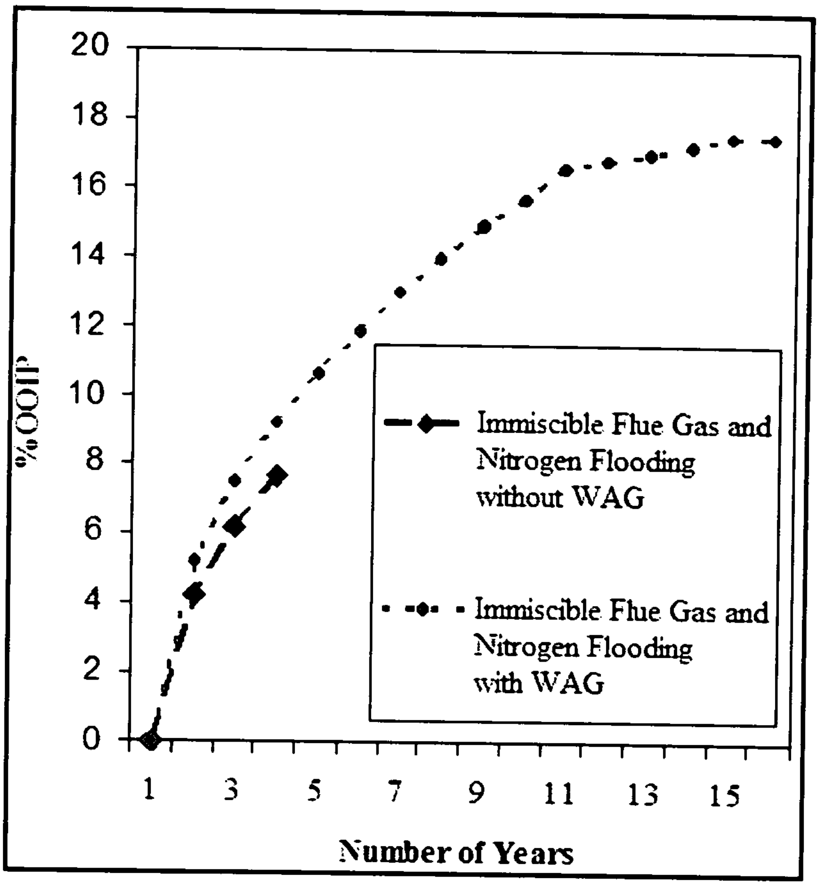


Figure 4.1 Cumulative Oil Production in Screening Cases

Results shown in Figure 4.1 indicate that if the immiscible gas is injected at high injection rate without injection of water, the early breakthrough of gas might occur. As a result of which, the project life will be limited to only 3 years. Thus, results obtained from the four cases in PRIze screening indicated that the use of water can be beneficial along with nitrogen or air as an injectant. It might achieve the recovery of around 17% to 18% of OOIP. However, the additional recovery is accompanied by high gas production. Further analysis of Dulang E12/13 and E14 reservoirs should be made using numerical simulation studies. The rate of water and gas injection suggested by PRIze is important to be used as input values in the numerical simulation studies.

4.3.3.3 Yearly Basis Calculation

The yearly basis calculated values by PRIze for the cases with nitrogen and flue gas injection with WAG is mentioned in Table F1 and Table F2 of Appendix F. Tables show that as the number of years increased, the increment in the gas production occurred due to the break through of gas with high mobility ratio at the surface. After 15 years of production, the cumulative amount of gas production was increased to more than 11 pore volume (PV). Figure 4.2 represents the yearly projected performance by PRIze for the immiscible nitrogen or flue gas with WAG. Figure 4.2 shows that the oil production in the first year is at maximum (24422 m^3 or 153613 bbl). This might be due to the high mobility of the oil bank as shown in Table E1 and Table E3 of Appendix E. Decrement in oil production occurred after the first year until it reached the value around 4500 m^3 or 28304 bbl in the eighth year of operation. Table F1 and Table F2 of Appendix F shows that after the sixth year, the cumulative gas production will reach to 7.5 PV. After 9 years of operation, this value reached to the value of 11 PV. This result suggests that the process might be applicable if the duration of the project limited to 6-7 years as the gas production will be relatively low compared with that of 9-10 years of operation.

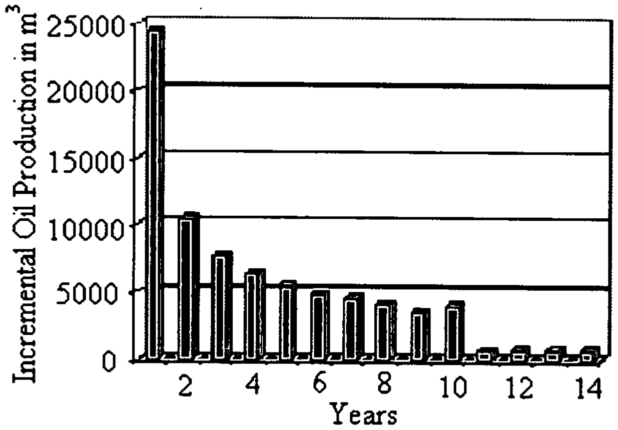


Figure 4.2 PRIze Estimation of Yearly Incremental Oil Production Using Immiscible Nitrogen and Flue Gas Injection with WAG

4.4 Simulation Studies

In the present research study, history matched model of Dulang E12/13 and E14 reservoirs for year 2003 was used. Details of the history method model and previous simulation studies on Dulang E12/13 and E14 reservoirs are mentioned in Section 2.8.1 of Chapter 2. Figure 4.3 shows the simulation grid block model of Dulang E12/13 and E14 reservoirs.

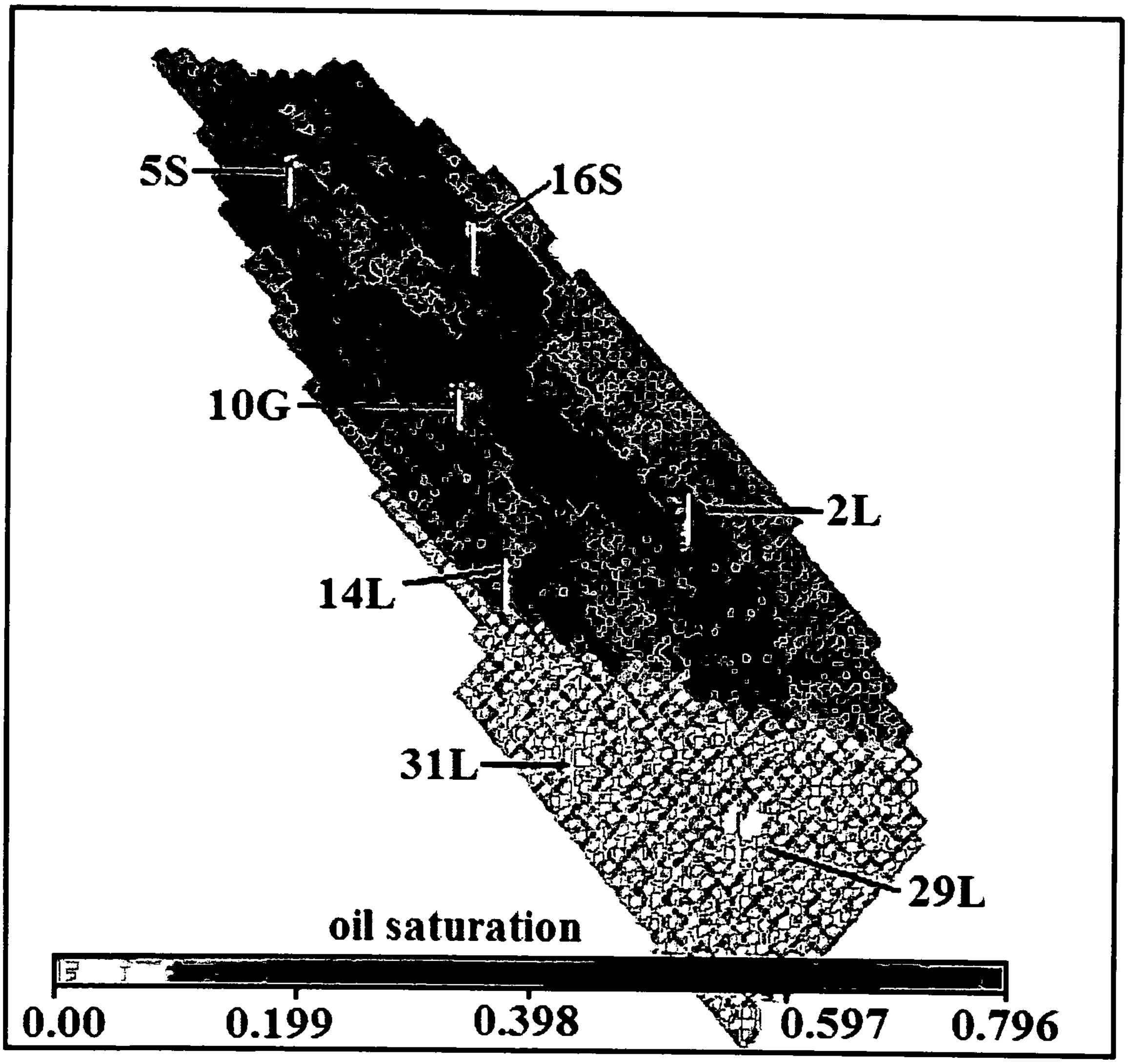


Figure 4.3 Top View of the Simulation Model of Dulang E12/13 and E14 Reservoirs

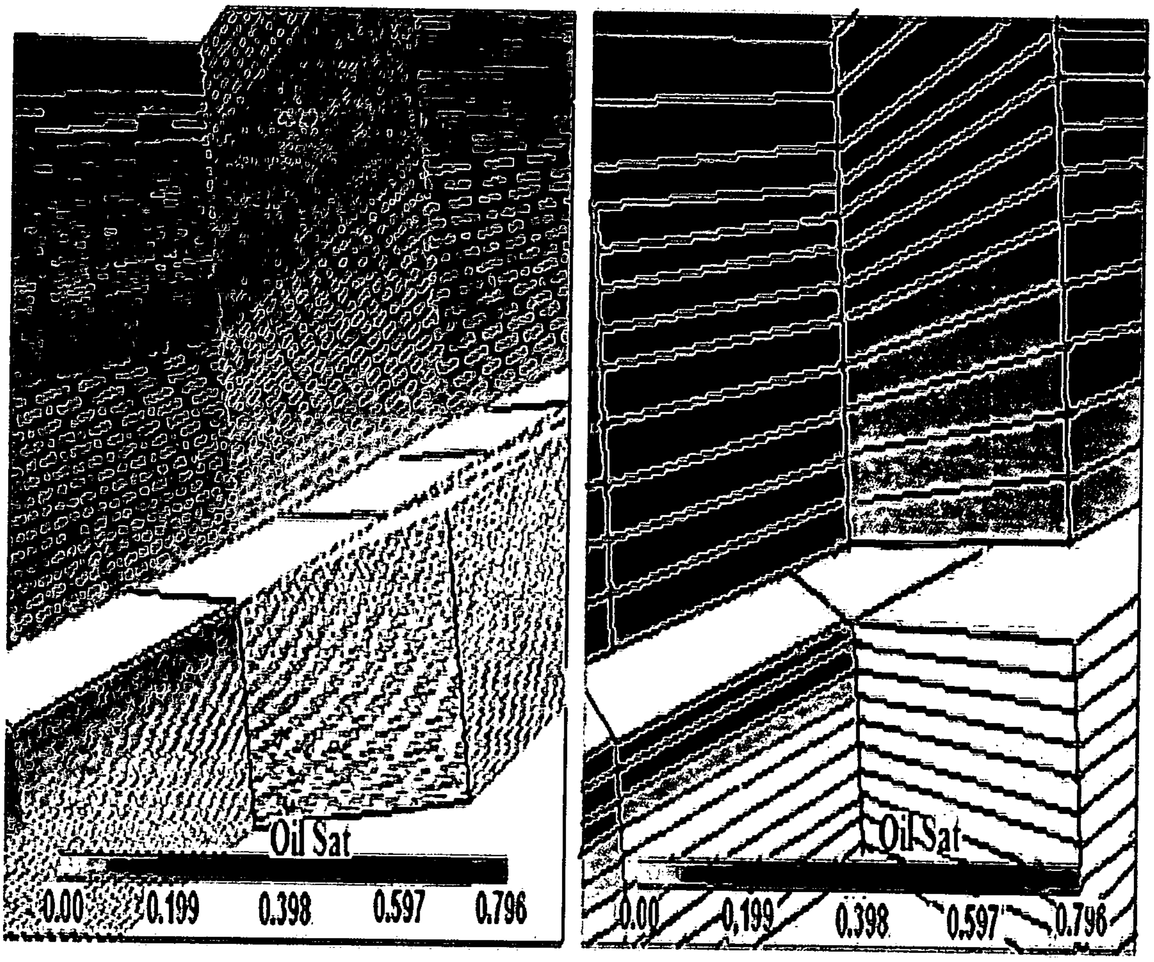


Figure 4.4 Side View of the Model - With and Without Refinement.

Extrapolation of history matched model with WAG was carried out from year 2003 to 2006. This extrapolated history matched model was restarted from year 2006 for the following two cases.

1. Injection of the gas with hydrocarbon (methane) gas density (0.0815 lb/ ft^3).
2. Injection of the gas with nitrogen gas density (0.07907 lb/ft^3).

Both cases were configured to inject 4000 Mscf/day of the respective gas. Both cases were restarted in 2006 which was continued to 2020. By simulating the two cases with increased number of layers, the effect of density variation of the injecting gas can be determined on oil, water and gas production. Figure 4.5 shows the simulation results.

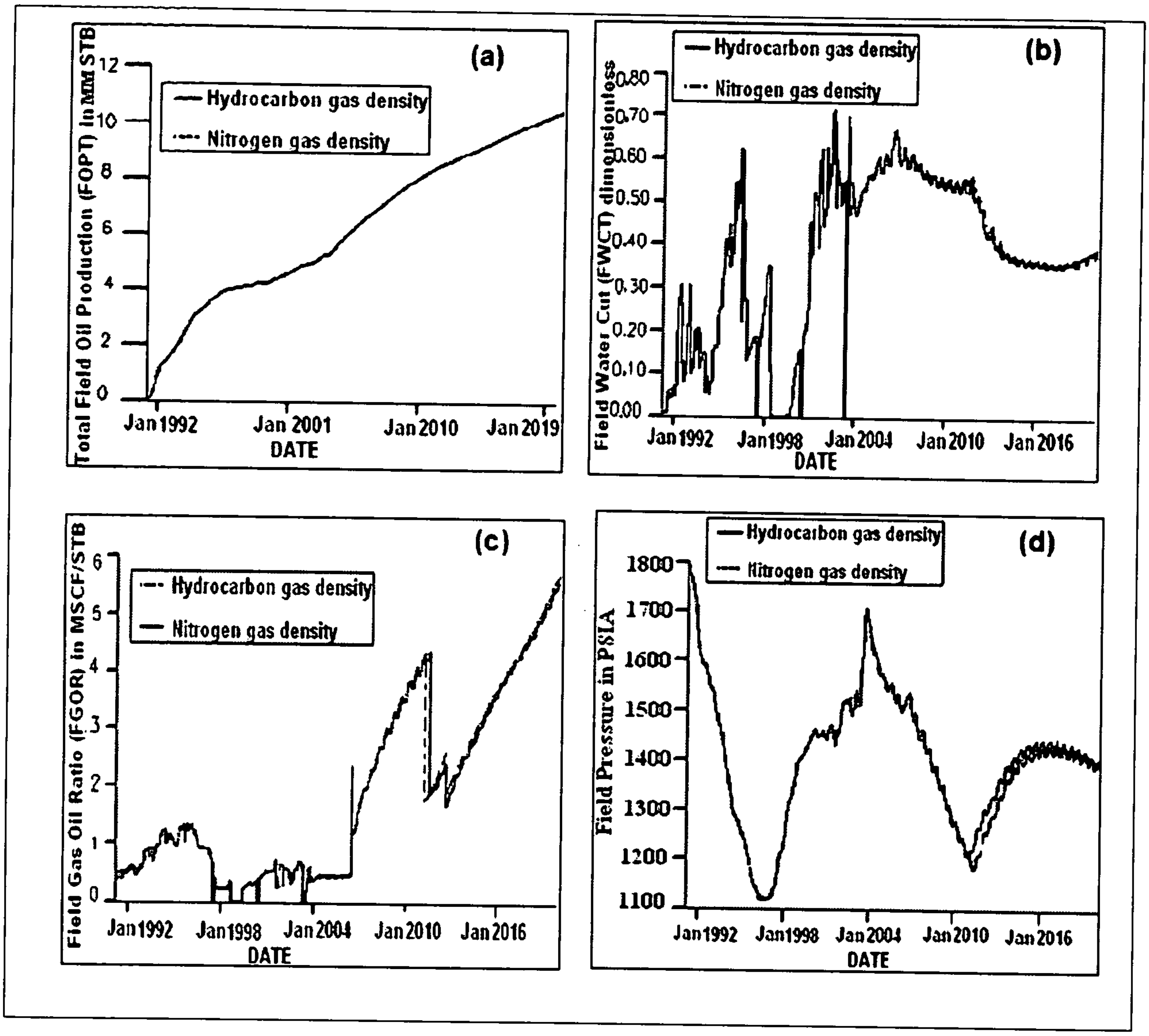


Figure 4.5 Simulation Results for the Comparison of the Injection Gas with Hydrocarbon and N_2 Gas Density.

Results comparison between these two cases in Figure 4.5 clearly shows the overlapping oil, water and gas production profiles. It indicates that the reservoirs are very less sensitive to the density change of the injecting gas. Since no significant change was observed in the sensitivity study of density, black oil simulation was used in the research study. Eclipse-100, black oil simulator of Schlumberger was therefore selected as the reservoir simulator in the research study to find early potentials of LOAI in selected Dulang E12/13 and E14 reservoirs.

4.4.2 Setting the Base Case for the Simulation Cases

To estimate the performance of the LOAI process in simulation optimization studies, a base case was required so that its performance will be compared with the performance of simulated optimized cases. Thus, current production scenario in Dulang E12/13 and E14 reservoirs was adopted as the base case, i.e. application of WAG in 2002 after secondary recovery which will continue till January 2020. Figure 4.6 illustrate the sequence of the process defined in the base case. In the base case, restarting of history matched simulation model was carried out from year 2003. Effect of WAG on different production parameters such as oil production and GOR was predicted till year 2020. All the production and injection values were adopted from the history matched model which shows the current production scenario. Upper oil production target rate was taken 3000 stb/day. Upper target for the gas injection rate at surface was taken 4000Mscf/day with voidage replacement fraction of 0.7. The target for the water injection at surface was taken 10000 stb/day, with no immediate control of injection rate. WAG time period was set 90 days to allow alternate cycling of water and gas. Table 4.4 represents the production wells configuration and Table 4.5 represents the injection wells configuration in the base case. The configurations of injection and production were taken from the history matched model.

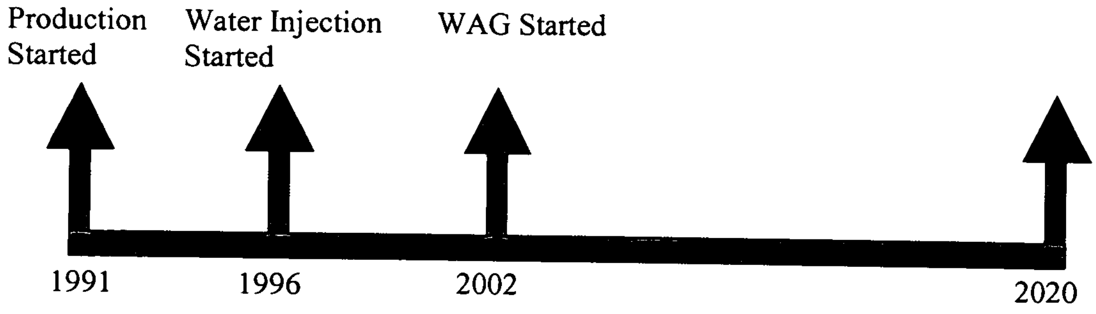


Figure 4.6 Schematic Illustration of the Base Case for Simulation Cases

Table 4.4 Production Wells Configuration in the Base Case

Wells	Min THP(psi)	Min BHP(psi)	Limiting values to shut the well
2L	300	14.7	• Production rate < 10 stb/day • Maximum water cut production > 0.9 • Maximum GOR production > 10
5S	200	14.7	
16S	200	14.7	

Table 4.5 Injection Wells Configuration in the Base Case

Injection Type	Injection Well	Injection Fluid Target	Injection Rate Control	BHP Limit (psia)
Gas	14L	1000 Mscf/day	Voidiage Replacement of 0.7	2800
Water	31L	1000 stb/day	None	
WAG	10L/G	2200stb/day and 3000 Mscf/day	Voidiage Replacement for Gas and None for Water	
	29L/G	2200stb/day and 3000 Mscf/day		

Figure 4.7 shows the simulation results obtained after simulation of the base case. Figure4.7 (a) shows that the application of WAG raised oil production in year 2002 before its gradual decline. The cumulative expected production is shown in Figure 4.7(b) which is about 9.4 MMstb. The GOR is estimated to maintain in a range of between 0.25 and 0.45 as shown in Figure 4.7(d). It might be due to the better sweep of alternate water and gas. Water cut was estimated to be relatively high as shown in Figure 4.7(c). Field pressure increases after the application of WAG in year 2002 which maintain itself to a moderate range 1350 psia after year 2010 as shown in Figure 4.7(e). The cumulative recovery factor of the reservoirs will estimated to be 32.7% after December, 2019. The performance of the optimized cases of the LOAI process will be compared with the performance of this base case. Based on that comparison, the overall performance of LOAI process can be judged which helps to find the potential of the method in Dulang E12/13 and E14 reservoirs.

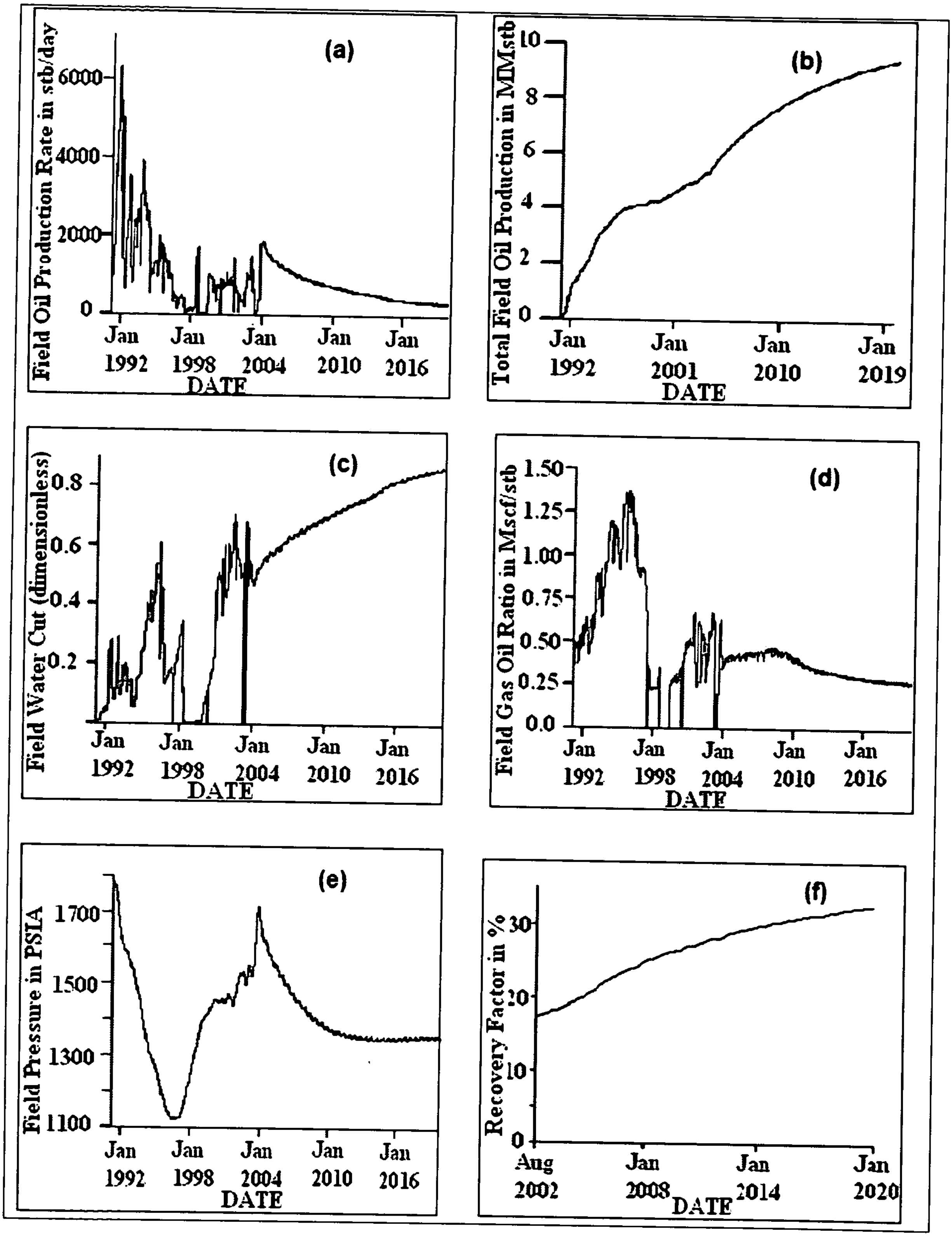


Figure 4.7 Simulation Results of the Base Case

4.4.3 Simulation Optimization Studies of LOAI in Dulang E12/13 and E14 Reservoirs

Optimization in simulation studies is required to find the best possible configurations for injection and production schemes. Different configurations of injection and production well(s) were thus simulated in Dulang E12/13 and E14 reservoirs. Optimization was carried out on 8 different injection/ production configurations. Details of these configurations are mentioned in Table G1 of Appendix G. Figure 4.8 shows the positions of injection and production wells in the 8 configurations.

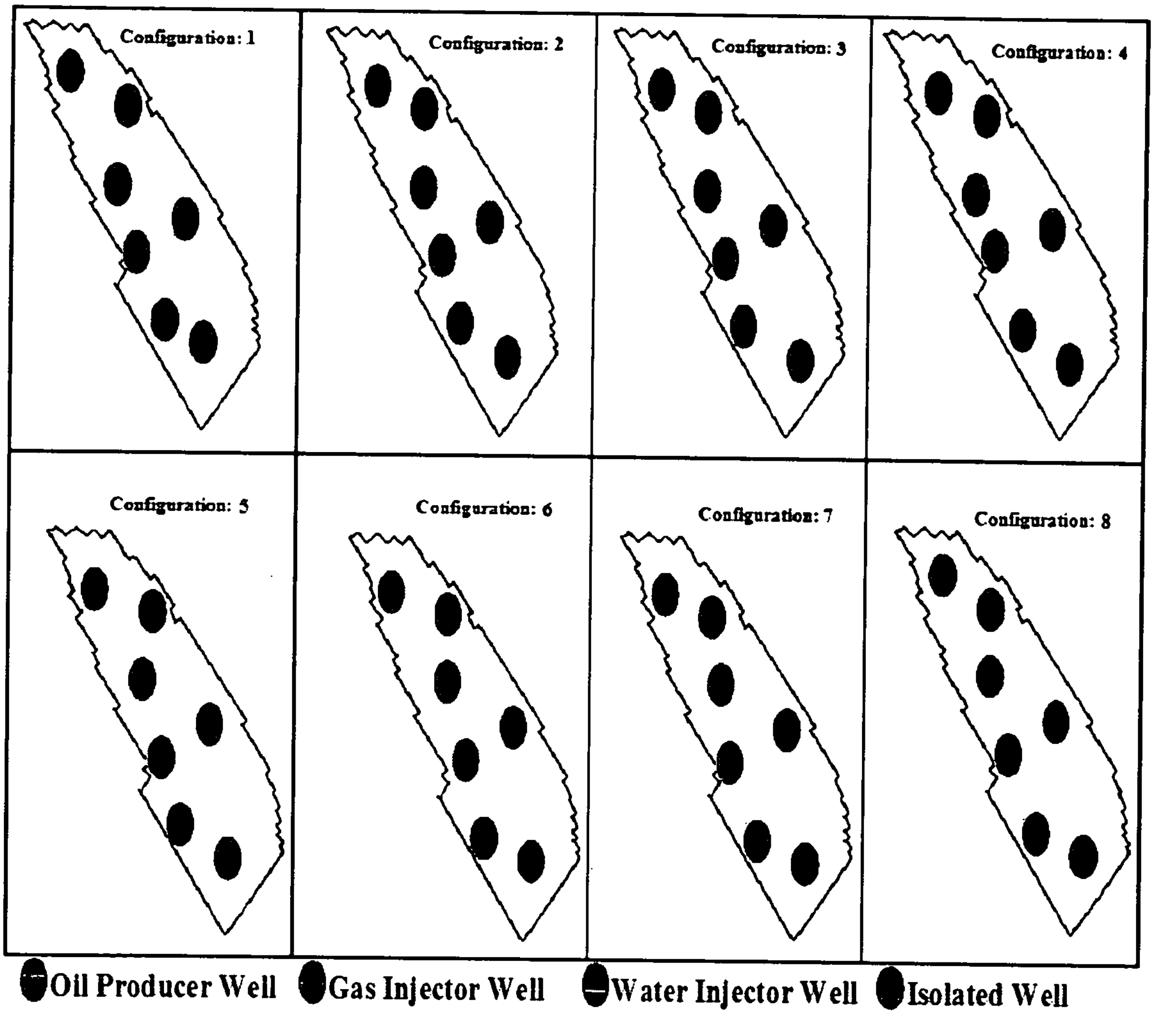


Figure 4.8 Schematic Illustration of Arrangement of Injection/Production Wells in Different Configurations

For each injection/production configuration, 3 different cases were simulated. Therefore, a total of 24 simulation runs were made in the optimization study. Values of group gas injection rate target and group oil production rate target in these 3 cases are shown in Table 4.6.

Table 4.6 Upper Targets of Oil Production and Gas Injection in the Three Main Cases

Case Number	Gas injection rate upper target	Oil production rate target
1	4000 Mscf/day	3000 stb/day
2	4500 Mscf/day	3500 stb/day
3	3000 Mscf/day	3500 stb/day

In all 24 simulated cases, the base case was restarted from 1 April 2006 to inject gas with nitrogen density and future predictions were made till January 2020.

In all of the simulated cases following limiting factors were applied i.e. production well will shut if any of the following condition is obtained:

1. Oil production rate < 10 stb/day
2. Maximum water cut production > 0.9 stb/stb
3. Maximum GOR production > 10 Mscf/stb

These limits were selected as extreme production status for all simulated cases. 10stb/day was selected as lower oil production rate limit in simulation study. This value was selected because it is considered to be very low value in terms of economical oil production. The upper water cut limit was selected to 0.9 stb/stb in simulation cases. This value was selected because of the fact that if the water cut increases to more than 0.9 stb/stb then it reflects the condition when the whole pore volume is occupied by water only. Moreover, the upper limit of GOR was specified as 10Mscf/stb which also considered being a very high value for gas production.

4.4.4 Results of Optimization Studies

The results obtained after the simulation studies are summarized in the following sections

4.4.4.1 Oil Production

Figure 4.9 and Figure 4.10 shows the simulation results of total field oil production and total field oil production rate respectively. Figure 4.9 shows that in all simulated configurations, except configurations 6, 7 and 8, the production of oil is more than that of the base case oil production (i.e. 9.4 MMstb). The results in Figure 4.9 show that the maximum oil production of 10.5 MMstb can be achieved in case 2 of configuration 4 when well 16S is converted into a gas injection well. Table 4.7 summarizes the incremental recovery factors (RF) of the simulated cases in the optimization study. Table 4.7 indicates that case 2 of configuration 4 can produce 12.8% OOIP incremental oil after the implementation of nitrogen/air injection in year 2006.

Table 4.7: Incremental Recovery Factor of the Optimization Simulation Study

Configuration No	**Case 1**	**Case 2**	**Case 3**
Configuration 1	12.02	12.23	10.20
Configuration 2	11.58	11.77	9.99
Configuration 3	9.78	10.64	9.95
Configuration 4	12.44	12.79	11.91
Configuration 5	11.32	11.52	10.68
Configuration 6	8.42	8.70	8.42
Configuration 7	5.32	5.02	5.33
Configuration 8	0.20	0.26	0.20

Table 4.7 and Figure 4.9 also show that the contribution of configurations 6, 7 and 8 in oil production is extremely low. It might be due to some of the factors like gas or water breakthrough in the production well.

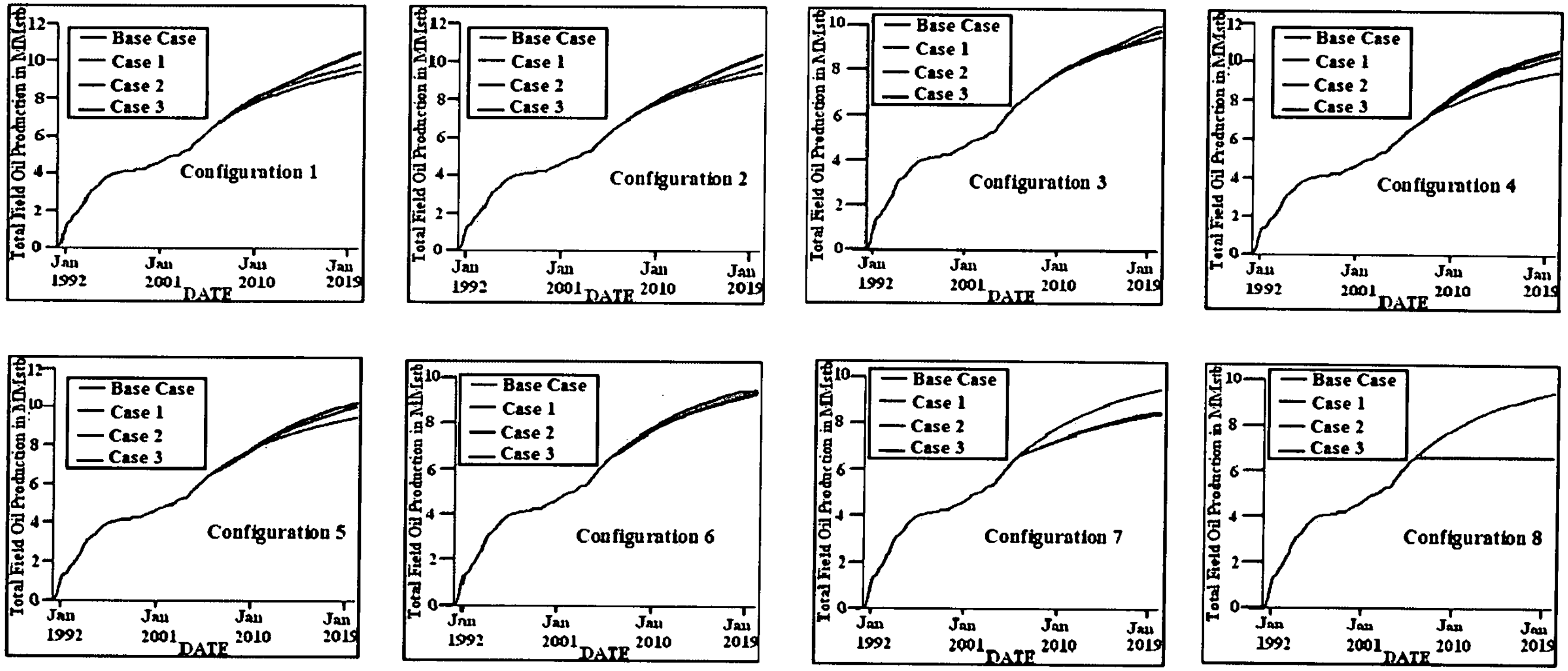


Figure 4.9: Total Field Oil Production of Different Configurations

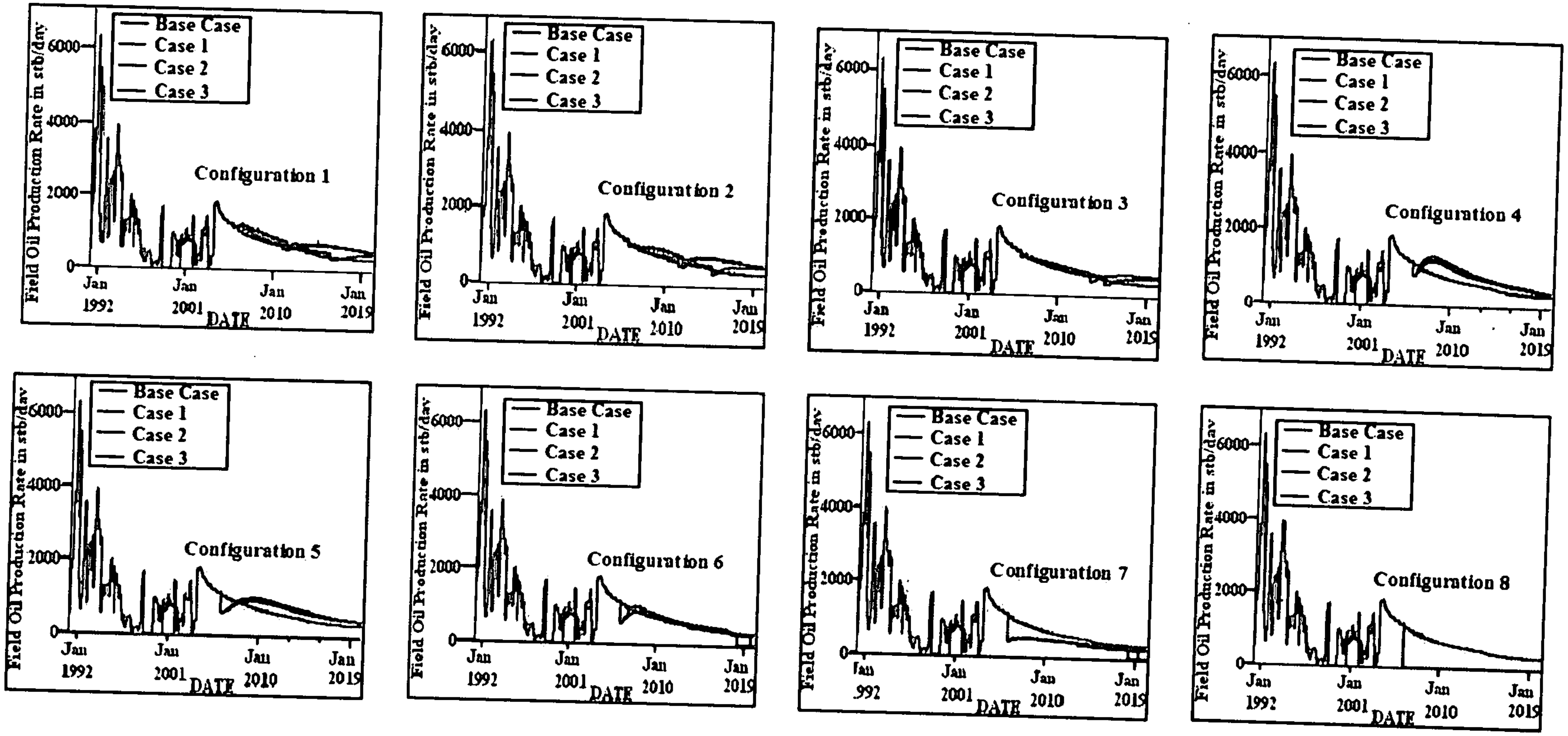


Figure 4.10: Total Field Oil Production Rate of Different Configurations

4.4.4.2 Gas Production

Results of the field gas oil ratio (GOR) in the simulation optimization studies are shown in Figure 4.11, which indicates the abnormal increment of GOR in all of the simulated cases except configuration 8. Results of configurations 4, 6 and 7 show the highest GOR among all configurations. Figure 4.11 also shows that in configurations 1, 2,3,4,6 and 7, the sudden decrement of GOR takes place after some time. It could be due to shutting of those production well(s) in which GOR exceeds the specified limiting value of 10 Mscf/stb. The shutting of the production well(s) may cause the pressure to rise in the reservoir. Figure 4.12 indicates that the reservoir pressure in all of the simulated cases gradually decline until the production well(s) shut down due to rise in GOR.

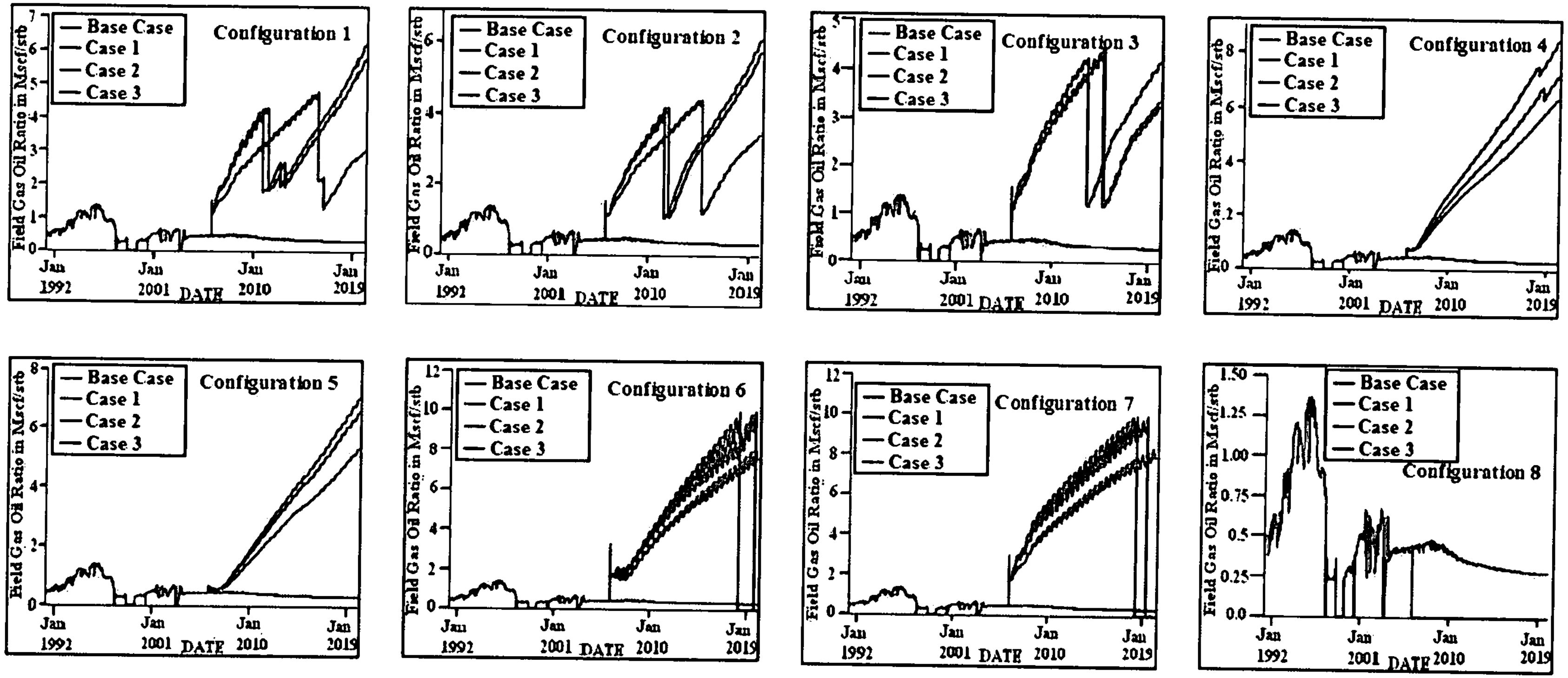


Figure 4.11: Gas Oil Ratio of Different Configurations

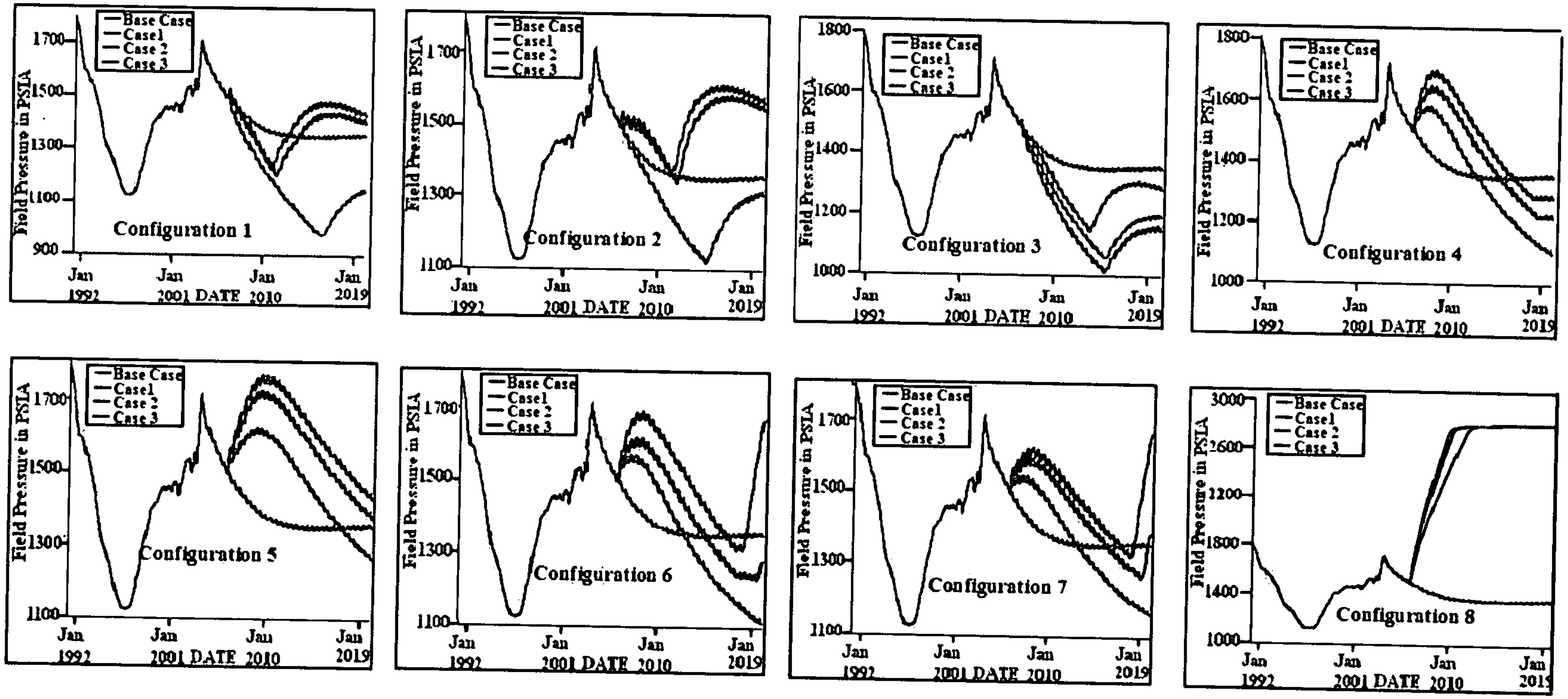


Figure 4.12: Field Pressure of Different Configurations

4.4.4.3 Water Production

Results of the field water cut (FWCT) in the simulation optimization studies are shown in Figure 4.13 which indicates a low water production profile. Water production in all the cases, except configuration 8, decreases. It shows that the injected water failed to reach the production wells, especially 5S and 16S, due to their updip location in the reservoir shown in Figure 4.3 of Section 4.4. In configuration 8, the water in production well breakthrough immediately after the injection of water and gas in year 2006 which is shown in Figure 4.13. Due to breakthrough of water in the well, the limiting value of 0.9 stb/stb reached immediately which causes the production well to shut.

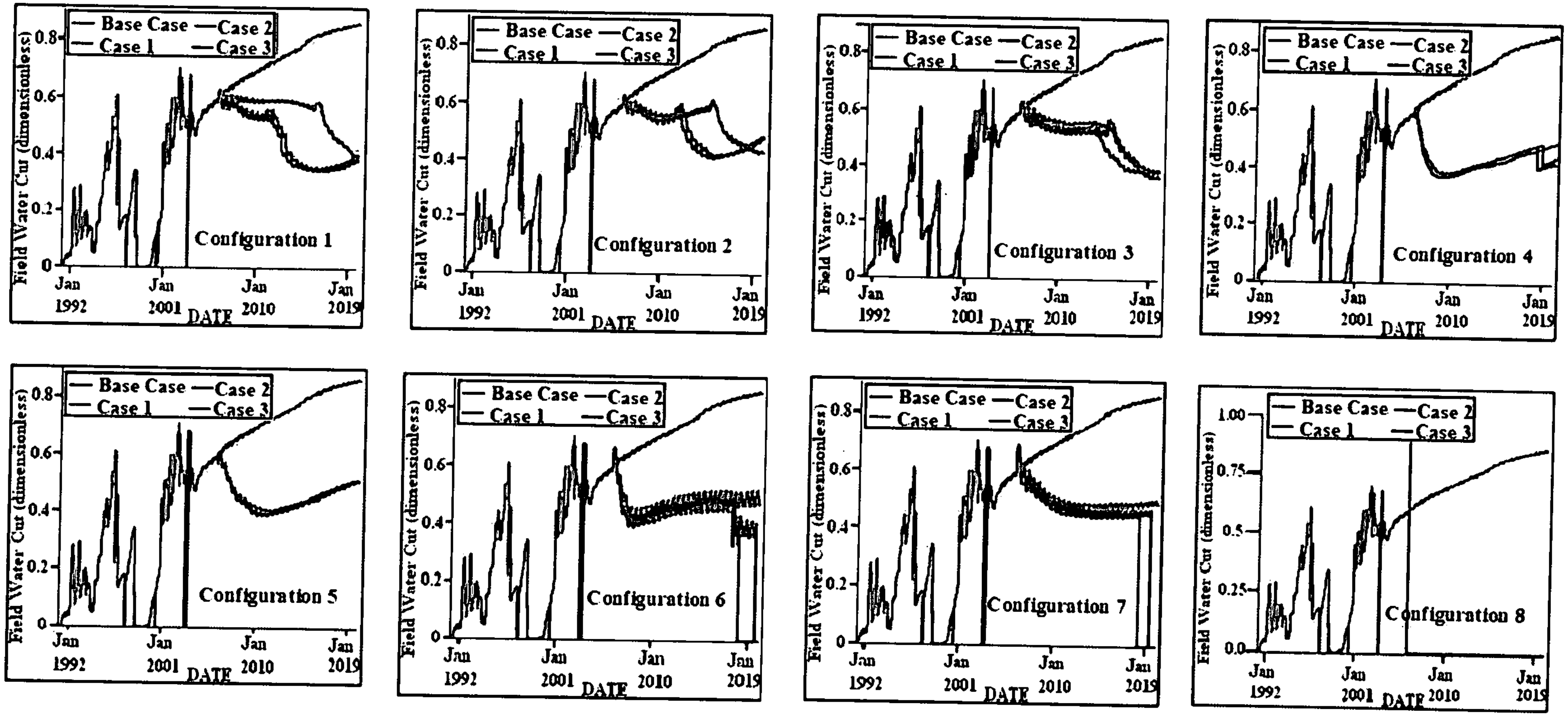


Figure 4.13: Field Water Cut of Different Configurations

4.4.5 Results Analysis of Optimization Studies

Results in Figures 4.9, 4.10, 4.11, 4.12 and 4.13 seems to suggest that injection of nitrogen could increase the production of oil. The maximum incremental RF obtained in case 2 of configuration 4 is 12.79% OOIP in comparison with 9% OOIP RF obtained in the base case. However, this increment in oil production is accompanied with high GOR as shown in Figure 4.11. In the optimization study, different configurations of injection and production were tested to minimize the GOR and increase the oil production. High GOR was attempted to handle by shutting in the offending wells, or by converting them to injection. However all of the configurations were failed to reduced GOR. The trend of GOR in case 2 of configuration 4 shows the GOR exceeds the range of 8 Mscf/stb. Two main reasons which might influence the increase in GOR are heterogeneity of the reservoir and mobility ratio of the injected (i.e. nitrogen) gas.

4.4.5.1 Effect of Reservoir Heterogeneities on GOR

Dulang E14 reservoir is less heterogeneous than Dulang E12/13. Therefore channeling or bypassing of the oil by the injected gas due to heterogeneity is likely occurs in Dulang E12/13 reservoir. Figure 4.14 shows the comparison of gas saturation (for case 2 of configuration 4) between layer 6 (E12/13 B reservoir layer) and layer 9 (E12/13C reservoir layer) of simulation model. It is to be noted that E12/13B is comparatively tight reservoir layer as compared with E12/13C. Figure 4.14 represents the comparison of the gas saturation between layer 6 and layer 9. Figure shows that due to the presence of relatively high permeability in E12/13C, the saturation of injected gas is expected to increase even after few years of operation. However, the saturation of gas in E12/13B is not increasing due to less permeability. This comparison of gas saturation between Dulang E12/13B and E12/13C confirms that high permeability channels exist within the reservoir that are enabling the channeling of injected gas through the reservoir. A review of the gas saturations across the reservoir suggests that gravity segregation effects are in-place and are exacerbating the gas channeling problem.

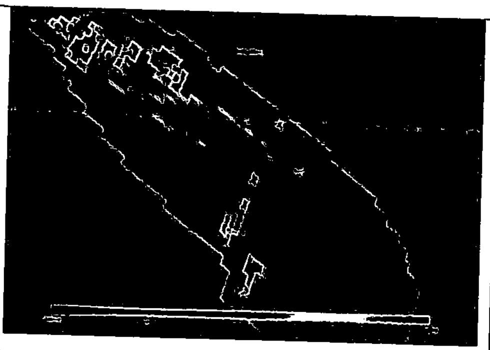
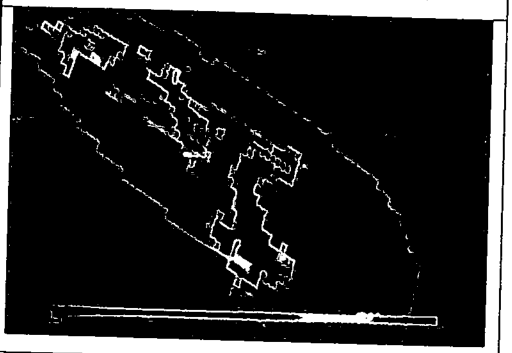
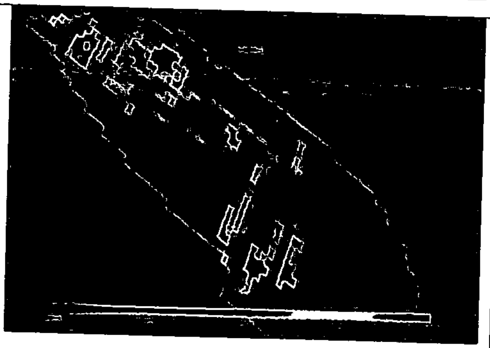
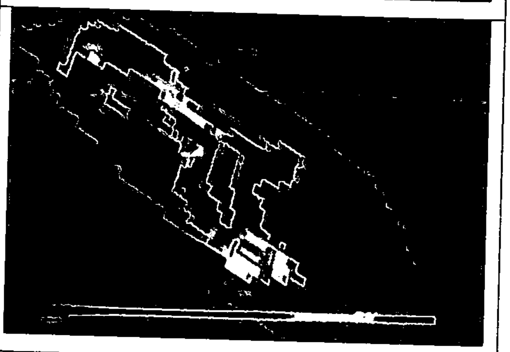
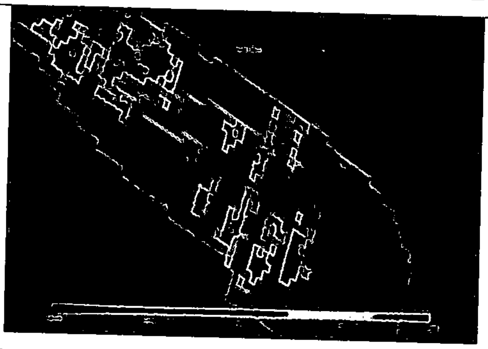
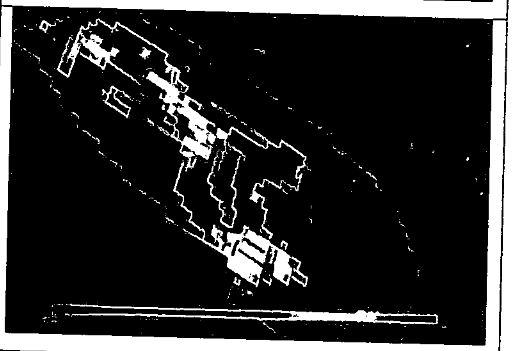
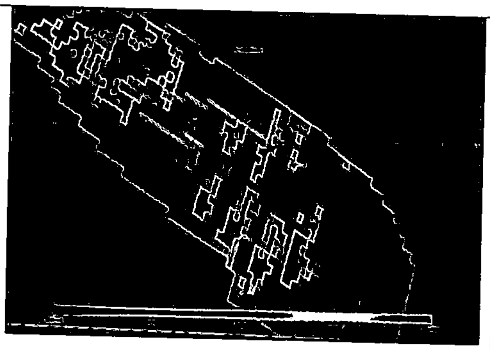
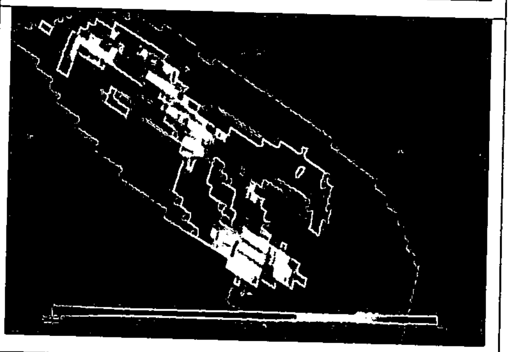
Year	Layer 6 (Dulang E12/13B)	Layer 9 (Dulang E12/13B)
2006		
2010		
2015		
2020		

Figure 4.14: Comparison of 2 Layers for Gas Saturation in Case 2 of Configuration 4

4.4.5.2 Effect of Nitrogen Mobility Ratio on GOR

The reservoir heterogeneities are further complex by the viscous fingering of the injected gas due to the unfavorable mobility ratio between the oil and the injected nitrogen gas, and leads to the poor sweep efficiency. Due to high mobility of nitrogen gas, it breaks through at the production well and causes high GOR.

Attempts were made in the optimization study to reduce the GOR due to above mentioned effects. Different configurations were thus simulated. In configuration 8, the pattern of injection and production was chosen like a double displacement process like in West Hackberry (Fassihi *et al.*, 1996). In this configuration, the gas was injected from the updip of the reservoir (from wells 16S and 5S) and water was injected from the downdip of the reservoir (from wells 29L and 31L). It was expected that the gas pushes the oil towards down and the injected water pushes the oil towards up. Oil is expected to be produced from the producer well 2L which lies mid way of the gas and water injectors. However, the simulation results obtained for this configuration are not promising. Water breakthrough occurs in the producer well so early which shuts the well.

It is clear from the results that GOR is very difficult to control in Dulang E12/13 and E14 reservoirs due to its permeability variation. Increased value of GOR negates the application of LOAI in Dulang E12/13 and E14 reservoirs. Due to bypassing of oil by the injected gas there are chances that the oxygen of the injected air will not come into contact with the oil. As a result, no combustion will occur which creates safety hazards in operation. However, LOAI could be used for the short time if the recovery factor is reasonably good with low GOR.

CHAPTER 5
CONCLUSION

Present research study attempts to find the potentials of light oil air injection (LOAI) in Malaysian light oil reservoirs as an alternate EOR method. To fulfill this objective, the screening criteria was developed to select the candidate Malaysian reservoir for LOAI. The selection of reservoir was then verified by using PRIze software. The study using PRIze was carried out to validate the screening criteria and selection of reservoir. Simulation of different configurations was performed to investigate the feasibility and applicability of LOAI for Malaysian reservoirs.

The developed screening criteria was based on reported LOAI successful case studies and consultation with people in the industry. It embedded the major reservoir properties such as the reservoir temperature, reservoir pressure, oil viscosity, and formation depth. Developed screening criteria suggests that a moderate pressure (1200-2500psi), high temperature (~100 °C), deep and thick light oil reservoir with low kv/kh value could be a candidate reservoir for LOAI. This screening criteria could be used on any sandstone reservoir to the select candidate reservoir(s) for the application of LOAI. The developed screening criteria was then applied on 22 light oil Malaysian reservoirs. Dulang E12/13 and E14 reservoirs were short listed after the screening process. Selection of Dulang E12/13 and E14 reservoirs was further verified by using commercial screening software, PRIze. In PRIze screening studies, nitrogen was used in place of air due to non availability test option for LOAI. Two types of screening were performed by PRIze i.e. primary and secondary screening. The results obtained in these screening studies suggest that application of LOAI in Dulang E12/13 and E14 reservoirs could produce 17.5% OOIP additional oil recovery. 17.5% OOIP recovery of oil was a considerable amount and therefore the reservoir was subjected to detailed black oil simulation studies. Black oil simulations were performed because oil swelling, viscosity reduction by CO_2 dissolution and thermal effects were not accounted in the research study. Usage of black oil simulation in the research study was further supported by the fact that Dulang E12/13 and E14 reservoirs were not found sensitive with the change in the injection gas density during the density sensitivity studies.

In the optimization simulation study, eight different configurations of injection and production were simulated. In each configuration, three cases were simulated with changes in the injection and production rate. Findings from the black oil simulations suggest that the RF obtained after implementation of LOAI lies in the range of 0-13% of OOIP. However, the increased oil production was accompanied with high GOR. The high GOR might be due to heterogeneous nature of Dulang E12/13 reservoir which promotes channeling or bypassing of the injected gas. Simulation studies suggest that if LOAI was applied in Dulang E12/13 and E14 reservoirs, the GOR would be very difficult to control. High GOR holds a number of challenges if it also contains unburned oxygen. If oxygen of the injected air remained unburned after combustion and produced at the surface, it might cause safety hazards. Furthermore, if oxygen remains unburned after combustion, it might also cause the production of hydroperoxides, which may undergo auto-decomposition reactions to damage the well bore as reported by Moore (2004). Furthermore, the presence of unburned oxygen could activate unwanted bacteria which could promote corrosion or reduce porosity (Darman, 2006). In view of the fact that high GOR will be expected to produce with limited oil production, the implementation of LOAI in Dulang E12/13 and E14 reservoirs is not recommend to be applied.

CHAPTER 6

RECOMMENDATIONS

1. Considering the little oil production increment and high gas production with a number of potential hazards as shown in results from black oil simulations, the LOAI is not recommended as a suitable EOR method for Dulang E12/13 and E14 reservoirs.
2. The present research study was conducted using limited data recourses. Dulang E12-14 reservoirs were selected in present research study based on the availability of data. Therefore, it is recommended to perform the advanced study on LOAI after having more detailed data of different Malaysian fields. Better screening will therefore be done utilizing the detail data.
3. The aim of present research study was to find only the early success level of the LOAI process. In this context, assumptions of negligible thermal effects, immiscible gaseous mixture and nitrogen utilization in place of air was made to simplify the process. Detailed study must be required without incorporating these assumptions and to notice the full effect of the process. Thermal simulations might be required in this regard.
4. Experiments might be required to assure the auto ignition of the remaining oil at reservoir conditions. Experiments might also be required to confirm that oxygen in the injected air will be fully consumed in reservoir. Moreover experimental study should be done which will provide information on the stability of the burn front, peak temperatures generated, oxygen utilization, composition of produced gases, properties (density/viscosity) of produced oils, pH of produced water (corrosion consideration), water production rates as a function of the location of the combustion front and amount of air needed to produce an incremental unit of oil.
5. Since surface facilities like compressors, platform refurbishment and gas separators might be required in the actual implementation of the LOAI process. It is recommended that one study should be done on the economical feasibility of LOAI in Malaysian oil fields.

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APPENDIX A

Details of Malaysian Reservoirs for LOAI Screening

	Required Para meter	Selected Criteria	1 St Joseph B/G	2 Tembungo West L-1	3 East Bunga Raya J-70	4 East Bunga Kekwa I-115	5 East Bunga Kekwa , J-70	6 West Bunga Kekwa I-90,
1	Current Reservoir Pressure (psi)	1200-2500	485	3500	3271	2,950	2,963	2,500
2	Present Reservoir Temperature	> 100 °C	52	93	132	116	127	118
3	Oil Sat So	> 30%	53	42.9	63.4	59.3	48.4	63.6
4	Pay Thickness (m)	> 10 m						
5	Porosity	> 20%	20	15	18.4	23	15	21.2
6	Maximum Kv/Kh	0.4	-	-	-	-	-	-
7	Dip	$> 7^{o}$	-	-	-	-	-	-
8	formation depth	> 800	686		2312		2235	
9	Gravity Stablized(m)	It slow the process	-	-	-	-	-	-
10	Oil Gravity (°API)	> 30	-	-	-	-	-	-
11	OOIP	Higher the best	552	51.1	30	53.8	9.6	61.3

APPENDIX A (Continued)

	Required Para meter	Selected Criteria	7 West Bunga Kekwa J-60	8 East Bunga Orkid K-21A	9 Dulang E10/11,	10 Dulang E12/13 ,	11 Dulang E14	12 Dulang E7
1	Current Reservoir Pressure (psi)	1200-2500	2,650	3934	1200	1200	1400	1200
2	Present Reservoir Temperature	> 100 °C	128	144	102	102	102	99
3	Oil Sat So	< 30%	49.3	43	47.9	51.9	52.2	52.8
4	Pay Thickness (m)	> 10 m	-	-	-	20	20	-
5	Porosity	> 20%	0.182	16	25	25	25	28
6	Maximum Kv/Kh	0.4	-	-	-	kv/kh =0.3	kv/kh=0.32	-
7	Dip	> 7^{o}	-	-	-	9	9	-
8	formation depth	> 800		2748	1290	1290	1290	1240
9	Gravity Stablized(m)	It slow the process	-	-	-	No	No	-
10	Oil Gravity (^{o}API)	> 30	-	-	-	37	37	-
11	OOIP	Higher the best	17.1	8.5	137.6	235	89.6	124.1

APPENDIX A (Continued)

			13	14	15	16	17	18
	Required Para meter	Selected Criteria	Dulang LD1	Kepong J18/20	Seligi K-10	Tabu Lower I	Tabu Upper I	Tapis Lower J
1	Current Reservoir Pressure (psi)	1200-2500	1400	2187	2119	2,265	1,675	2248
2	Present Reservoir Temperature	> 100 °C	99	87	103	118	118	120
3	Oil Sat So	< 30%	52.4	40	51.4	34.4	31.3	31.4
4	Pay Thickness (m)	> 10 m	-	-	-	-	-	-
5	Porosity	> 20%	28	25	24	???	20	20.5
6	Maximum Kv/Kh	0.4	-	-	-	-	-	-
7	Dip	> 7°	-	-	-	-	-	-
8	formation depth	> 800	-	-	-	-	-	-
9	Gravity Stablized(m)	It slow the process	-	-	-	-	-	-
10	Oil Gravity (°API)	> 30	-	-	-	-	-	-
11	OOIP	Higher the best	90.2	44	105	146.4	208	821.7

APPENDIX A (Continued)

			19	20	21	22
	Required Para meter	Selected Criteria	Tapis upper J	Tinggi J18/20	Betty L7	Baronia RV2
1	Current Reservoir Pressure	1200-2500	1885	1630	2475	3324
2	Present Reservoir Temperature	> 100 °C	110	91	89	80
3	Oil Sat So	< 30%	32	25.4	31.9	46.5
4	Pay Thickness	> 10 m				
5	Porosity	> 20%	20	27	26.4	17.5
6	Horiz Perm	0.4	-	-	-	-
7	Dip	> 7°	-	-	-	-
8	formation depth	> 800	-	-	2377	2387
9	Gravity Stablized	It slow the process	-	-	-	-
10	Oil Gravity	> 30	-	-	-	-
11	OOIP	Higher the best	145.2	98.4	51.2	92.8

APPENDIX B

Details of Shortlisted Malaysian Reservoirs for LOAI

Required Parameter	Criteria Developed	Tapis J Reservoirs	Tabu I Reservoirs	Dulang Reservoirs
Current Reservoir Pressure (psi)	1200-2500	2100 psia	1500 psia	1400 psia
Present Reservoir Temperature (^oC)	> 100	119	98	101
Oil Saturation (So) %	> 30%	33%	40%	52.20%
Water Saturation (Sw) %	< 60%	67%	60%	–
Pay Thickness (m)	> 10	50	50	28
Porosity (%)	> 20%	17%	18%	25%
Maximum Kv/Kh	0.4	0.1	0.1	0.32
Dip (Degree)	> 7	2	2	7
Formation Depth(m)	> 800	1800m TVDSS	1700m TVDSS	1229m TVDSS
Homogeneity	Preferred	Heterogeneous	Heterogeneous	Heterogamous
Gravity Stabilized	It slow the process	Yes	Yes	No
Oil Gravity ^{o}API	> 30	45	44	37
Sec Recovery (%)	20	38	19	18

APPENDIX C

Oil Composition of Dulang E12 -14 Reservoirs (Aidil, 2006)

Test	Wt%
C1	0
C2	0
C3	0.01
C4	0.04
C5	0.1
C6	0.27
C7	0.92
C8	2.71
C9	3.67
C10	4.02
C11	4.11
C12	4.48
C13	6.45
C14	6.64
C15	6.61
C16	5.19
C17	4.79
C18	7.25
C19	4.11
C20	3.34
C21	3.18
C22	3.09
C23	3.03
C24	2.9
C25	3.07
C26	2.83
C27	2.83
C28	2.56
C29	2.58
C30	2.04
C31	1.96
C32	1.47
C33	1.41
C34	0.75
C35	0.54
C36	0.36
C37	0.15
C38	0.12
Total	100

APPENDIX D

Input Values of Reservoir Parameter in PRIze Software

Parameter	Value
Depth:	1290 m
Formation Type:	Sandstone
Clay Content:	None
Reservoir Temperature:	101 ° C
Water Hardness:	300 PPM
Water Salinity:	40000 PPM
Initial Pressure:	12382.98 kPa
Bubble Point Press (BPP):	12196.825 kPa
Current Pressure:	9652.65 kPa
Solution Gas Oil Ratio:	100(st)m^3/m^3
Oil Density (surface):	840 kg/m^3
Dead Oil Visc. (surface):	2 mPa*s
Live Oil Visc. (at BPP):	0.98 mPa*s
Fracturing:	No
Horizontal Permeability:	100 md
Vertical Permeability:	32 md
Dykstra-Parsons Coeff.:	0.72
DIP (non-reef resv):	7 °
Active Water Drive:	No
Bottom Water:	Local
Secondary Mechanism:	Waterflood
Secondary Inj Rate:	1589 m^3/day(pool)
No of Product Wells:	3
No of Inject Wells:	4
No of Shut In Wells:	0
Current Mech Oil Prod:	8000 m^3/yr
Water Oil Ratio:	8.14 ratio
Producing Gas Oil Ratio:	500(st)m^3/m^3
Gross Pay Thickness:	20 m
Net Pay Thickness:	13 m
Porosity:	0.265 fraction
Connate Water Saturation:	0.47 fraction
Oil Volume Factor:	1.201
Original Oil In Place:	4586060 m^3
Cumulative Produced Oil:	1001170 m^3
Remaining Recov. Reserves:	1500000 m^3
Total Recov. Reserves:	2501170 m^3
Oil Relative Permeability end point *:	0.8 fraction
Residual Oil Saturation:	0.14 fraction

APPENDIX E

Calculated Parameters for E12-14 Reservoir in PRIze

Table E1: Calculated Parameters for E12-14 Reservoir in Immiscible Nitrogen with WAG

Parameter	Value
Water viscosity (mPa*s)	0.279
Remaining recoverable reserves (m^3)	1.50E+06
Residual oil sat g (fraction)	0.112
Residual gas sat (fraction)	0.139
Current oil sat (fraction)	0.4
Dykstra parsons coefficient	0.822
Gas viscosity (mPa*s)	0.024
N_2 gas compressibility	1.068
Pore volume	1.10E+06
Production pressure (kPa)	2147.7
Injection pressure (kPa)	23220
Injection rate water (m^3/day)	1510.26
Oil volume factor at BPP	1.201
Oil viscosity at BPP (mPa*s)	0.98
Residual oil sat (fraction)	0.112
Residual oil sat (fraction)	0.14
Water end point relative permeability	0.2
Connate water saturation (fraction)	0.47
Water oil ratio	8.14
Gas viscosity (mPa*s)	0.024
Mobility oil bank	0.467
Years WAG injection	8.282
Years water injection	14.013
Chase water velocity	6.849
Gas water velocity	2.861
Oil bank velocity	2.861
Total incremental oil (m^3)	78186.852
Duration (years)	15
Percent current mechanism OOIP produced (%)	1.365
Percent IOR OOIP produced (%)	17.437
IOR ultimate recovery (%)	39.268

APPENDIX E (Continued)

Table E2 Calculated Parameters for E12-14 Reservoir in Immiscible Nitrogen Gas Injection without WAG

Parameter	**Value**
Water viscosity (mPa*s)	0.279
Remaining recoverable reserves (m^3)	1.50E+06
Oil density surface condition (kg/ m^3)	840
Oil viscosity at BPP (mPa*s)	0.98
Oil volume factor at BPP	1.201
Current reservoir pressure (KPa)	9652.65
Reservoir temperature (° C.)	101
Porosity (fraction)	0.265
Connate water saturation (fraction)	0.47
Dykstra parsons coefficient	0.72
Residual oil saturation g (fraction)	0.098
Dykstra parsons coefficient	0.822
Gas viscosity (mPa*s)	0.024
N_2 gas compressibility z	1.068
Pore volume	1.10E+06
Production pressure (KPa)	2147.7
Injection pressure (KPa)	23220
Gas volume factor (m^3/sm^3)	0.009
Injection rate (solv) (m^3/day)	37257.246
Mobility ratio	41.525
Years gas injection	2.849
Total incremental oil (m^3)	35124.645
Percent IOR OOIP produced (%)	7.675
IOR ultimate recovery (%)	29.506

APPENDIX E (Continued)

Table E3 Calculated Parameters for E12-14 Reservoir in Immiscible Flue Gas Injection with WAG

Parameter	**Value**
Water viscosity (mPa*s)	0.279
Remaining recoverable reserves (m^3)	1.50E+06
Residual oil sat g (fraction)	0.112
Residual gas sat (fraction)	0.139
Current oil sat (fraction)	0.4
Dykstra parsons coefficient	0.822
Gas viscosity (mPa*s)	0.024
N_2 gas compressibility	1.068
Pore volume	1.10E+06
Production pressure (kPa)	2147.7
Injection pressure (kPa)	23220
Injection rate water (m^3/day)	1510.26
Oil volume factor at BPP	1.201
Oil viscosity at BPP (mPa*s)	0.98
Residual oil sat (fraction)	0.112
Residual oil sat (fraction)	0.14
Water end point relative permeability	0.2
Connate water saturation (fraction)	0.47
Water oil ratio	8.14
Gas viscosity (mPa*s)	0.024
Mobility oil bank	0.467
Years WAG injection	8.282
Years water injection	14.013
Chase water velocity	6.849
Gas water velocity	2.861
Oil bank velocity	2.861
Total incremental oil (m^3)	78186.852
Duration (years)	15
Percent current mechanism OOIP produced (%)	1.365
Percent IOR OOIP produced (%)	17.437
IOR ultimate recovery (%)	39.268

APPENDIX E (Continued)

Table E4 Calculated Parameters for E12-14 Reservoir in Immiscible Flue Gas Injection without WAG

Parameter	**Value**
Water viscosity (mPa*s)	0.279
Remaining recoverable reserves (m^3)	1.50E+06
Oil density surface condition (kg/ m^3)	840
Oil viscosity at BPP (mPa*s)	0.98
Oil volume factor at BPP	1.201
Current reservoir pressure (KPa)	9652.65
Reservoir temperature (° C.)	101
Porosity (fraction)	0.265
Connate water saturation (fraction)	0.47
Dykstra parsons coefficient	0.72
Residual oil saturation g (fraction)	0.098
Dykstra parsons coefficient	0.822
Gas viscosity (mPa*s)	0.024
N_2 gas compressibility z	1.068
Pore volume	1.10E+06
Production pressure (KPa)	2147.7
Injection pressure (KPa)	23220
Gas volume factor (m^3/sm^3)	0.009
Injection rate (solv) (m^3/day)	37257.246
Mobility ratio	41.525
Years gas injection	2.849
Total incremental oil (m^3)	35124.645
Percent IOR OOIP produced (%)	7.675
IOR ultimate recovery (%)	29.506

APPENDIX F

Yearly Basis Calculation by PRIze

Table F1: Yearly Basis Calculation by PRIze for Immiscible nitrogen with WAG effect.

Number of Years	Improved oil recovery, cumulative incremental oil production [Mstb]	Cumulative Gas produced [% PV]
0	0	0
1	24422.54	1
2	34901.29	2.2
3	42622.25	3.5
4	48963.79	4.8
5	54444.61	6.1
6	59329.14	7.5
7	63773.79	8.8
8	67876.69	10.2
9	71347.34	11
10	75339.98	11.1
11	76068.88	11.1
12	76820.27	11.1
13	77589.6	11.1
14	78374.38	11.2
15	78186.85	11.2

APPENDIX F (Continued)

Table F1: Yearly Basis Calculation by PRIze for Immiscible nitrogen with WAG effect.

Number of Years	Improved oil recovery, cumulative incremental oil	Cumulative Gas produced [% PV]
0	0	0
1	24422.54	1
2	34901.29	2.2
3	42622.25	3.5
4	48963.79	4.8
5	54444.61	6.1
6	59329.14	7.5
7	63773.79	8.8
8	67876.69	10.2
9	71347.34	11
10	75339.98	11.1
11	76068.88	11.1
12	76820.27	11.1
13	77589.6	11.1
14	78374.38	11.2
15	78186.85	11.2

APPENDIX G

Table G1: Details of the Configurations in Optimization Study

Configuration Number	Oil Producer Wells	Gas Injector Wells	Isolated or Shut Well	Water Injector Wells
1	5S, 16S and 2L	10G and 14L	--	29L and 31 L
2	5S and 16S	2L, 10G and 14L	--	29L and 31 L
3	5S and 16S	10G and 14L	2L	29L and 31 L
4	5S and 2L	16S, 10G and 14L	--	29L and 31 L
5	5S and 2L	10G and 14L	16S	29L and 31 L
6	16S and 2L	5S, 10G and 14L	--	29L and 31 L
7	16S and 2L	10G and 14L	5S	29L and 31 L
8	2L	5S and 16S	10L and 14L	29L and 31 L