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Evaluation of Alkaline, Surfactant and Polymer Flooding for Enhanced Oil Recovery in the Norne E-segment Based on Applied Reservoir Simulation

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Master's Thesis in Reservoir Engineering
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Disclaimer

All views expressed in this project are mine and do not necessarily reflect the views of Statoil and the Norne license partners.

Abstract

The world needs energy – and over the short and medium term it is clear that much of our global energy consumption will come from fossil sources such as oil, gas and coal. With the current growing demand for oil led by major energy consuming countries such as China and India, securing new oil resources is a critical challenge for the oil industry. Each year, new production is needed to compensate the natural decline of existing wells, and the additional production required to satisfy the yearly demand for hydrocarbon energy that will represent approximately 9% of the worldwide total production. For this growth to be sustainable, a strong focus will have to be placed on finding new discoveries and/or optimizing oil production from current resources. The cost associated with the first option is significant. Therefore, reservoir management teams all over the world will have to cater for this demand mainly by maximizing hydrocarbon recovery factors through Enhanced Oil Recovery (EOR) processes. EOR consists of methods aimed at increasing ultimate oil recovery by injecting appropriate agents not normally present in the reservoir, such as chemicals, solvents, oxidizers and heat carriers in order to induce new mechanisms for displacing oil.

Chemical flooding is one of the most promising and broadly applied EOR processes which have enjoyed significant research and pilot testing during the 1980s with a significant revival in recent years. However, its commercial implementation has been facing several technical, operational and economic challenges. Chemical flooding is further subdivided into polymer flooding, surfactant flooding, alkaline flooding, miscellar flooding, alkaline-surfactant-polymer (ASP) flooding. ASP flooding is a form of chemical enhanced oil recovery (EOR) that can allow operators to extend reservoir pool life and extract incremental reserves currently inaccessible by conventional EOR techniques such as waterflooding. Three chemical inject in the ASP process which is synergistic.

In the ASP process, Surfactants are chemicals that used to reduce the interfacial tension between the involved fluids, making the immobile oil mobile. Alkali reduces adsorption of the surfactant on the rock surfaces and reacts with acids in the oil to create natural surfactant. Polymer improves the sweep efficiency.

By simulating ASP flooding for several cases, with different chemical concentrations, injection length, time of injection, current well optimization and new well placement, this report suggests a number of good alternatives. Simulations showed that the most effective method was not the most profitable.

From the simulation results and economic analysis, ASP flooding can be a good alternative for the Norne E-segment. But the margins are not significant, so fixed costs (such as equipment rental) will be of crucial importance.

Acknowledgements

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Chapter 1

Introduction

1.1 Introduction

New discoveries of conventional oil fields are declining while demand for oil is estimated to increase approximately 1.5% per year. Water flood is commonly used as an economic and effective method in secondary recovery after primary methods have been exhausted. Many of sandstone or carbonate reservoirs have low primary and waterflood recovery due to poor sweep efficiency as the result of bypassed or unswept oil. In general, water flood still leaves 50-70% oil in the formation and oil cannot be further removed without the use of chemical, thermal or gas injection processes.

Chemical flooding was, up to 2000's, less common EOR method than thermal & gas but now, huge projects are initiated or revisited. As the use of chemical flooding spreads to new reservoirs, especially oil-wet and mixed-wet reservoirs, the importance of surfactant-based wettability alteration will become important. There are also many oil-wet and mixed-wet naturally fractured reservoirs with significant amounts of remaining oil in place. Middle East presents a significant opportunity to implement enhanced recovery methods on the fields with large remaining conventional oil resources and for future production growth.

Chemical processes have been shown to be effective in recovering unswept oil by improving the mobility ratio (polymer flooding), or by reducing residual oil saturation (micellar or surfactant polymer flooding (SP), alkaline/surfactant/polymer (ASP)). Parameters such as mineralogy, permeability and viscosity ranges, temperature, salinity, have an impact on the feasibility of the process and also on the economics.

Polymer flooding is the most important EOR process, improving the water-oil mobility ratio. The polymers act basically increasing the viscosity of the injected water and reducing the swept zone permeability, allowing an increase in the vertical and areal sweep efficiency of the water injection, and, consequently, increasing the oil recovery. The polymer is almost always hydrolyzed polyacrylamide (HPAM). Economic and technical successes are reported for polymer floods in both sandstones and carbonates.

Processes using surfactant are classified as SP (Surfactant-Polymer), MP (Micellar-Polymer) and ASP (Alkaline Surfactant Polymer). Basically, the method consists in injecting the surface-active agent (surfactant) to reduce the interfacial tension and mobilize the residual oil saturation The addition of an alkaline agent increases the process efficiency by decreasing the surfactant retention. Additional surface active agents may be produced in the case of acidic crude.

The ASP method can be applied as an improved waterflooding with large slug of low surfactant concentration. Chemicals used in the ASP flood are an alkali (NaOH or Na2CO3), a surfactant and a polymer. The alkali washes residual oil from the reservoir mainly by reducing interfacial tension between the oil and the water. The surfactant is mixed with the alkali and enhances the ability of the alkaline to lower interfacial tension. The polymer injected after the AS slug is added to improve sweep efficiency. Some of ASP floods in the world were commercially successful; however, the projects were generally small. Difficulties in applying large reservoir scale surfactant flooding are due to the evaluation of potential recoveries mainly because reservoir modeling is not available yet. ASP flooding is an important technology for enhanced oil recovery. The production rates of the 100 largest oilfields in the world are all declining from plateau production. The challenge is to develop EOR methods that ensure an economical tail end production from these fields. Field practice has shown that more than 20% OOIP incremental recoveries can be obtained with the ASP process. Better ASP systems need to be developed with more cost-effective surfactants in weak alkaline systems [15].

1.2 Norne Field

Norne Field located 200 km from Norwegian coast line in the geological blocks 6608/10 and 6508/1 in the Norwegian Sea. Structure size is approximately 3x9 km and sea depth in the area is 380 m whereas reservoir depth is 2500 - 2700 m. It was discovered in December 1991. The production of oil and gas started November 1997 and 2001 respectively. Reservoir is operated by Statoil Hydro Petroleum AS (63.95%) and partners: Petoro (24.55%) and Eni Norge AS (11.5%). Data is provided through Integrated Operations in the Petroleum Industry (IO). The field parameters have quite good quality. Porosity is in the range of 25-30%, net-to-gross ratio 0.7 - 1 and permeability varies from 20 to 25000 mD. Reservoir thickness changes from 120 m to 260 m from south to north [1].

Figure 1: The Norweigian Continental Shelf.

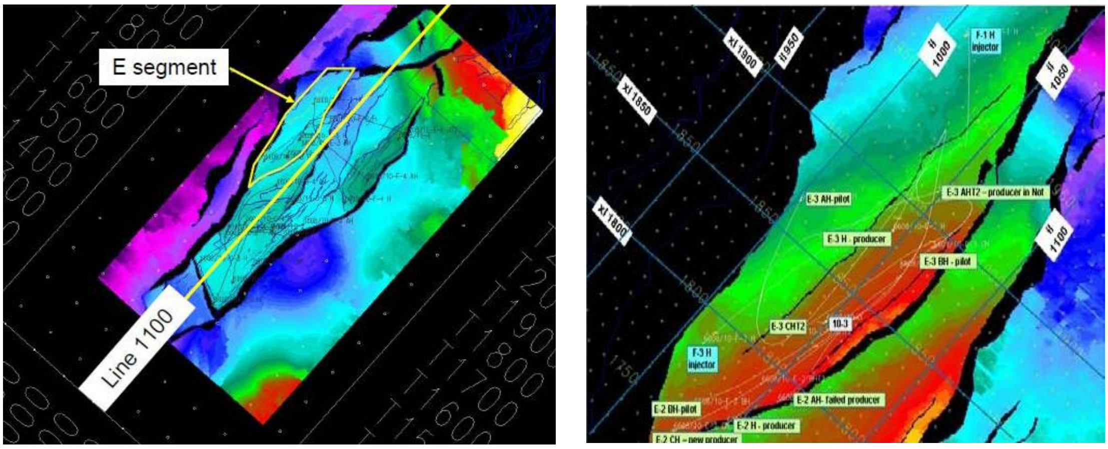


Figure 2: Map of Norne E-segment.

As capillary forces limit the oil recovery in a reservoir to approximately 10 %, enhanced oil recovery (EOR) methods are used to increase recovery to 30–70 %. The search of new EOR is catalyzed by the oil price. As the North Sea oil price has increased from 18 to 90 USD/bbl from 1998 to 2012, there has been an increase in search for improvement of EOR methods. Because of high expenditures of EOR (chemical cost, transport, pre- and post treating for environmental concerns), the oil price has to be high enough for EOR to be profitable. Some of the Enhanced Oil Recovery technologies that have been conducted in the North Sea from 1975 to 2005 include HC gas injection, Water Alternating Gas injection (WAG), Simultaneous Water Alternating Gas Injection (SWAG), Foam Assisted Water Alternating Gas (FAWAG) and Microbial Enhanced Oil Recovery (MEOR) [42]. By considering this entire ASP flooding could be the best EOR method for Norne field.

1.3 Goals to achieve

This thesis is an expansion of the work done in the reservoir specialization project. This work focuses on possibility of increasing oil recovery in the Norne Field’s E Segment located in the Norwegian Continental Shelf by the use of ASP flooding, which is a chemical method of Enhanced Oil Recovery (EOR). Therefore, the report consists of two parts: theory and application. The theory part contains an insight into alkaline-surfactant-polymer flooding, why it’s done and how it can be done, followed up by a detailed description of the Norne field. The application part consists of the following subjects:

- EOR techniques
- Chemistry of alkali, surfactant and polymer
- General knowledge on ASP flooding
- Build a synthetic model and analysis for different scenario
- Effect of Continuous ASP flooding
- Effect of injecting slug injection followed by water.
- Amount of ASP needed
- Timing of ASP flooding

- Optimization of production and injection
- Effect of new well
- Economic Evaluation
- Uncertainty Analysis

1.4 Outline of the Thesis

This work contains 9 chapters in total; chapter 2 introduces and describes the Enhance Oil Recovery (EOR). Chapter 3 describes the details chemistry of alkali, surfactant and polymer.

Chapter 4 describes the Norne field in details and the major sections in this chapter gives the general field information, talks about the field geology, main processing system, the recoverable reserves, drainage strategy, Norne E-segment and reservoir simulation model which is made by using Eclipse 100.

Chapter 5 describes the Enhance Oil Recovery at the Norne E-segment and Chapter 6 briefly describe the ASP flooding with simulation model and keyword required for activation in Eclipse 100.

Chapter 7 deals with the results of synthetic model and ASP model in the Norne E-segment. Here impact of ASP flooding in the Norne E-segment by considering different scenario is briefly discussed and most optimum solution is taken into consideration.

In Chapter 8 economic evaluation discussed briefly and finally the conclusions and uncertainties are summarized in chapter 9.

Chapter 2

Techniques and Theory

2.1 Enhanced Oil Recovery

Oil recovery is traditionally subdivided into three stages: primary, Secondary, and tertiary. Many a time, reservoir production operations are not conducted in the specified order that tertiary process may be applied at secondary stage instead of waterflooo ding. Thus, the term “tertiary recovery” fell into disfavour in petroleum engineering literature and the designation of “enhanced oil recovery” (EOR) became more accepted. Another descriptive designation normally used is “improve oil recovery” (IOR), which includes EOR but also a broader range of activities, like reservoir characterization, improved reservoir management, and infill drilling [11]. The Norwegian Petroleum Directorate (1993) defined IOR as: “Actual measures resulting in an increased oil recovery factor from a reservoir as compared with the expected value at a certain reference point in time.”

2.1.1 Primary recovery

Primary oil recovery refers to simple pressure depletion where only reservoir energy, through different mechanisms, is used to extract the oil. These natural energy sources are; solution-gas drive, gas-cap drive, natural water drive, fluid and rock expansion, and gravity drainage. The particular mechanism of lifting oil to the surface, once it is in the wellbore is not a factor in the classification scheme [11].The recovery factor after this depletion period is usually low, and normally, only 5-30 % of the original oil in place (OOIP) can be produced [43].

2.1.2 Secondary recovery

Secondary recovery is normally implemented when the reservoir natural energies are not sufficient to produce hydrocarbon. This involves injection of water or gas, either for pressure support or for displacement of oil towards the production wells. About 30-70 % of OOIP is left unproduced after the process [43]. Gas injection is either into a gas cap for pressure maintenance and gas-cap expansion or into oil column wells. In this process, oil is displaced immiscibly according to relative permeability and volumetric sweep out considerations [11].

2.1.3 Tertiary recovery/EOR processes

Unfavorable reservoir characteristics such as heterogeneous rock properties (fractures, layers with large permeability contrasts, impermeable layers), unfavourable wettability conditions, or capillary trapped and bypassed oil, results in areas of the reservoir not flooded by the injected fluid. Approximately 30-70 % of OOIP in the reservoir is left after these conventional secondary oil recovery processes [41,43]. It is the residual oil that is left in the reservoir after the secondary recovery that is the target for EOR processes. Thus, the purpose of initiating tertiary oil recovery processes is to extend lifetime of oil reservoirs which are approaching economical limit by support of water flooding or other conventional methods [45] .Tertiary processes use miscible gases, chemicals, and/or thermal energy to mobilize and displace additional oil after the secondary recovery processes become uneconomical [11]. EOR is defined by Baviere as: "*EOR consists of methods aimed at increasing ultimate oil recovery by injecting appropriate agents not normally present in the reservoir, such as chemicals, solvents, oxidizers and heat carriers in order to induce new mechanisms for displacing oil"* [43]. Zhang also proposed the definition of EOR as any method, which is aiming to improve the fluid flow by means of changing physical property of the reservoir rock or fluids, including wettability, interfacial tension, fluid density, viscosity, permeability, porosity, pore size, etc [44].

2.2 Basic Mechanisms of Enhanced Oil Recovery

The main objective of all methods of EOR is to increase the volumetric sweep efficiency and to enhance the displacement efficiency, as compared to an ordinary waterflooding. One mechanism is aimed towards the increase in volumetric sweep by reducing the mobility ratio and the other mechanism is targeted to the reduction of the amount of oil trapped due to the capillary forces [13].

2.2.1 Mobility Ratio

Mobility ratio is defined in Equation 1 as the ratio between mobility of displacing fluid and displaced fluid where λ is the mobility.

$$M = \frac{\lambda_{displacing}}{\lambda_{displaced}} \tag{1}$$

Mobility of a fluid is a measure of how easy the fluid flows in a porous media. It is defined as ratio of permeability and viscosity (Equation 2) where k is the effective permeability, μ is the fluid viscosity and i could be oil, water or gas.

Where mobility of a fluid can be shown as:

$$\lambda = \frac{K_i}{\mu_i} \tag{2}$$

In the most efficient displacement, *M is* smaller than 1. It is possible to improve the mobility ratio by lowering the viscosity of the displaced fluid, increasing the viscosity of displaced fluid, increasing the effective permeability to oil or decreasing the effective permeability to the displacing fluid.

2.2.2 Capillary Forces

The capillary forces have great influence on oil recovery efficiency, but the influence differs fundamentally for non-fractured and fractured reservoirs. Strong capillary forces during waterflooding will trap oil and cause relatively high residual oil saturation in a non-fractured reservoir. Reduction in the oil-water IFT to remobilizing residual oil is in this case the preferred conditions. In fractured reservoirs, spontaneous imbibition of water due to strong capillary forces is regarded as an important and necessary mechanism to attain high displacement efficiency[12].

Capillary pressure is defined as the pressure of the non-wetting fluid minus the pressure of the wetting fluid. For oil/water systems, water is regarded as a wetting phase. For oil/water systems, water is regarded as a wetting phase and expressed by the Equation 3 where P_c is the capillary pressure, P_{NW} is the Pressure of non-wetting phase at interface (oil) and P_W is the pressure of wetting phase at interface (water) [11].

$$P_c = P_o - P_w = P_{NW} - P_W \qquad (3)$$

Capillary Number (Nc) is a dimensionless ratio between the viscous forces and the capillary forces (Equation 4). Where υ is the Darcy's velocity, μ is the viscosity of the displacing fluid while σ is the interfacial tension between the displaced and the displacing fluid; k is the effective permeability to the displaced fluid and $\Delta P/L$ is the pressure gradient [11]. By reducing the interfacial tension between the displacing and displaced fluids the effect of capillary forces is lowered, yielding a lower residual oil saturation and hence higher ultimate oil recovery [13].

$$N_C = \frac{\mu v}{\sigma} = \frac{k\Delta P}{\sigma L} \qquad (4)$$

Figure 3 shows the fingering effect in to the oil bank in case of unfavourable conditions that is when M is greater 1.

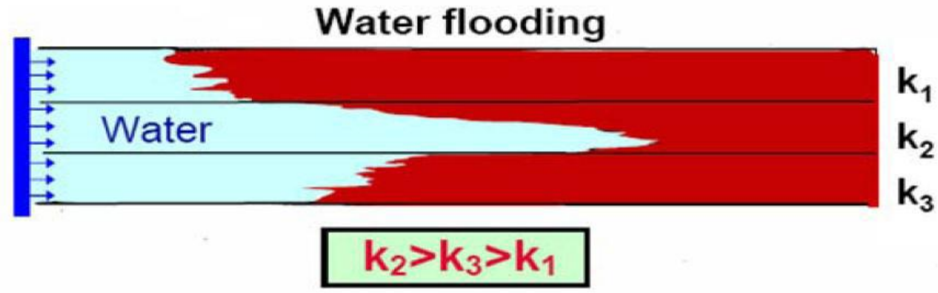


Figure 3: Water fingering for unfavourable mobility ratio (M>1)

2.3 Classification of EOR Processes

EOR technologies can be classified in different manners: depending upon the type of agents used EOR economics, etc. [13]. A broad classification is basically thermal and non-thermal where thermal methods are applied to heavy oil reservoirs and non-thermal applied to light oils (Figure 4). The three major types of enhanced oil recovery operations are chemical flooding, gas injection and thermal recovery. Some EOR methods described in the below part of this chapter.

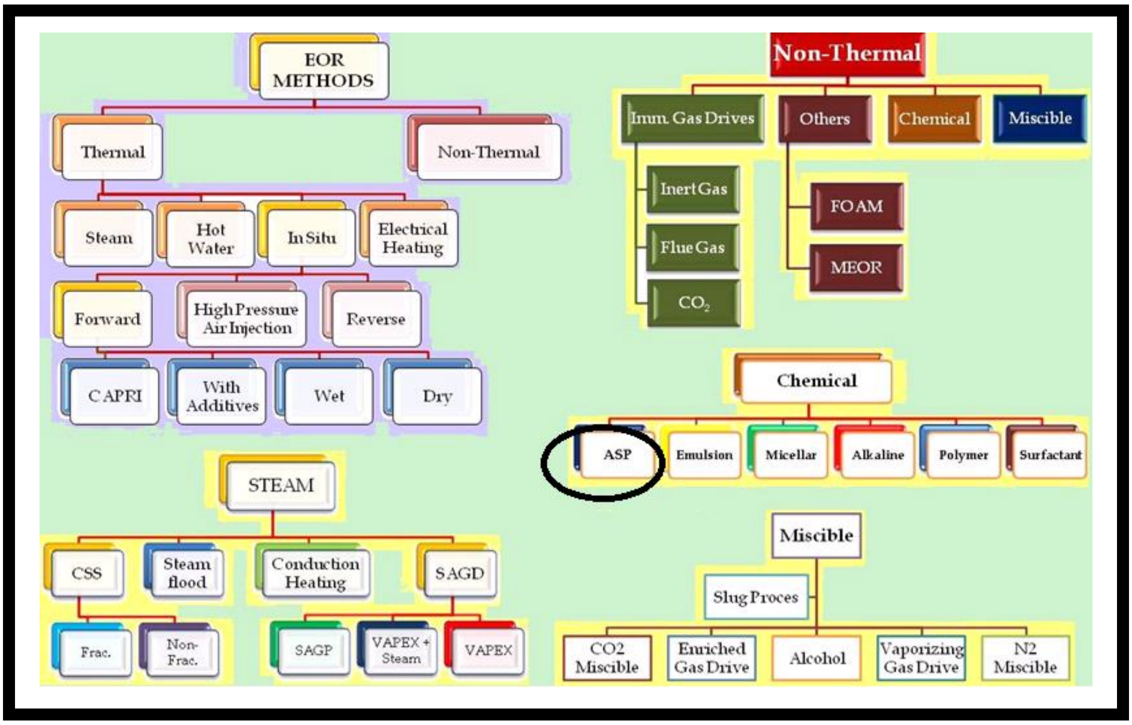


Figure 4: Classifications of EOR Processes.

2.3.1 Chemical flooding

Chemical flooding, an EOR processes involve injection of specific liquid chemicals such as surfactants and alkaline agents (Figure 5). They also require phase-behaviour properties that results in decrease in interfacial tension (IFT) between the displacing liquid and oil. The process has the potential to increase both microscopic and macroscopic displacement efficiency due presence of polymer mobility buffer [12]. Chemical flooding is further subdivided into polymer flooding, surfactant flooding, alkaline flooding, miscellar flooding, alkaline-surfactant-polymer (ASP) flooding.

Surfactant Flooding

Surfactant flooding represents one of the most promising methods in EOR, to recover the capillary trapped residual oil after waterflooding. These microscopic oil droplets usually constitute more than half the residual oil. By the injection of surfactant solution, the residual oil can be mobilized through a strong reduction in the interfacial tension (IFT) between oil and water [13]. The addition of an alkaline agent increases the process efficiency by decreasing the surfactant retention. Additional surface active agents may be produced in the case of acidic crude [15].

Figure 5: Schematic of Chemical Flooding.

Polymer Flooding

Polymer flooding is an EOR method where polymer is added to the injected water results in increase in the viscosity of water and reduction in relative permeability to water (displacing phase). Polymer flooding will be favorable in reservoirs where the oil viscosity is high, or in reservoirs that are heterogeneous, with the oil-bearing layers at different permeabilities (Stratified reservoirs). Some of the North Sea reservoirs with a high permeability contrast are good candidates for polymer flood [13].

Alkaline Flooding

Alkaline flooding is a very complex process. Alkaline flooding improves oil recovery by using *in situ* surfactants produced from the reaction of alkali and the natural organic acids. There are three possible mechanisms of alkaline flooding to improve oil recovery which include-dispersion and entrainment of oil, wettability reversal, emulsification and entrapment of oil as well. It is pointed out that each mechanism worked under different injection conditions with respect to oil, formation rock, and injection water properties, and, therefore, each process should be designed to improve oil recovery in a somewhat different manner. Alkaline flooding has been extensively studied in EOR for conventional oils, including numerous laboratory experiments and some field tests. For heavy oils, the investigations on EOR by alkaline flooding are very limited due to the adverse mobility ratio between the water and oil phases [21].Alkaline flooding began with the injection of sodium carbonate solution in Bradford area of Pennsylvania in 1925 and since then, work on this process has continued.

ASP Flooding

This process, as the name suggests, is a combination of the three processes namely alkaline, surfactant and polymer flooding in which the three slugs are used in sequence. Alternatively, the three fluids could be mixed together and injected as a single slug. The objective of the ASP flooding process is to reduce the amount of chemical consumed per unit volume of oil required [52] and invariable a reduction in cost.

2.3.2 Gas Injection

The concept of injecting gases into reservoirs to improve oil recovery is an old theory. While the thermal EOR process and its variations are aimed mainly at recovering heavy oils by lowering their viscosity to enable their flow, the chemical and miscible gas processes targeted the light and medium gravity crude oil by lowering the interfacial tension between the inject fluid and the crude oil to minimize the trapping oil in the rock pores by capillary or surface forces [48].

Carbon Dioxide Injection

Miscible flooding with carbon dioxide or hydrocarbon solvents is considered one of the most effective enhanced oil recovery processes applicable to light to medium oil reservoirs. CO2 has a viscosity similar to hydrocarbon miscible solvents. Both types of solvents affect the volumetric sweep-out because of unfavorable viscosity ratio. However, CO2 density is similar to that of oil. Therefore, CO2 floods minimize gravity segregation compared with the hydrocarbon solvents. Miscible displacement between crude oil and CO2 is caused by the extraction of hydrocarbon fractions, as well as the heavier gasoline and has oil fractions, are vaporized into the CO2 front. Consequently, vaporizing-gas drive miscibility with CO2 can occur with few or no C2 to C6 components present in the crude oil [50]. Figure 6 shows the schematic of carbon dioxide injection.

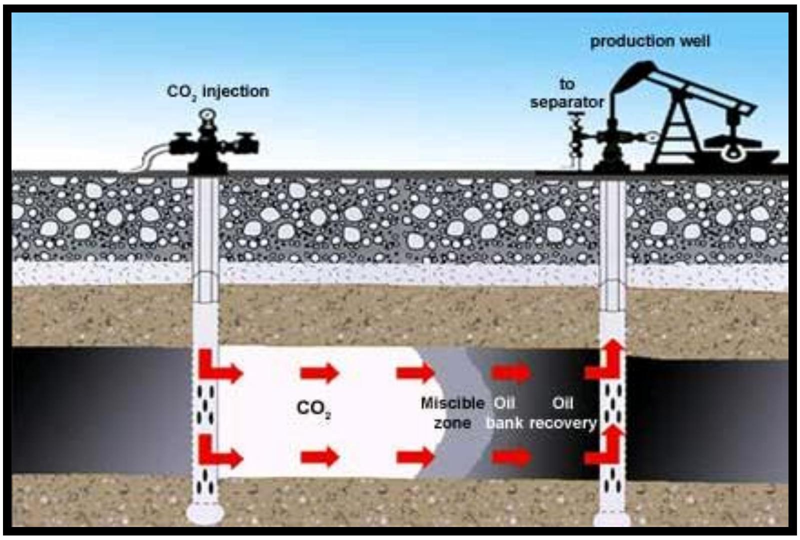


Figure 6: Carbon Dioxide Injection.

2.3.3 Thermal Recovery

In thermal recovery methods, hot fluids, such as steam or hot water, are injected into hydrocarbon to reduce the retaining forces responsible for oil entrapment and enhance recovery efficiency [46]. This is typical for oil reservoirs with very high viscosities and low API gravities, otherwise known as heavy oil reservoirs. These heavy oil reservoirs are typical in Indonesia, Canada, Venezuela and USA. Thermal recovery is subdivided into the following;

- ➢ Steam-based thermal recovery process
    - ▪ Cyclic Steam Stimulation (CSS)
    - ▪ Steam Assisted Gravity Drainage (SAGD)
- ➢ In Situ Combustion
    - ▪ Toe-to-Heel Air Injection (THAI)
- ➢ Solvent-based Tertiary Resources
    - ▪ VAPEX
    - ▪ Thermal Solvent
- ➢ Solvent-based Tertiary Resources
    - ▪ Hybrid (Steam-solvent) and co-injection processes

Thermal recovery comprises the techniques of steam flooding, cyclic steam stimulation and in situ combustion. The alteration of oil viscosity, favorable phase behavior, and in some cases, chemical reaction, are the primary mechanisms leading to improve oil recovery. Some common types of thermal recovery used in the oil industries are discussed below:

Cyclic Steam Stimulation (CSS)

Cyclic steam stimulation (Figure 7), also known as the “huff-and-puff” method, is sometimes applied to heavy-oil reservoirs to boost recovery during the primary production phase. Steam is injected into the reservoir, and then the well is shut in to allow the steam to heat the producing formation around the well. After a sufficient time, generally a week or two, the injection wells are placed back in production until the heat is dissipated with the produced fluids. This cycle may be repeated until the response becomes marginal because of declining natural reservoir pressure and increased water production. At this stage a continuous steamflood is usually initiated to continue the heating and thinning of the oil and to replace declining reservoir pressure so that production may continue.

Steam-Assisted Gravity Drainage (SAGD)

Steam Assisted Gravity Drainage (SAGD), illustrated in Figure 8, is an enhanced oil recovery method that is used to extract heavy oil or bitumen from underground. It is an advanced form of steam flooding which involves the drilling of two in the reservoir with one well located a few meters above the other. Low pressure steam is flowing through the upper well as heat source to heat the oil and reduce its viscosity, enabling the oil to become mobile and flow into the lower well for production [22].

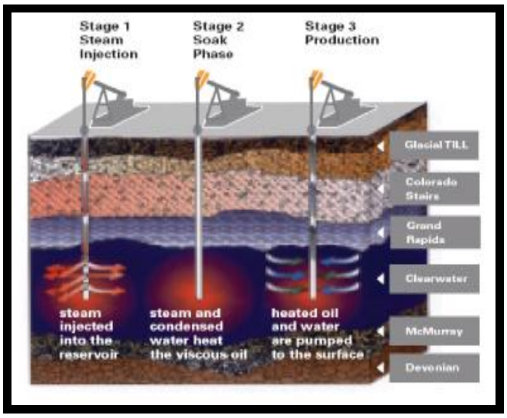


Figure 7: Cyclic steam injection (CSS).

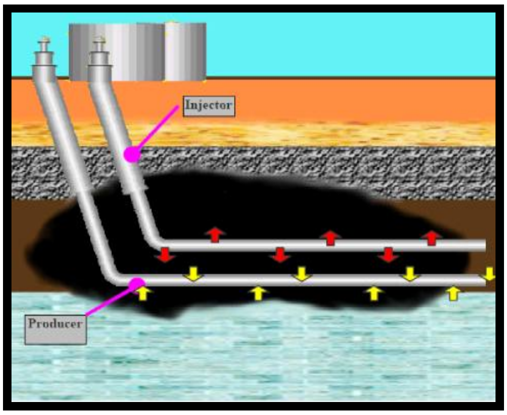


Figure 8: Steam-Assisted Gravity Drainage.

Toe to Heel Air Injection (THAI)

It is an in-situ combustion method for producing heavy oil. In the *Toe to Heel Air Injection (THAI)* technique (Figure 9), the first fire flooding starts from a vertical well, while the oil is produced from a horizontal well having its toe in close proximity to the vertical air-injection well. This production method is a modification of conventional fire flooding techniques in which the flame front from a vertical well pushes the oil to be produced from another vertical well.

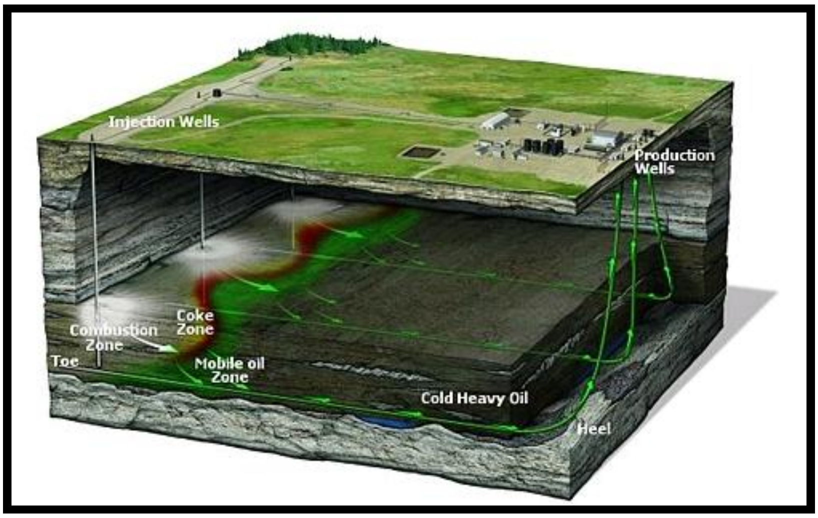


Figure 9: Toe to Heel Air Injection (THAI)

2.4 EOR Screening

The world petroleum industry has extensive experience in the application of EOR methods. A variety of conditions, both geological and geographical, require systematic analysis of the applicability of EOR processes under varying reservoir conditions. Screening EOR techniques has various applications:

- Identifying EOR methods that are technically feasible for given reservoir conditions. This implies defining *ranges* for some critical reservoir/fluid parameters.
- Predicting EOR reserve potential for a given field. Combined with the result of a simple economic calculation it enables determining if there exists a realistic possibility for any field application.
- Predicting EOR reserve potential for a number of fields.
- Evaluating the economy of various EOR techniques.
- Uncertainty analysis by relating the uncertainty in EOR production to that of the critical reservoir/fluid parameters.

A feasibility study for screening potential EOR methods should be done at early stage of a project design. It improves the timing of important planning decisions [13].

Chapter 3

Surfactant, Polymer and Alkali

3.1 Overview of Surfactant

A shortened form of "surface-active agent", a surfactant is a chemical that stabilizes mixtures of oil and water by reducing the surface tension at the interface between the oil and water molecules. Because water and oil do not dissolve in each other a surfactant has to be added to the mixture to keep it from separating into layers [4]. A surfactant or surface active agent is a substance that, when dissolved in water, gives a product the ability to remove dirt from surfaces such as the human skin, textiles, and other solids. Surfactants also use as an emulsifier in cosmetics; everyday life like soap, shampoo etc.; industry as pharmaceutical products, paints, textiles or plastics [26].

3.1.1 Types of Surfactant and Their Structure

Surfactants are usually organic compounds that are amphiphilic, meaning they contain both hydrophobic groups (*tails*) and hydrophilic groups (*heads*). Therefore, a surfactant molecule contains either a water insoluble or oil soluble component and a water soluble component. Depending on the nature of the hydrophilic group, surfactants are classified into four (anionic, cationic, zwitterionic and nonionic) groups [5].

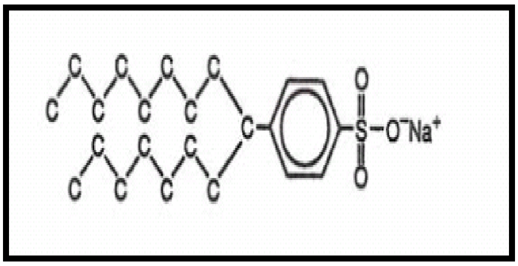


Figure 10 : Surfactant molecule.

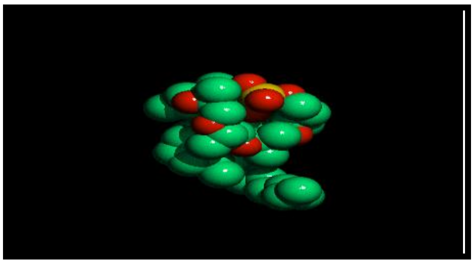


Figure 11: 3-D Plot of Sulfate.

The surface-active portion of anionic surfactants bears a negative charge, e.g. carboxylate (COO^{-}), sulfate (SO^{-4}) or sulfonate (SO^{-3}). Cationic surfactants have a hydrophilic part bears a positive charge. cetyl ammonium bromide ($C_{16}H_{33}N(CH_3)Br$) is an example of a cationic surfactant. When this surfactant dissolves in water, the positive charge will be on the N-atom. zwitterionic surfactants have both a positive and a negative charge, e.g. $RN^{+}H_2CH_2COO^{-}$ (Long chain amino acid), $C_{17}H_{37}NSO_3$ (alkyldimethylpropanesultaine). Nonionic surfactants bear no apparent ionic charge. However the hydrophilic part is soluble in water because of polar groups. These groups can be hydroxyl (OH) or polyethylen oxides (OCH2CH2)*n*[26]. Examples of high performance surfactants are N67-7PO-Sulfate and N67-7PO-Sulfonate. Figure 10 shows a structure of a surfactant molecule and Figure 11 shows the schematic of sulfate.

3.1.2 Principles of surfactants

Surfactants have several functions. They must first reduce the interfacial tension so the oil and water can create emulsion and flow in continuous phases [37]. Surfactant molecules will diffuse in water and adsorb at interfaces between air and water or at the interface between oil and water, in the case where water is mixed with oil. The insoluble hydrophobic group may extend out of the bulk water phase, into the air or into the oil phase, while the water soluble head group remains in the water phase. This alignment of surfactant molecules at the surface modifies the surface properties of water at the water/air or water/oil interface.

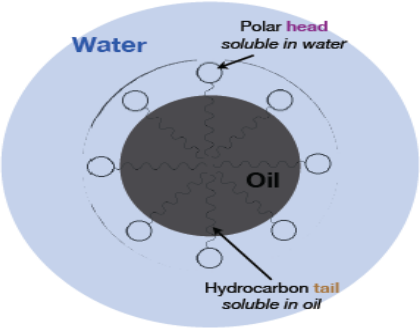


Figure 12: Principles of Surfactants.

Surfactants can be used to dissolve two immiscible fluids (e.g. oil and water) into each other. This is called an emulsion. To be able to do this, surfactants form micelles spontaneously water when the concentration of surfactants is high enough. A micelle can be spherical, cylindrical or a bilayer. The hydrophobic part dissolves in the oil phase, and the hydrophilic part dissolves in the water phase (Figure 12). The micelle acts like a barrier between the two phases so they never come in direct contact to each other. The surface tension between the two phases will decrease with increasing amounts of surfactants up to a critical micellar concentration (CMC). At CMC the maximum limit is obtained, and the surface tension will not change. The same happens to other properties, e.g. osmotic pressure and conductivity.

3.1.3 Mechanism

The aim of surfactant flooding is to recover the capillary-trapped residual oil after water flooding. By the injection of surfactant solution, the residual oil can be mobilized through a strong reduction in the interfacial tension (IFT) between oil and water. A typical plot of residual oil saturation as a function of N_C called the Capillary Desaturation Curve (CDC) is shown in Figure 13. From the figure it can be illustrates that a surfactant floods should perform best in a water-wet reservoir [13].

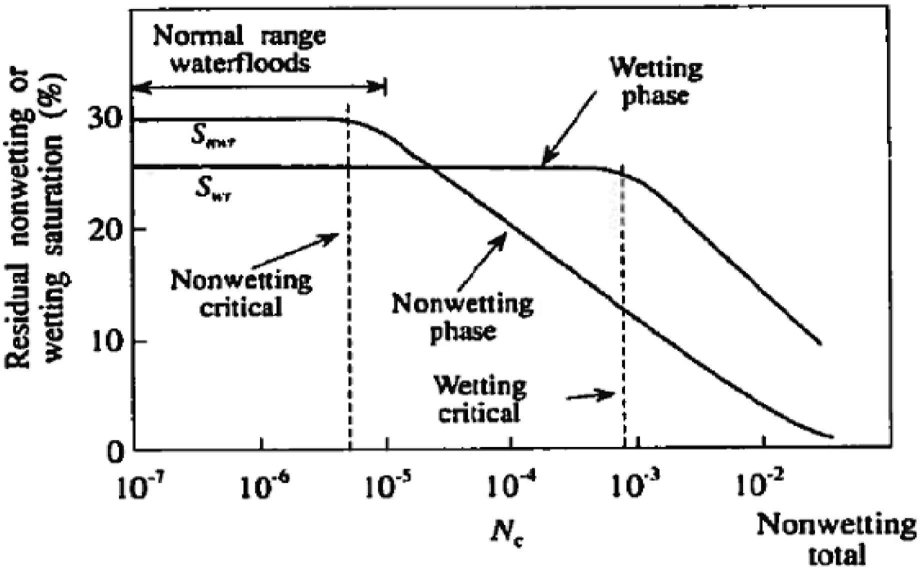


Figure 13: Schematic Capillary Desaturation Curve.

3.2 Overview of Polymer

The word ***polymer*** is derived from the Greek words *poly* means "many" and *meros* meaning "part". A polymer is a high-molecular-weight organic compound, natural or man-made, consisting of many repeating simpler chemical units or molecules called monomers. Therefore, polymers are large molecules whose molecular weight can range from the thousands to millions. Because of the extraordinary range of properties of polymeric materials, they play an essential and ubiquitous role in everyday life. This role ranges from familiar synthetic plastics and elastomers to natural biopolymers such as nucleic acids and proteins that are essential for life [6].

3.2.1 Types of Polymer Used for EOR and Their Structure

Polymers molecules are long chains of repeating units (monomers) linked by covalent bonds. There are two sets extensively used for enhancing oil recovery, namely *synthetic polymers* and *biopolymers*. The major field experience is with synthetic polymers. The most used polymer in field operations is *polyacrilamide*, *PAM* or *hydrolyzed polyacrilamide*, *HPAM* etc. These are polymers where the monomeric unit is acrylamide. The chemical structure of HPAM is shown in Figure 14.

Two biopolymers are used for EOR purposes, named *xanthan* and *seleroglucan*. Both have a helical, rodilike structure and are extremely pseudoplastic with high viscofying effect. They are formed from polymerization of saccaride molecules in fermentation processes.

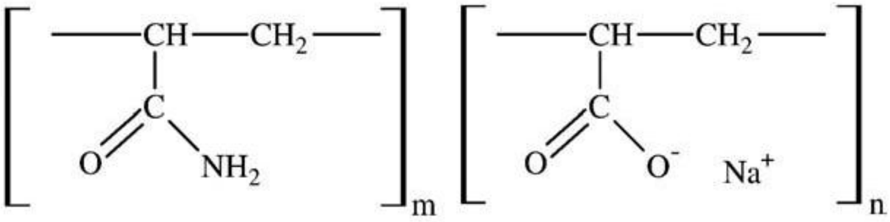


Figure 14: Structure of HPAM

3.2.2 Principles of polymer

Polymer solutions behave like Newtonian fluids at very low and at very high shear rates. However, at intermediate shear rates they behave as pseudo-plastics obeying the power-law of the dependency of their viscosity on the shear rate. An overall behavior of polymer solutions in a wide range of shear rates can be well described by the Carreau model which is shown by the Figure 15 where μ is the viscosity, μ_o is zero shear rate viscosity, μ_∞ is infinite shear rate viscosity, τ is relaxation constant, $\dot{\gamma}$ is shear rate and η is power law exponent. Carreau model explains the behavior of polymer solutions at pure shear flows where the velocity gradient is orthogonal to the direction of flow which is shown in Figure 16[13].

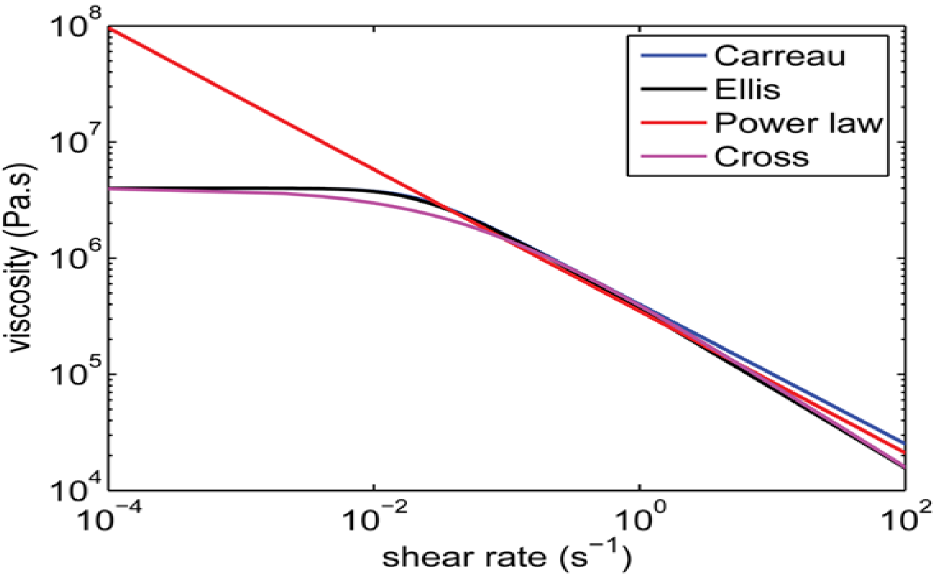
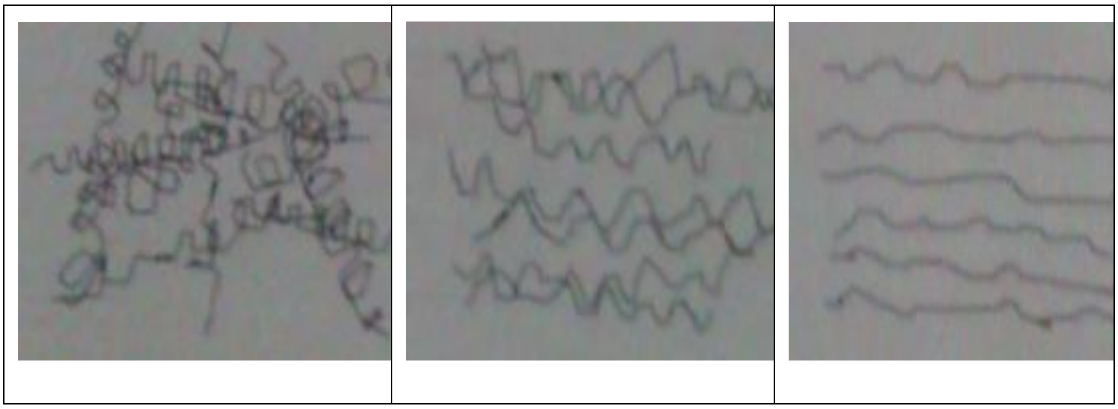


Figure 15: Carreau Model for Viscosity of Polymers.

Based on Carreau model, macromolecules rotate at a constant angular velocity at low shear rates. Hence, the viscosity remains constant and the regime of flow is Newtonian. When shear rates increase, macromolecules start to deform or orient themselves in the direction of flow which results in a reduced interaction between macromolecules and cause a gradual reduction of viscosity *shear-thinning flow regime*. At high shear rates all the macromolecules are oriented in the flow direction and do not affect the viscosity of polymer solution. Regime of flow is again Newtonian but at lower viscosity [13].



Newtonian behavior (high viscosity) | Power law type of behavior (shear-thinning regime) | Newtonian behavior (low viscosity)

Figure 16: Orientation of Polymer Molecules and Flow Regimes of a Polymer Solution at Different Shear Rates.

3.2.2.1 Stability of Polymers

HPAM is subjected to mechanical degradation because of an elastic behavior PAM will easily degraded by high shear rates in porous media. PAM is stable up to 90^0C at normal salinity and up to 62^0C at seawater salinity, which put certain restrictions to their use in off-shore operations.Temperature stability for xanthan is reported in the range 70^0C to above 90^0C, and above 105^0C for scleroglucon. The polymers and especially the biopolymers are susceptible to bacterial attack in the low-temperature region in the reservoir. To prevent biological degradation, biocides like formaldehyde in concentrations 500 to 1000 ppm are effectively used [13].

3.2.2.2 Retention of Polymers

Retention is a term used to cover all the mechanisms responsible for the reduction of mean velocity of polymer molecules during their propagation through porous media. Polymers molecules can be retained by reservoir rock by means of

- Adsorption on the surface of pores;
- Mechanical entrapping in pores;
- Precipitation, i.e. local ion of polymer molecules.

Figure 17 shows the types of polymer retention in the porous media. In order to calculate the amount of polymer required for successful polymer flooding the following mass balance formulation can be used [13]:

Mass of Polymer Injected = Mass of Polymer Retained.

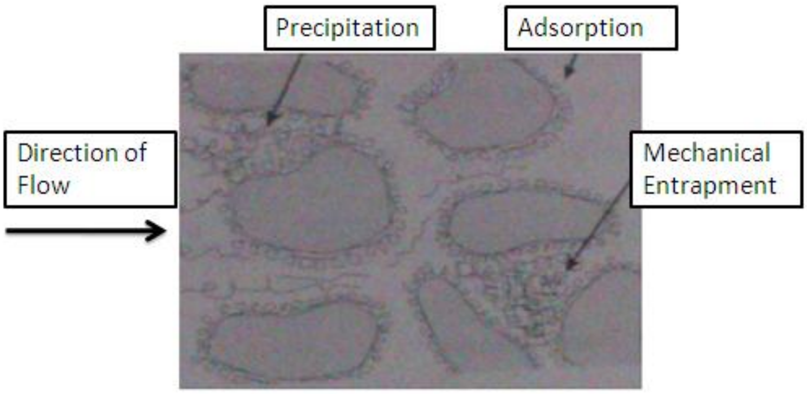


Figure 17: Types of Polymer Retention in Porous Media.

3.2.2.3 Inaccessible pore volume

Due to the bigger size of macromolecules, narrow pore throats can serve as obstacles for polymer invasion thus creating a so-called inaccessible pore volume (IPV). The IPV can reach as much as 30% of the pore volume swept by polymer flooding.

3.2.2.4 Apparent Viscosity and Shear Rates

Due to the microheterogeneity of formation and the fact that polymer solution has non-Newtonian properties the shear rate and thus, the viscosity of the solution will vary within the porous medium. In order to predict effectiveness of polymer flooding one has to deal with averaged, i.e. apparent values of a polymer solution viscosity. Since the effective shear rate $\dot{\gamma}$ is proportional to flow rate Q. Based on a simple capillary bundle model the effective shear rate $\dot{\gamma}$ can be determined by the equation 5 where is a constant related to the pore geometry and type of porous media [13].

$$\dot{\gamma} = \alpha \frac{4u}{\sqrt{8\Phi k}} \tag{5}$$

3.2.2.5 Resistance and Permeability Reduction Factor

There are two important factors that must be taken into account while simulating polymer flooding, namely *Resistance factor* and *Residual resistance factor*. *Resistance factor R* can be defined as the ratio of mobility of water (brine) λ_w to that of polymer solution λ_p under the same conditions which is shown in equation 7.

$$R = \frac{\lambda_w}{\lambda_p} \tag{6}$$

Residual resistance factor is the mobility ratio of water before λ_w and after polymer injection λ_{wp} under the same conditions, where k_p is permeability to polymer solution.

$$R = \frac{\lambda_w}{\lambda_{wp}} = \frac{k_w}{k_{wp}} \approx \frac{k_w}{k_p} \tag{7}$$

The last term of equation 7 is called *Permeability Reduction factor R* and often used for the quality estimation of polymer solution.

3.2.3 Polymers application in the oil industry

Significant increases in recovery when compared to conventional water flooding projects. It reduces the unfavorable effect of permeability variations. The Primary features for effectiveness of reservoir heterogeneity and mobility ratio of reservoir fluids. Hydrolyzed polyacrylamide(HPAM) is the only commonly used polymer in the field and can be used up to about 185 F depending on the brine hardness. Modified polyacrylamidessuch as HPAM-AMPS co-polymers are commercially available now for about $1.75/lb and are stable to higher temperatures.

3.2.4 Potential of polymer flooding in the Norwegian shelf

The North Sea reservoir conditions put strong restrictions on the use of polymers: high injection rates, high temperatures, large interwell distances which means that the polymer must be stable over a long time at high temperatures and the use of seawater with high salinity [13].

3.3 Overview of Alkali

Alkali (from Arabic: Al-Qaly) is a basic, ionic salt of an alkali metal or alkaline earth metal element. Alkalis are best known for being bases that dissolve in water. Bases are compounds with a pH greater than 7. There is a vast uses of alkali like Sodium hydroxide is used to make paper, detergents and soap; Potassium hydroxide; Calcium carbonate is used as a building material; Magnesium hydroxide is used to help with stomach aches or indigestion. It makes the contents of a stomach less acidic.

3.3.1 General structure of Alkali

Alkalis are all Arrhenius bases, which form hydroxide ions (OH-) when dissolved in water. Common properties of alkaline aqueous solutions include: Moderately concentrated solutions (over 10−3 M) have a pH of 10 or greater. Concentrated solutions are caustic (causing chemical burns). Alkaline solutions are slippery or soapy to the touch, due to the saponification of the fatty acids on the surface of the skin.

Most basic salts are alkali salts, of which common examples are: sodium hydroxide (often called "caustic soda"), potassium hydroxide (commonly called "caustic potash"), lye, calcium carbonate, magnesium hydroxide is an example of an atypical alkali since it has low solubility in water. Nowadays, instead of sodium hydroxide (NaOH), sodium bicarbonate ($NaHCO_3$) or sodium carbonate (Na_2CO_3) is used to reduce emulsion and scale problems.

3.3.2 Mechanisms

Alkali reduces adsorption of the surfactant on the rock surfaces and reacts with acids in the oil to create natural surfactant. Alkaline chemicals can cause improved oil recovery through the formation of emulsions. In alkaline flooding, emulsification is instant, and emulsions are very stable. Emulsification mainly depends on the water/oil IFT. The lower the IFT, the easier the emulsification occurs. The stability of an emulsion mainly depends on the film of the water/oil interface. The acidic components in the crude oil could reduce IFT to make emulsification occur easily, whereas the asphaltene surfactants adsorb on the interface to make the film stronger so that the stability of emulsion is enhanced. Local formation of highly viscous emulsions is not desirable since these would promote viscous instability. In carbonate reservoirs where anhydrite ($CaSO_4$) or gypsum ($CaSO_4 \cdot 2H_2O$) exists, the $CaCO_3$ or $Ca(OH)_2$ precipitation occurs when Na_2CO_3 or NaOH is added. Carbonate reservoirs also contain brine with a higher concentration of divalents and could cause precipitation. To overcome this problem, Liu (2007) suggested $NaHCO_3$ and Na_2SO_4. $NaHCO_3$ has a much lower carbonate ion concentration, and additional sulfate ions can decrease calcium ion concentration in the solution.

3.3.3 Alkaline application in the oil industry

Alkali reacts with the petroleum acids during the alkaline flooding in the reservoir. To form a surfactant hydroxide ion reacts with a pseudo-acid component which is known as hydrolysis reaction (Equation 8). When pseudo-acid is not present in the crude oil then little surfactant can be generated.

$$HA_o + NaOH^- \longleftrightarrow NaA_o + H_2O \tag{8}$$

The reaction depends strongly on the aqueous solution pH and occurs at the water/oil interface. A fraction of organic acids in oil become ionized with the addition of an alkali, whereas others remained electronically neutral. The hydrogen-bonding interaction between the ionized and neutral acids can lead to the formation of a complex called acid soap. Thus, the overall reaction, equation 9, is decomposed into a distribution of the molecular acid between the oleic and aqueous phases,

$$HA_o \longleftrightarrow HA_w \tag{9}$$

and an aqueous hydrolysis where, HA denotes a single acid species, A- denotes anionic surfactant, and subscripts o and w denote oleic and aqueous phases, respectively [29].

$$HA_w \longleftrightarrow H^+ + A^- \tag{11}$$

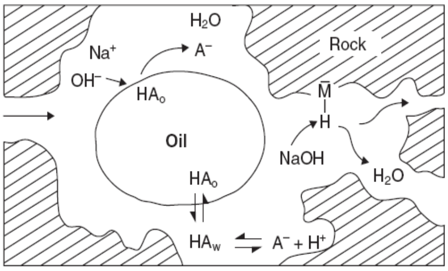


Figure 18: Schematic of alkaline recovery process.

Chapter 4

Norne Field

4.1 General Field Information

Norne is an oil and gas field on the Norwegian continental shelf operated by Statoil Petroleum AS with Eni Norge AS and Petoro AS as partners. The field is located 200km west of Brønnøysund and 80km north of the Heidrun field, in blocks 6608/10 and 6508/10, the southern part of the Nordland II area, see Figure 1.1. It was first discovered in December 1991 and oil production started from 6th November, 1997. But gas production started in 2001. The field is subsea developed with six subsea templates, connected to a production and storage vessel. In April 2008 an updated plan for development and operation (PDO) for Norne and Urd was approved. This plan also includes 6608/10-11 S Trost and other prospects around Norne and Urd [1,53,54].

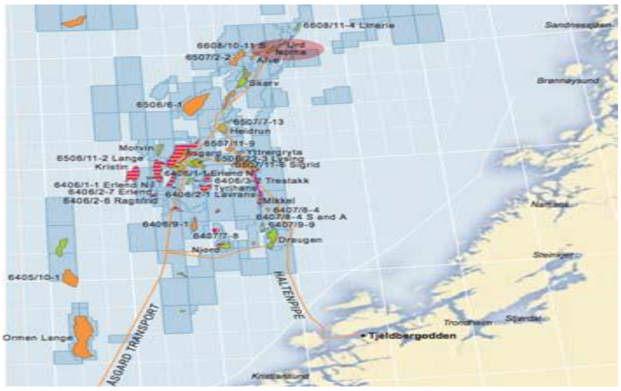


Figure 19: Fields and discoveries in the Norwegian Sea, Norne field circled in red.

4.2 Reserves

Most likely in-place volumes reported in the Revised National Budget (RNB) 2006 were 157,0 MSm3 oil in place (OIIP) and 29,8 GSm3 gas in place (GIIP). By August 2009 they had produced 82,1 MSm3 oil and 6,0 GSm3 gas, or recovery of 52,3% and 20,1% for oil and gas respectively.25 The Norwegian Petroleum Directorate (NPD) estimated the recoverable reserves to be 94,9 MSm3 oil and 11,0 GSm3 gas. This indicates that they expect a recovery of 60,4% for oil and 36,9% for gas[56].

4.3 Structure

The field has two separate compartments:

- **Norne Main Structure (Norne C, Norne D and E-segment)**

Relatively Flat with generally a gas filled Garn Formation and the gas oil contact in the vicinity of the Not formation clay stone. The Norne main structure includes 97% of the oil in place.

- **Northeast Segment (Norne G-Segment)**

The northen flank dips towards north-northwest with an oil leg in the Garn Formation.

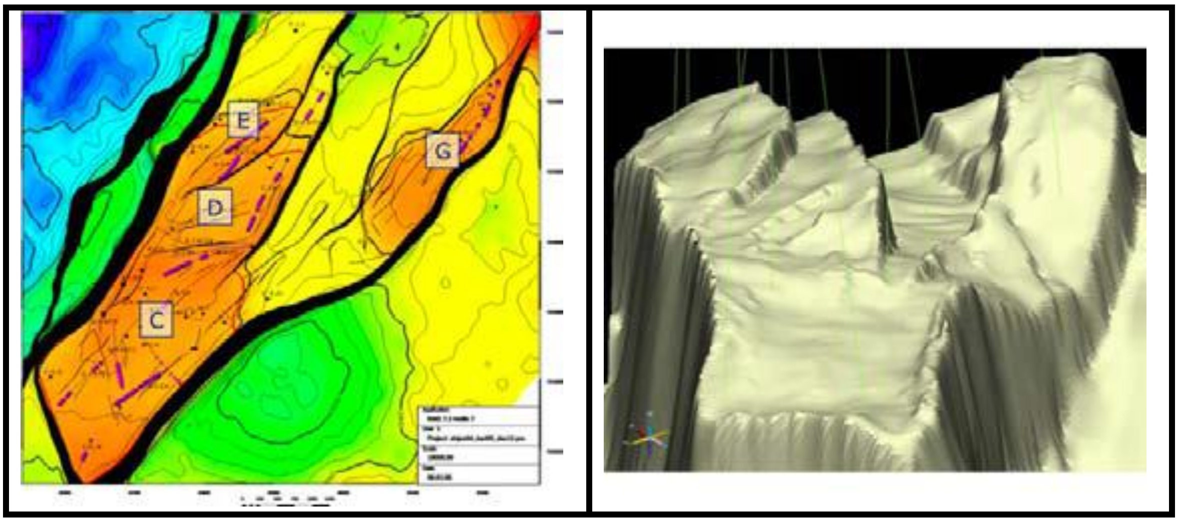


Figure 20: Main fault blocks are denoted C. D, E and G.

The hydrocarbons are proven in the rocks of Lower and Middle Jurassic age. An oil column of 110m, and a gas cap of 25m were proven in exploration well 6608/10-2 and confirmed in well 6608/10-3, the two exploration wells in the Main Structure. A third exploration well, 6608/10-4, were drilled in the Northeast Segment. As much as 98% of the total hydrocarbons were proven in the Main Structure.

The Norne field is a raised fault block, a at horst structure, bounded by normal faults. In the Main Structure the Garn Formation is gas filled; the structure dips towards north-northwest and has an oil leg. The gas oil contact is in the proximity of the Not Formation. Reservoir pressure data from the wells shows that there is no reservoir communication across the Not Formation. Oil is mostly found in Ile and Tofte Formations [55,56].

4.4 Geology

The reservoir is situated in a fault complex in the Norwegian Sea. Rifting of the area occurred in Permian and Late Jurassic - Early Cretaceous. Normal faults with north-northeast to south-southwest trends are common from the first rifting period. Footwall uplift and erosion of the higher structures appeared in the second rifting. In between the rifting periods there was limited tectonic activity, subsidence and transgression was dominating. As time goes the reservoir has been buried deeper, increasing the diagenetic processes. Norne reservoir rocks are of, as already mentioned, from Late Triassic to Middle Jurassic age [57].

4.4.1 Stratigraphy and Sedimentology

The reservoir sandstones in the formations Garn, Ile, Tofte and top Tilje, have a near shore marine depositional environment with source area to the north-east and east. They are fine-grained, well to very well sorted sub-arkosic arenites. Tilje Formation has origin from a marginal marine, tidally influenced environment, and the Not Formation clay stone was deposited in quiet marine environment. Being buried at a deep between 2500m and 2700m, mechanical compaction is an important process which reduces the quality of the reservoir. The reservoir rocks have still good quality with porosity in range of 25-30% and permeability varies from 20 to 2500 mD [56]. Figure 4.1 shows the formations and their properties of the reservoir.

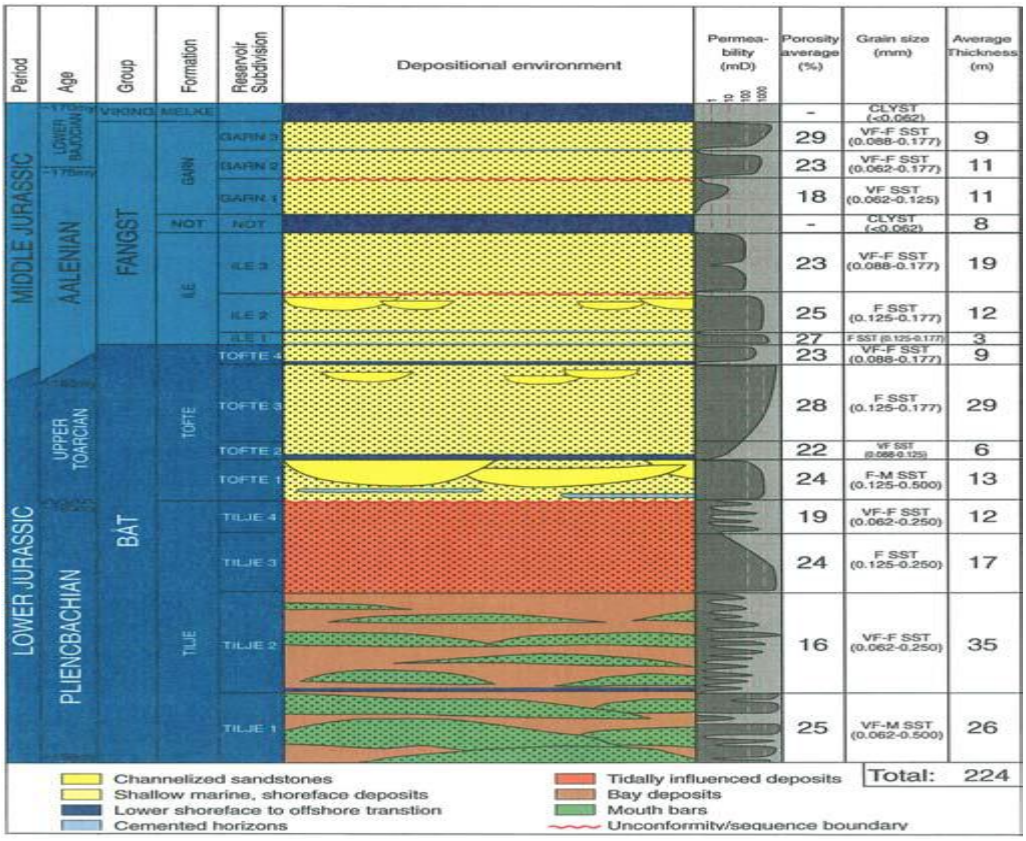


Figure 21: Stratigraphical sub-division of the Norne reservoir [56].

The source rocks are believed to be in the Spekk Formation shale and Åre Formation coal beds. They were deposited in Upper and Lower Jurassic, respectively. Åre has alluvial to delta plain setting and contain mainly channel sandstones interblended with mudstones, shales and coal.

Due to increased erosion to the North reservoir thickness varies over the entire field. From Top Åre to Top Garn it goes from 260m in the southern parts to 120m in the northern part. From seismic mapping it has been found that particularly the Ile and Tilje Formations decrease [57].

4.4.2 Reservoir Communication

Both structural and stratigraphic barriers influence the vertical and lateral flow within a reservoir. Structural barriers such as faults, at least major faults, can be seen on seismic. If the faults are sealing and extend over the whole reservoir height it is considered as a trap. This is beneficial in order to trap the hydrocarbons. If it is an intra-reservoir fault this is not wanted as it's limiting the reservoir communication. No faults have been cored out from Norne, so it is impossible to measure the permeability in these. The Heidrun field located 80km south of Norne is the best analog and three main types are found here. Results from two different fault analysis indicates that both the intra-reservoir faults at Norne most likely are non sealing [57]. Table 1 shows the GOC and OWC in the different formations and segments in the Norne Field and Figure 22 shows the Structural cross sections through the Norne Field with fluid contacts.

Table 1: GOC and OWC in the different formations and segments in the Norne Field.

Formation	**C-segment**		**D-segment**		**E-segment**		**G-segment**	
	OWC	**GOC**	**OWC**	**GOC**	**OWC**	**GOC**	**OWC**	**GOC**
Garn	2692	2582	2692	2582	2618	2582	2585	No gas cap
Ile	2693	2585	2693	2585	2693	2585	Water filled	Water filled
Tofte	2693	2585	2693	2585	2693	2585	Water filled	Water filled
Tilje	2693	2585	2693	2585	2693	2585	Water filled	Water filled

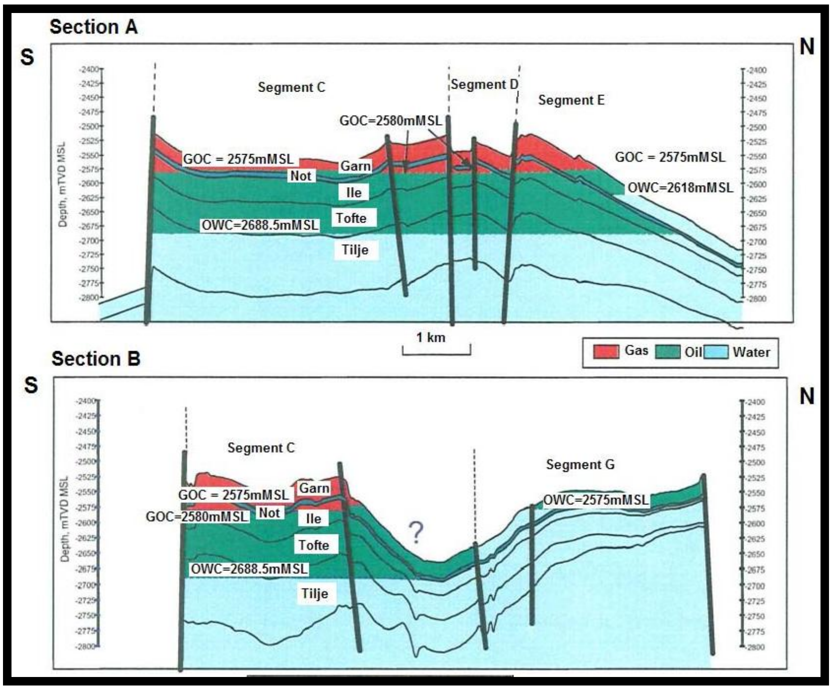


Figure 22: Structural cross sections through the Norne Field with fluid contacts [Statoil, 2001].

In the formations Tofte, Ile and Garn there are interpreted three continuous calcareous cemented layers. These are believed to act as stratigraphic barriers to vertical flow. They have a thickness in the range of 0.5-3m. However, there are many intra-reservoir faults which offset the sealing layers and enable vertical reservoir communication. In addition the Not Formation with a thickness of 7-10 m is sealing. From well data and RFT (Repeat Formation Tester) pressures such lateral barriers can be shown. These are of variable extension but generally thin, below seismic resolution, and partially sealing [56].

4.5 Field Development

As of November 2009 the field are developed using six subsea templates connected to a production vessel. There are 8 wells injecting water and 16 wells producing oil. In total there are 4 exploration wellbores and 48 production and injection wellbores. The drainage strategy was originally pressure support by water injection in the water zone and re-injection of gas into the gas cap. Experience from the first year of production showed that the Not Formation was sealing over the Norne Main Structure and gas injection discontinued in 2005.

The Norne field is developed using only near horizontal producers. In Figure 5.1 the general drainage pattern are shown. Water injectors at the bottom and the water-oil contact (WOC) will gradually move upwards with production. Figure 23 shows the drainage strategy of the Norne field where vertical arrows illustrates injection streams, horizontal arrows illustrates production streams as well as red, green and blue color illustrates gas, oil and water phase respectively [55,57,58].

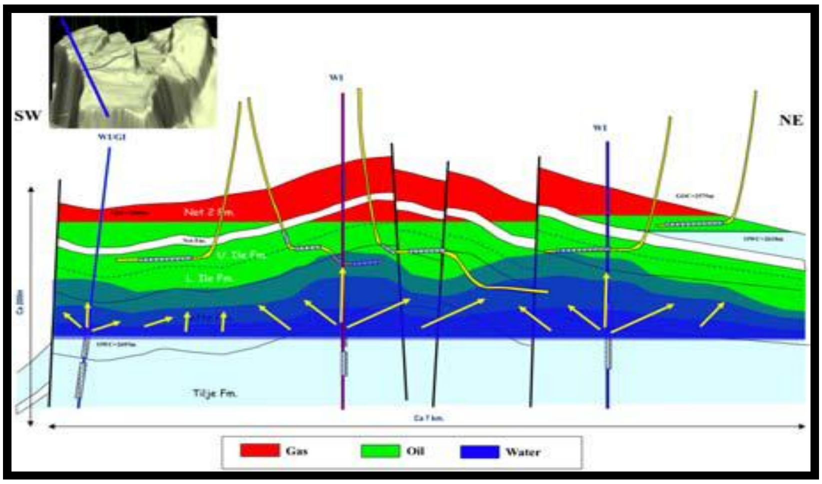


Figure 23: General drainage pattern [2]

Since the Norne field now are considered to be a mature field and in tail production, see Figure 23, increased oil recovery (IOR) techniques are needed to achieve their high recovery goal. Uncertainties regarding infill drilling and reservoir performance are major. Infill drilling is being performed using through tubing rotary drilling (TTRD). TTRD meaning drilling through the existing production tubing and conveniently creating multilateral wells, effectively optimize the reservoir drainage. Also to effectively update the reservoir models, time laps seismic are used. Using seismic to interpret the changes in a reservoir over time is beneficial as the production and fluid movements influence the seismic reflection properties. Techniques are developed to estimate reservoir properties and optimize the simulation models giving more accurate predictions. From such updated models, reservoir performance, water-cut (WC) and gas-oil ratio (GOR) development can be predicted more accurate. As a result wells can be plugged and sidetracked in overlaying formations to optimize reservoir drainage, see Figure 54 [1,58].

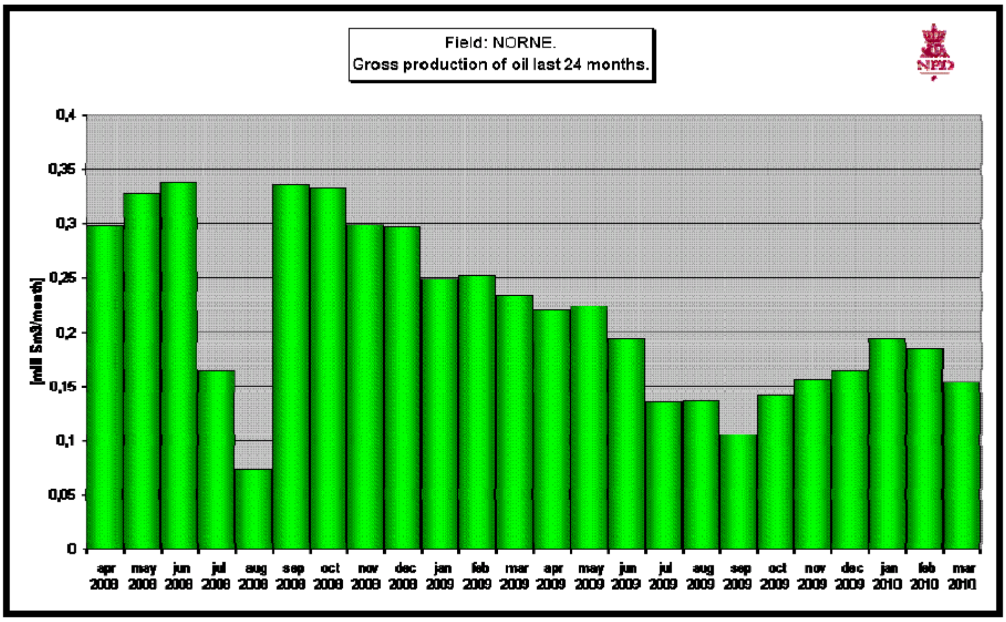


Figure 24: Gross Production of Oil, April 2009 - March 2010 [NPD, 2010] [1]

4.6 Norne Model in Eclipse

The reservoir simulation model at the Norne field is an Eclipse 100 model, a fully-implicit, three phases, three dimensional black oil simulators. A coarsened model was made from the original full field reservoir simulation model and used in this thesis. The coarsened model was made by Mohsen Dadashpour at the IO center and can be seen in Figure 25. The model is runs from November 1997 until December 2004 and history matched until December 2004 by Statoil.

ECLIPSE from Schlumberger is one of the leading reservoir simulators in oil industry. It is a batch program. As an input user creates text file with a set of keywords that must be located in particular section. Such data file gives complete description of a reservoir.

The Norne Field model starts at 06 November 1997. The dimensions are 46 × 112 × 22, the unit system is metric and five phases gas, oil, water, dissolved oil and vapour gas are activated in the simulation. The grid consists of 113344 cells, where 44927 are active cells and the grid units are meters. The model is physically divided into two sections by a shale layer which is called NOT formations. The upper and lower sections are consists of 3 and 18 layers respectively. Reservoir properties are assigned to every cell then they are modified according to specific segments, wells and layers. Net-to-gross, porosity and

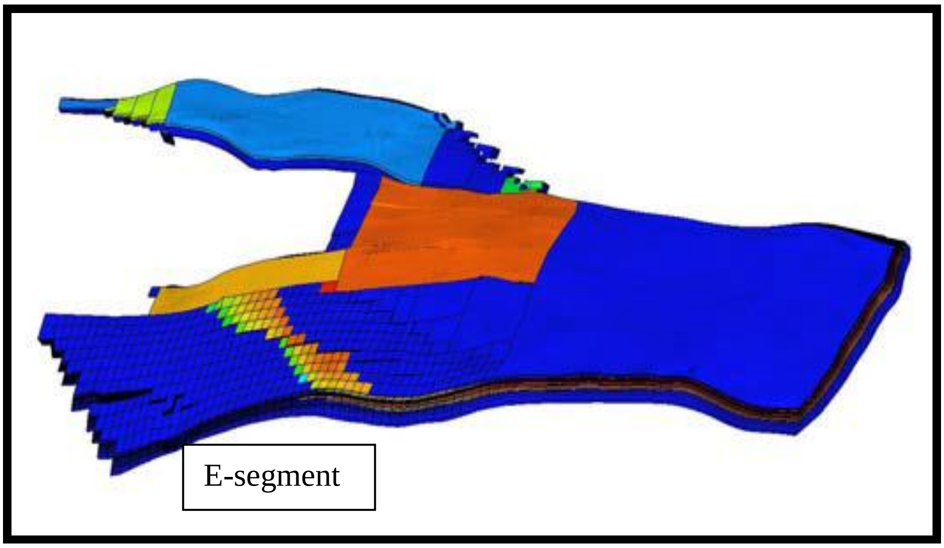


Figure 25: Norne model grid and E-segment

permeability appear to have a layer-dependent structure. The defined permeability in X direction is copied to Y direction and Z direction. However, permeability Z is reduced using multipliers according to particular layer. This means that permeability in X and Y direction are the same while permeability Z differs. Specified transmissibilities are modified further in the edit section to honour the changes in a reservoir structure made by drilling through the faults and the layers. Areas near the wells have set increased transmissibility multipliers. For Norne the value varies from 0.00075 to 20. Transmissibility multipliers only for two faults are bigger than 1 what means that appearing of these faults increased easy with which flow goes through that fault. The initial reservoir properties of Norne field has shown in the Table.

The reservoir can be subdivided into regions if there is a need to set different local properties for the field. There are 4 flux regions for each geological layer: Garn, Ile, Tofte, Tilje-top and Tilje-bottom. Thus there are 20 regions in total in Norne Field. There are transmissibility multipliers specified between each pair of neighbouring regions.

4.7 Norne E-segment

The E segment of the Norne field is part of the Norne main structure which also comprise of the C and D segments. The Ile and the Tofte formations are the most important in this segment because about 80% oil in the Norne field is contained in these formations. There are five wells in the E segment, two injectors and three producers. Table 2 gives the details status of the wells. Wells localization can be seen in the Figure 26 and Table 3.

Table 2: Norne E-segment current well status.

Well	Type	Status
F-1H	Water Injector	Active
E-3H	Oil Producer	Shut
E-3AH	Oil Producer	Active
E-2H	Oil Producer	Active
F-3H	Water Injector	Active

I_1	I_2	J_1	J_2	K_1	K_2
6	6	45	88	1	22
7	7	45	90	1	22
8	8	47	91	1	22
9	9	49	92	1	22
10	10	54	94	1	22
11	11	55	94	1	22
12	12	57	96	1	22
13	13	60	97	1	22
14	14	62	99	1	22
15	15	65	100	1	22
16	16	70	100	1	22

Table 3:E-segment definition by grid cell positions.

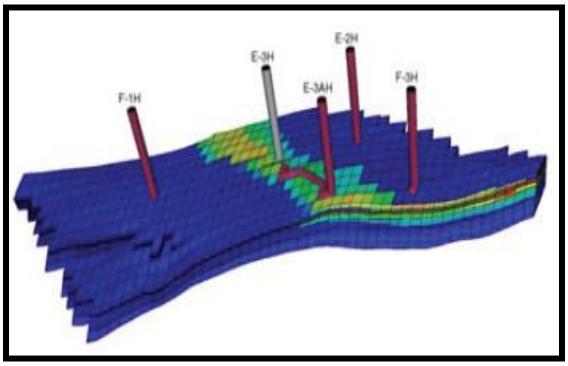


Figure 26: Localization of wells in E-segment.

The Norne E-segment is separated from the rest of the field by keeping the E-segment part as original grid and coarsening the rest.

E-segment contains 8733 active cells. Size of the blocks is between 80 m to 100 m in the horizontal direction. In total it 8 wells have been drilled in the E-segment part. These comprise of one observation, 2 injector and 5 producers. Some properties of the oil and gas in the Norne Field are shown in the Table 4.

Table 4: Properties of the Norne Field.

Initial Pressure	273 bar at 2639 m TVD
Reservoir temperature	98^0 C
Oil density	859.5 Kg/m^3 API =32.7
Gas density	0.854 Kg/m^3
Water density	1033 Kg/m^3
Oil formation volume factor	1.32
Gas formation volume factor	0.0047
Rock wettability	Mixed
Pore Compressibility	4.84×10-5 1/bar at 277 bar

Chapter 5

EOR at the Norne E-Segment

5.1 Fluid Properties of the Reservoir

Figure 27 shows the graph of fluid properties vs pressure of the reservoir. First one is gas formation volume factor vs pressure, second one R_{SO} and R_{SG} vs pressure, third one is oil formation volume factor vs pressure and final one is oil as well as gas viscosity vs pressure.

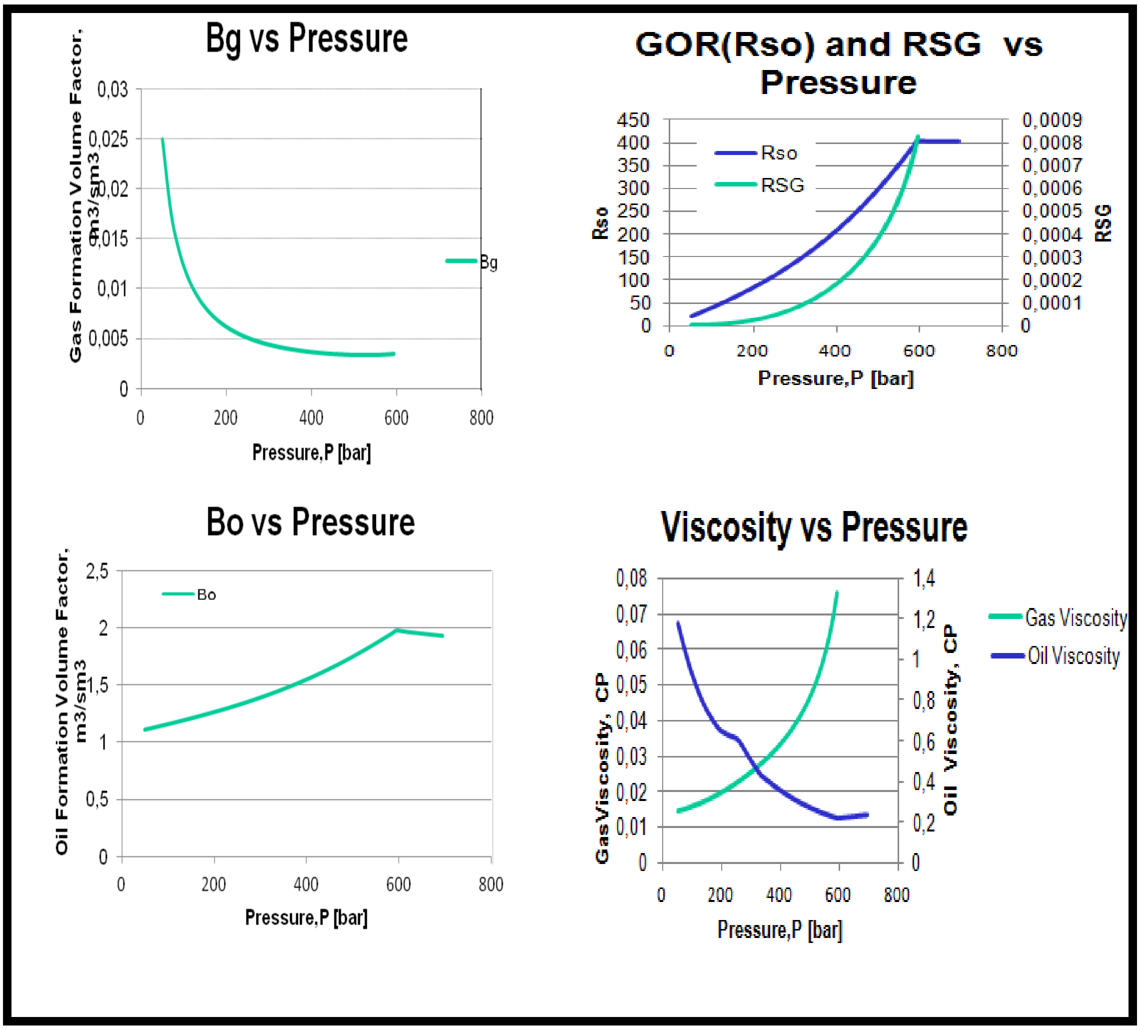


Figure 27: Fluid Properties of the Norne Field.

5.2 Pressure Profile of the Reservoir

The initial reservoir pressure of Norne field was 277 bars which decline with oil and gas production due to the injection of gas into the Garn formation as well as injection of water into the Tilje formation. As there was no communication between Garn and Ile formation, the injection of gas had to discontinue. Later gas injected into the Tilje formation. The bubble point pressure for the Norne Main Structure is 251 bars while for the Norne-G Segment are 216 bars. The pressure profile for the Norne field is shown in Figure 28. The plot of Formation volume factor and reservoir pressure profile shows that the Norne reservoir is still in the undersaturated region. This is because the reservoir pressure is above the bubble point pressure.

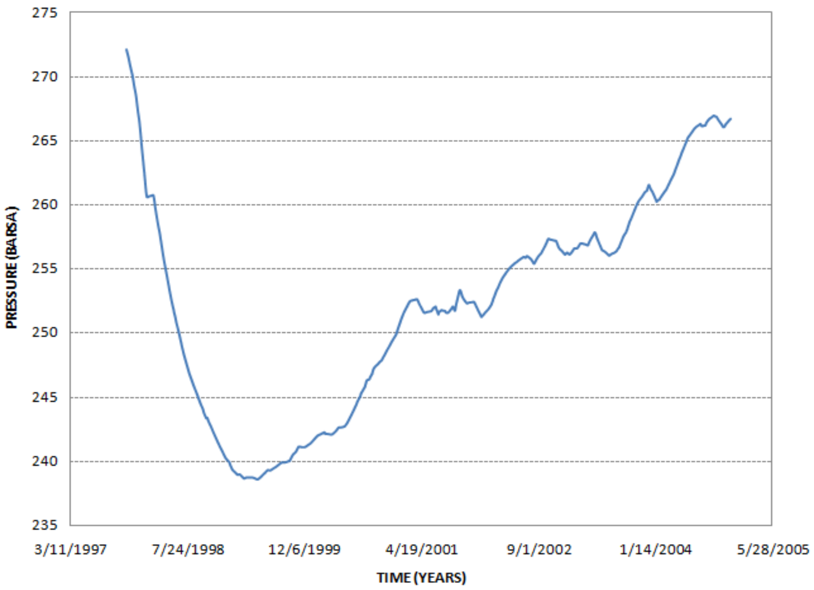


Figure 28: Reservoir pressure vs Time for the Norne Field.

5.3 EOR Potentiality at the Norne E-segment

As most of the oil in Norne E-segment is located in the Ile and Tofte formation, therefore these two formations are chosen as the target area for EOR. Figures 31 through 34 shows the oil saturations in top and bottom of both Ile and Tofte layer in 1997 and 2004. Ihe Ile and Tofte formations are represented by layers 5–18 in the Eclipse model and oil have been produced from 1997 to 2004. In some areas the oil saturation are still high, as you can see from the different layers. This indicates that the best target area for further production and EOR methods for the Norne E-segment is between layers 5–12, the Ile formation. Here the oil saturation is higher than further down in the reservoir, and a lower water cut will be achievable.

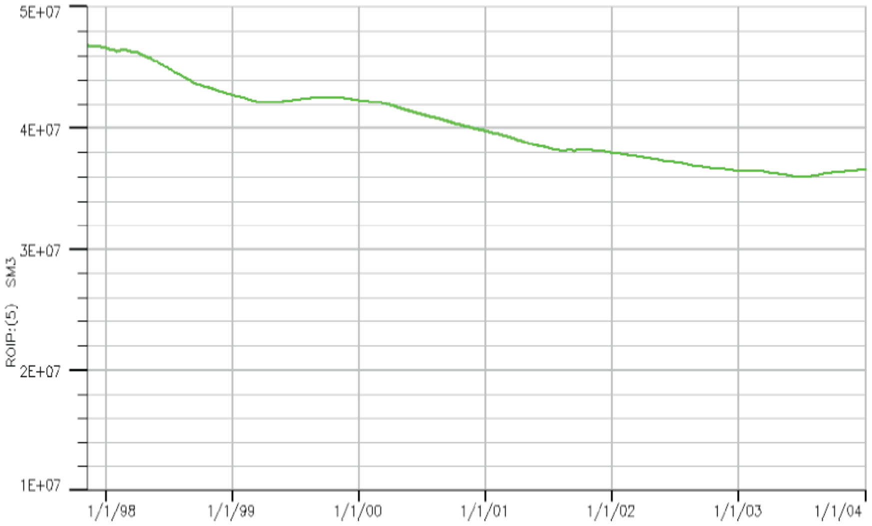


Figure 29: Reservoir oil in place in top of the Ile formation.

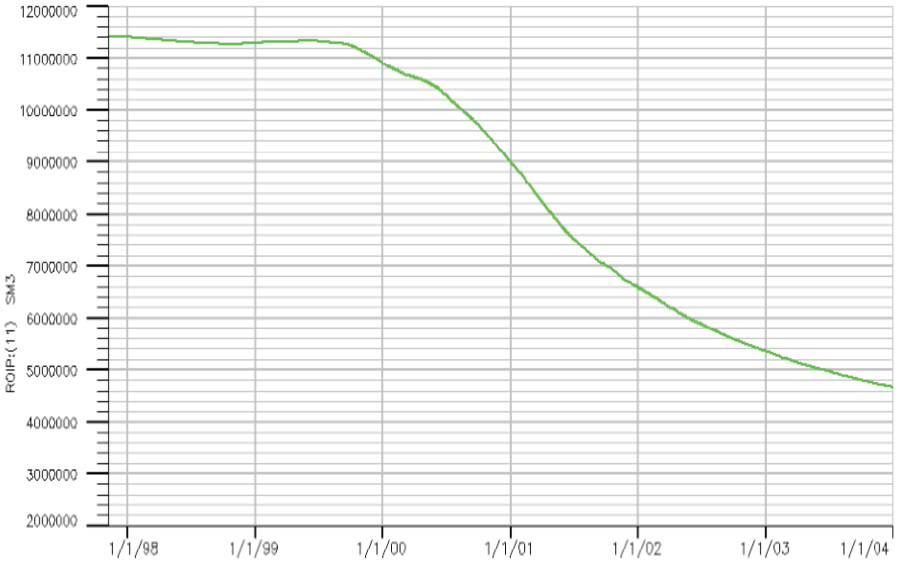


Figure 30: Reservoir oil in place in bottom of the Ile formation.

The 3-D Plots, (Figures 35 and 36) show the oil left in 2005 after long time production from the field in the Ile and Tofte formations, respectively. In 2004, the top of Ile formation still had 78 % of oil in place left, which means that the recovery factor only was 22 % and there still was a lot of producible oil left which is shown in Figures 29 and 30.

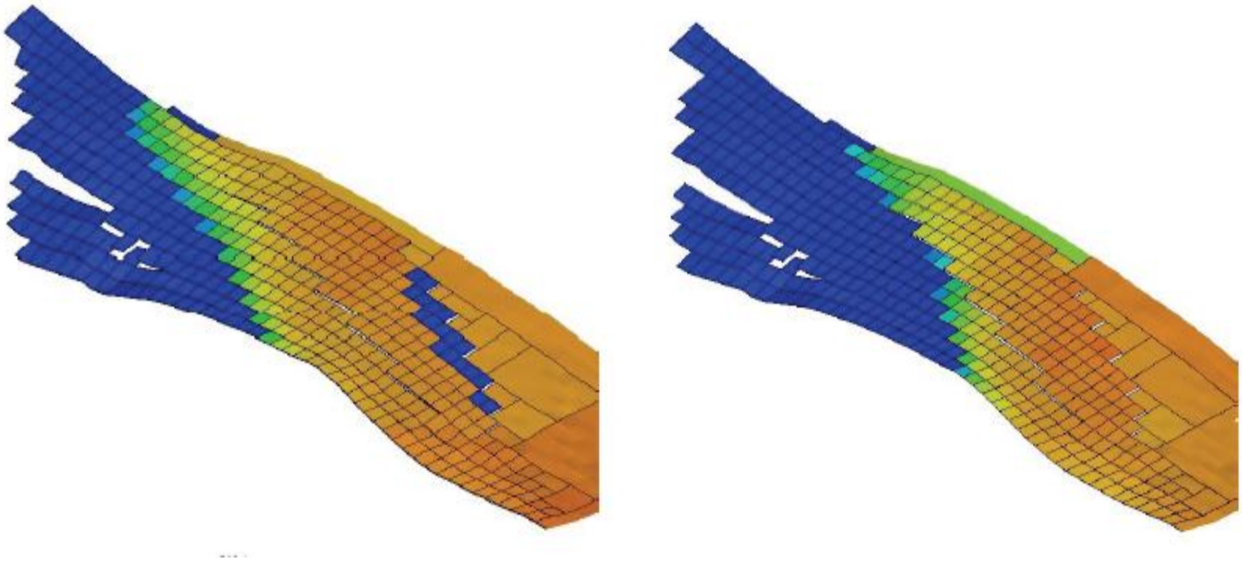


Figure 31: Oil saturation in the Ile top and bottom layer in 1997.

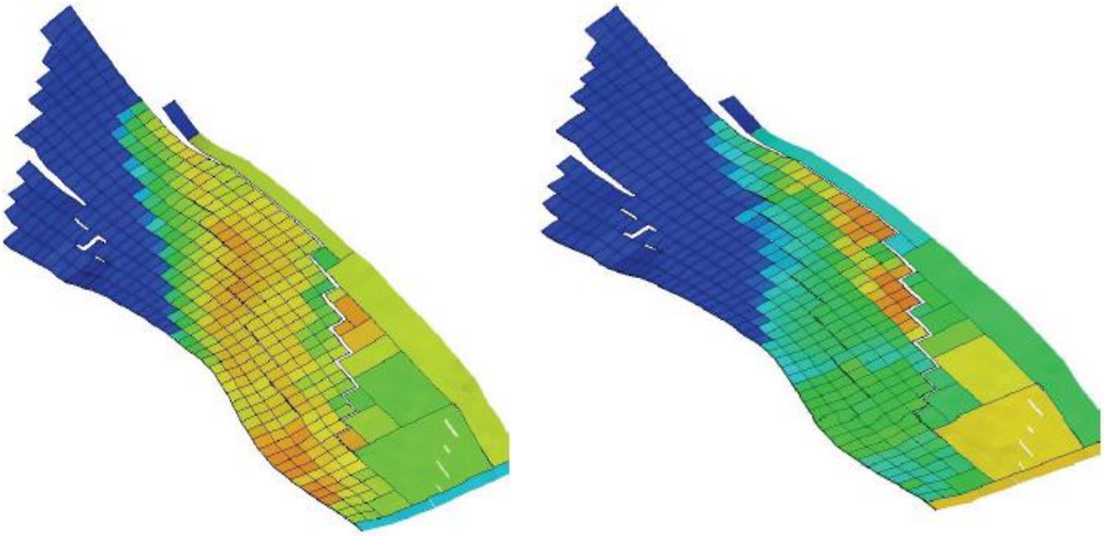


Figure 32: Oil saturation in the top and bottom Ile layer in 2004

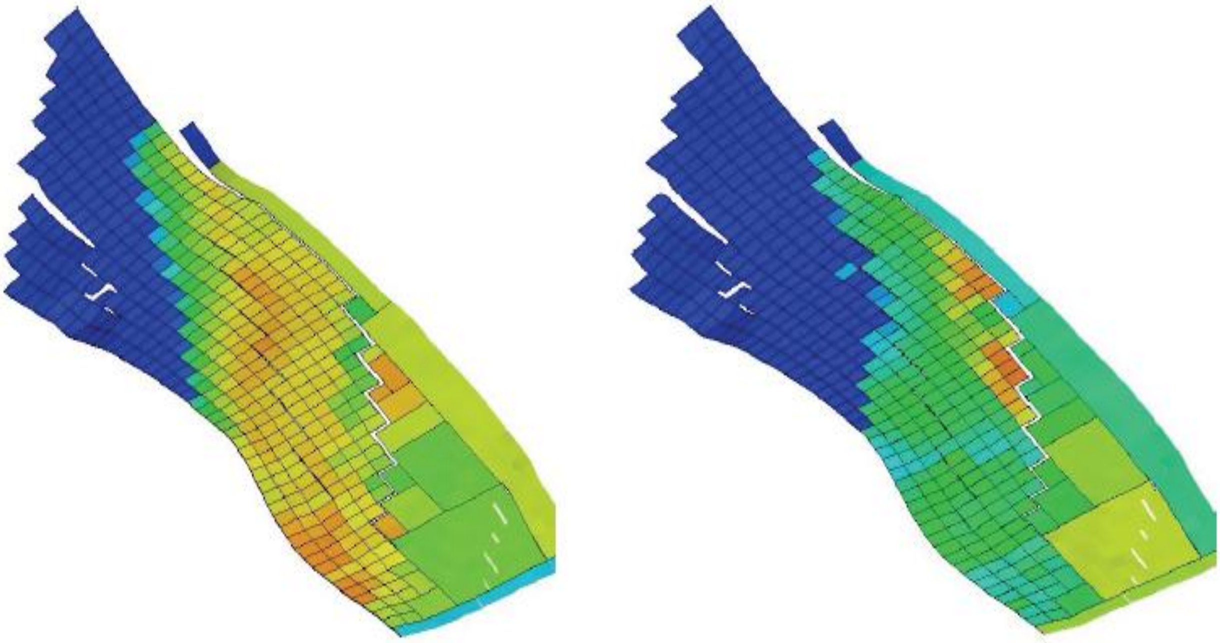


Figure 33: Oil saturation in the Tofte top and bottom layer in 1997.

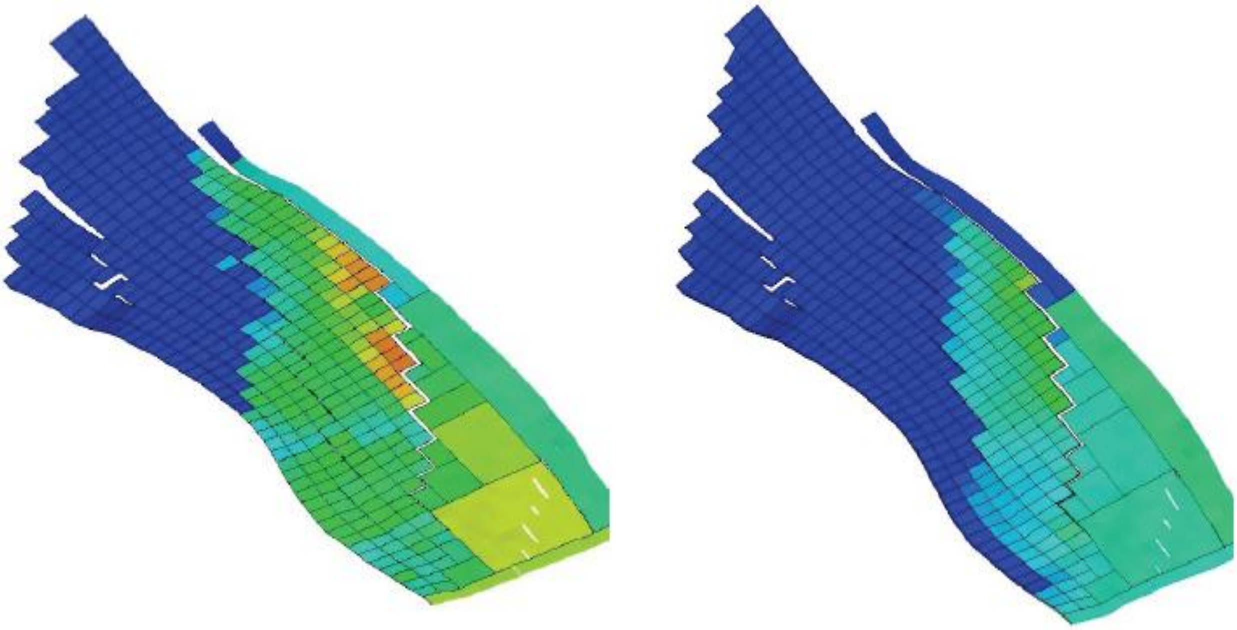


Figure 34: Oil saturation in the Tofte top and bottom layer in 2004.

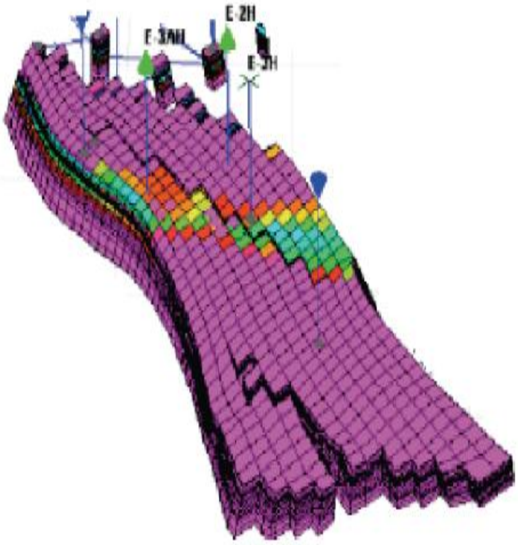


Figure 35: Oil saturation in the Norne E-segment after 2005.

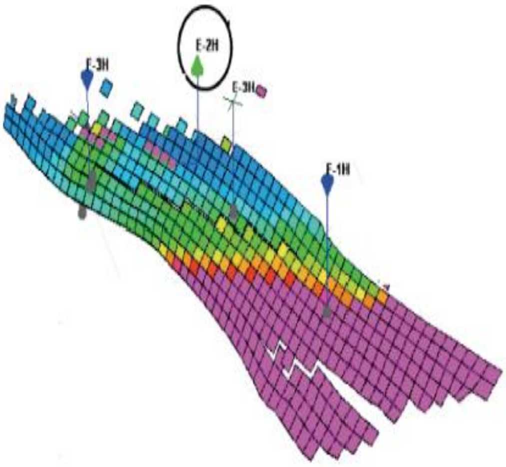


Figure 36: Oil saturation in the Ille formation after 2005.

Figure 37 shows the recovery factor vs. time for the Norne E-segment. The green line is the history and end at 37,6 % in November 2004, which is the end of the history matched model used in this thesis. Further prediction was made by an Eclipse 100 simulation, and the result in oil recovery is displayed as the blue line in Figure 37 which end at around 54 % in December 2021. A recovery factor is about 55 % which is very good result and

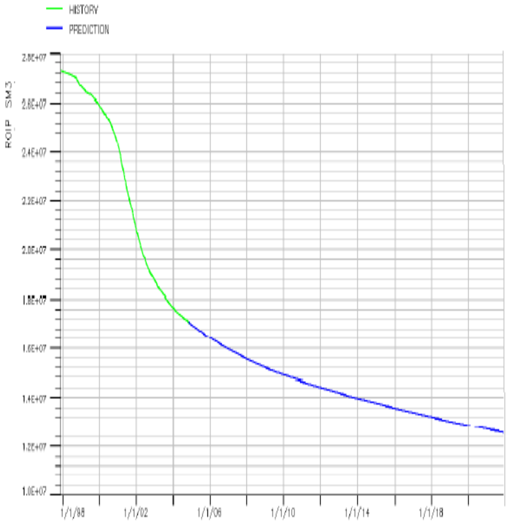


Figure 37: Oil in place at the Norne E-segment.

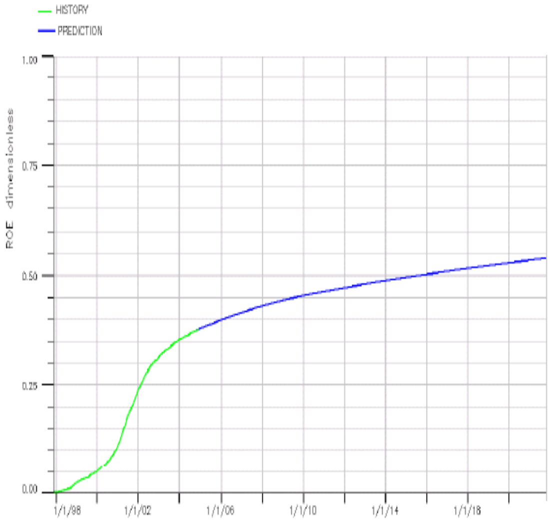


Figure 38: Oil Recovery vs Time at the Norne E-segment

satisfy the target set by NPD of a recovery factor of 50 %. The remaining 45% will amount around 12,5 million Sm3 which is displaced in Figure 38 and a 2 % increase in recovery will have a present value of 304 million USD with an oil price of 90 USD/BBL.

5.4 ASP Model at Norne E-segment

As 80 % oil still trapped in the Ile and Tofte formation, it is required to add extra chemical to get the higher recovery. Also the above observation (Figure 29-38) demands for an EOR method by which oil production can be increased with good pressure maintenance. Thus, there is a need for chemical flooding into the reservoir. It may be surfactant flooding or polymer flooding or AS flooding or all together. As three is synergistic, therefore ASP flooding is the good option to add. Again surfactant is very expensive. Therefore in addition of alkali reduce the cost and maximize the profit.

Also, a plot of block oil saturation for block I=15, J=74 and K=7 shows (Figure 39) that the oil saturation is still very high. When this use with surfactant and polymer flooding to perform an Alkaline-Surfactant Polymer (ASP) flooding, the low cost alkaline can reduce the adsorption of both surfactant and polymer on the rock surface, therefore the effectiveness of the surfactant and polymer drive is enhanced. Other reasons to use alkaline-surfactant-polymer (ASP) flooding is lower cost alternative to traditional SP flooding. Therefore, ASP flooding is the best option to get the higher oil recovery at the Norne E-segment.

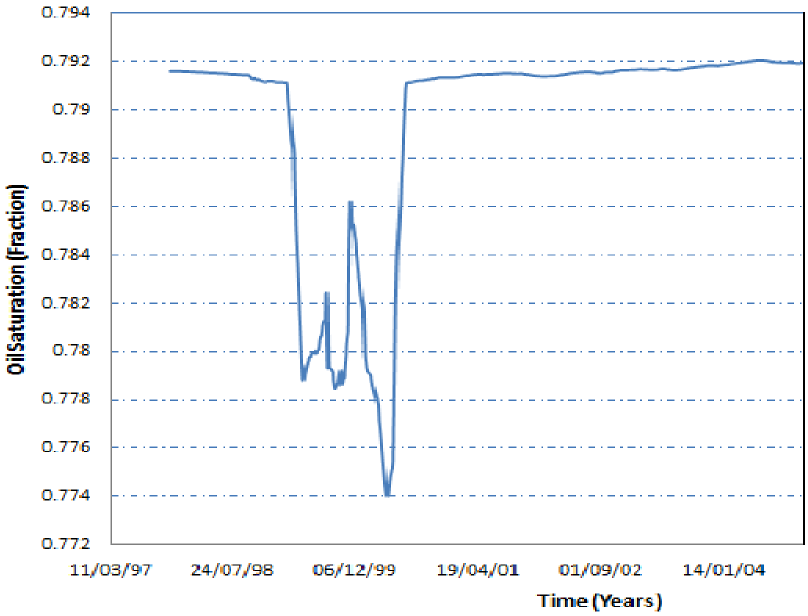


Figure 39: Oil saturation at Block 15, 74 and 7 in the Norne E-segment.

Chapter 6

ASP Flooding

6.1 Overview of ASP Flooding

ASP flooding is a form of chemical enhanced oil recovery (EOR) that can allow operators to extend reservoir pool life and extract incremental reserves currently inaccessible by conventional EOR techniques such as waterflooding. Although a relatively new and progressing technology, many ASP floods have been successfully conducted worldwide in recent years, commonly achieving 20% incremental oil recovery. One Albertan example of an ASP flood is the Husky Taber South Mannville B Pool which began ASP flooding in 2006 and is currently ongoing.

6.2 Process

ASP flood slug is the process where high concentration of Alkali as well as low concentration of Surfactant and Polymer is injected in to the reservoir. Alternately, alkaline and surfactant are injected followed by Polymer slug for mobility control. Upon completion of the ASP and polymer injection, regular waterflooding behind the ASP wall resumes again.

6.3 Mechanism

In the Alkaline Surfactant Polymer (ASP) process, a very low concentration of the surfactant is used to achieve ultra low interfacial tension between the trapped oil and the injection fluid/formation water. The ultra low interfacial tension also allows the alkali present in the injection fluid to penetrate deeply into the formation and contact the trapped oil globules. The alkali then reacts with the acidic components in the crude oil to form additional surfactant in-situ, thus, continuously providing ultra low interfacial tension and freeing the trapped oil. In the ASP Process, polymer is used to increase the viscosity of the injection fluid, to minimize channeling, and provide mobility control.

6.4 ASP Process in the Oil Industry

Oil recovery can be greatly improved by using two or three chemical together. To use alkaline, surfactant and polymer together has been recognized to be one of the major EOR techniques because this process reduces the quantity of surfactant used singly. Also typical alkali can be used which is much cheaper than surfactant. Therefore, it is the most economical process.

Field implementation of an ASP flood requires much thorough research. Laboratory testing must be conducted to determine the most suitable alkali, surfactant and polymer type and concentrations for the reservoir oil and rock. Radial and linear corefloods tests should be conducted as well as simulation studies to determine flood effectiveness and feasibility.

As conventional reserves diminish and reservoirs mature, it is crucial and financially beneficial to maximize existing reserve potential. As research and technology progress, the potential and feasibility of ASP flooding continues to grow and offers much potential for increased oil recovery.

6.5 ASP Model with Eclipse Simulator

The combination of the three chemicals is synergistic. Together they are more effective than as components alone. Addition of a surfactant lowers the interfacial tension between water and oil which helps to reduce capillary pressure in the reservoir. This allows residual oil to be mobilized and produced from the formation. The use of alkali adds many benefits to an ASP flood. The alkali reacts with elements of the oil to form in-situ surfactants. Additionally, it helps make the reservoir rock more water wet, thus increasing the flood effectiveness. The injection of only alkaline will not mobilize residual oil – one must inject the alkaline along with some surfactant to do an EOR flood. Once you inject some surfactant then the alkaline will help the surfactant to reduce the IFT. The polymer increases the vertical and areal sweep efficiencies of the flood by increasing water viscosity. The increased viscosity decreases the chance of fingering and allows more oil to be contacted on a macroscopic scale. Therefore, ASP flooding is the more encouraging EOR to increase the oil recovery.

To make ASP model by using Eclipse 100, it is required to activate three model-surfactant, polymer and alkaline. The details of surfactant model, polymer model as well as alkaline model with eclipse discussed in this chapter.

6.5.1 The Surfactant Model

The Eclipse 100 surfactant model does not provide a detailed chemistry of a surfactant flooding, but modeling the most important features is full field basis. The surfactant distribution is modeled by solving the conservation equation for surfactant within the water phase. The surfactant concentration is calculated fully implicit at end of each time step, after the calculation of water, oil and gas is done. The input of surfactant to the reservoir is specified by concentration of the surfactant in the injected water and occurs only in the water phase [36].

6.5.1.1 Calculation of the capillary number

The capillary number is a dimensionless group that measures the ration of viscous forces to capillary forces. The capillary number is given by Equation 10, where K is the

Permeability, *P* is the potential, *ST* is the interfacial tension and C_{unit} is a conversion factor.

$$N_C = \frac{|K.gradP|}{ST} C_{unit} | \tag{10}$$

$|K.gradP|$ is calculated as:

$$|K.gradP| = \sqrt{(K_x.gradP_x)^2 + (K_y.gradP_y)^2 + (K_z.gradP_z)^2} \tag{11}$$

Where for cell i

$$K_x \cdot gradP_x = 0.5\left[(P_i - P_{i-1}) \cdot (\frac{K_x}{D_x})_{i-1,i} + (P_{i+1} - P_i) \cdot (\frac{K_x}{D_x})_{i,i+1} \right] \tag{12}$$

6.5.1.2 Relative Permeability Model

The Relative Permeability model is essentially a transition from immiscible relative permeability curves at low capillary number to miscible relative permeability curves at high capillary number. A transition between these curves are made, and a table that describes the transition as a function of log10 of the capillary number must be included

Figure 40 illustrates the calculation for the relative permeability for oil, the relative permeability for water is calculated in the same way. First an interpolation between the endpoints are made (point A); then the miscible and immiscible curves are scaled between A and B. Then the relative permeability is found for both curves, and the final relative permeability is an interpolation between these two values.

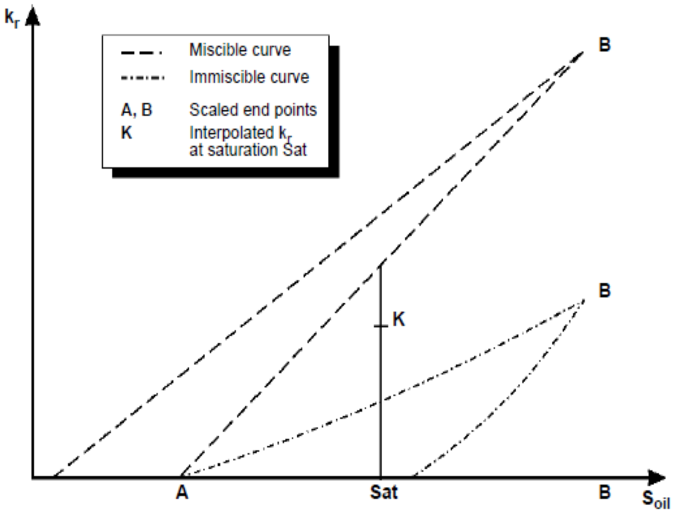


Figure 40: Calculation of the relative permeability.

6.5.1.3 Capillary Pressure

The capillary pressure will be reduced along with the increase in surfactant concentration, but it is only the reduction in the oil water capillary pressure that will reduce the residual oil saturation. The oil water capillary pressure is given in Equation 13.

$$P_{cow} = P_{cow} \cdot S_w \cdot \frac{ST(C_{surf})}{ST(C_{surf} = 0)} \tag{13}$$

Where ST(C$_{surf}$) is the surface tension at the present surfactant concentration, ST(C$_{surf}$ = 0) is the surface tension at zero concentration and P$_{cow}$(S$_W$) is the capillary pressure from the immiscible curves initially scaled to the interpolation end-points calculated in the relative permeability model.

6.5.1.4 Water PVT Properties

When surfactant is injected the water input in PVTW is modified according to Equation 14 where μ_s is the surfactant viscosity, μ_w is the water viscosity, μ_{ws} is the water-surfactant solution viscosity for a given concentration of surfactant viscosity and P$_{ref}$ is the reference pressure in the PVTW.

$$\mu_{ws}(C_{surf} \cdot P) = \mu_w \cdot P \cdot \frac{\mu_s(C_{surf})}{\mu_w(P_{ref})} \tag{14}$$

Equation 16 shows that the viscosity of the water surfactant solution differs from the pure water, but in low surfactant concentrations it is assumed the same viscosity for the water surfactant solution as pure water.

6.5.1.5 Adsorption

The adsorption of the surfactant is assumed to happen immediately, and the amount of the adsorbed surfactant is a function of the surfactant concentration is given in Equation 15.

$$\text{Mass of adsorbed surfactant} = PORV \cdot \frac{1-\phi}{\phi} . MD \cdot CA(C_{surf}) \tag{15}$$

Where PORV is the pore volume of the cellsurfactant viscosity, Φ is the porosity, MD is the mass density of the rock and CA (C$_{surf}$) is the adsorption isotherm as a function of local surfactant concentration in solution.

6.5.2 The Polymer Model

To achieve maximum efficiency, the polymer solution is often applied in the form of a tapered slug. At the front edge of the slug, the displacement is stable but the interface between the water and the polymer solution smears due to physical dispersion of the polymer. At the rear edge, the mobility ratio is unfavorable and is dominated by viscous fingering. Both effects cause deterioration of the slug, and are modeled in ECLIPSE by means of a mixing parameter applied to the viscosity terms in the fluid flow equations.

6.5.2.1 The polymer flood simulation model

The flow of the polymer solution through the porous medium is assumed to have no influence on the flow of the hydrocarbon phases. Therefore, standard black-oil equations use to describe the hydrocarbon phases in the model.

It is required to modify the standard aqueous equation and additional equations are needed to describe the flow of polymer and brine within the finite difference grid. The water, polymer and brine equations used in the model are given in Equation 16-18.

.

$$\frac{d}{dt}\left(\frac{VS_W}{B_rB_W}\right)=\sum\left[\frac{Tk_{rw}}{B_w\mu_{weff}R_k}\left(\delta P_w-\rho_w gD_z\right)\right]+Q_w \tag{16}$$

$$\frac{d}{dt}\left(\frac{VS_WC_P}{B_rB_W}\right)+\frac{d}{d_t}\left(V_\rho {C_P}^a\frac{1-\phi}{\phi}\right)=\sum\left[\frac{Tk_{rw}}{B_w\mu_{Peff}R_k}\left(\delta P_w-\rho_w gD_z\right)\right]C_P+Q_wC_P \tag{17}$$

$$\frac{d}{dt}\left(\frac{VS_WC_n}{B_rB_W}\right)=\sum\left[\frac{Tk_{rw}C_n}{B_w\mu_{seff}R_k}\left(\delta P_w-\rho_w gD_z\right)\right]+Q_wC_n \tag{18}$$

6.5.2.2 Treatment of fluid viscosities

The viscosity terms used in the fluid flow equations define the effects of a change of viscosity in the aqueous phase due to the presence of polymer and salt in the solution. However, to incorporate the effects of physical dispersion at the leading edge of the slug and also the fingering effects at the rear edge of the slug the fluid components are allocated effective viscosity values that are calculated using the Todd-Longstaff technique. The effective polymer viscosity is calculated by the Equation 19 where ω is the Todd-Longstaff mixing parameter.

$$\mu_{P,eff}=\mu_m\left(C_P\right)^{\omega}{\mu_P}^{1-\omega} \tag{19}$$

Here, the viscosity of a fully mixed polymer solution is an increasing function of the polymer concentration in solution ($\mu_m(C_P)$) and viscosity of the solution at the maximum polymer concentration also needs to be specified which denotes the injected polymer concentration in solution (μ_P).

The mixing parameter is useful in modeling the degree of segregation between the water and the injected polymer solution. If $\omega = 1$ then the polymer solution and water are fully mixed in each block. If $\omega = 0$ the polymer solution is completely segregated from the water.

6.5.2.3 Treatment of polymer adsorption

Adsorption is treated as an instantaneous effect in the model. The effect of polymer adsorption is to create a stripped water bank at the leading edge of the slug while desorption effects may occur as the slug passes. The isotherm adsorption can be specified in two ways such as:

- Look-up table of adsorbed alkaline which is a function of alkaline concentration
- A generic analytical adsorption model.

If desorption is prevented then the adsorbed polymer concentration may not decrease with time. If desorption is allowed then each grid block retraces the adsorption isotherm as the alkaline concentration rises and falls in the cell.

6.5.2.4 Treatment of permeability reductions and dead pore volume

The adsorption process causes a reduction in the permeability of the rock to the passage of the aqueous phase and is directly correlated to the adsorbed polymer concentration. In order to compute the reduction in rock permeability, it is required to specify the residual resistance factor (RRF) for each rock type.

The actual resistance factor can be calculated by Equation 20 where C_P^{amax} is the maximum adsorbed concentration and depends on the rock type. This value must be non zero. The dead pore volume must also be specified for each rock type. It represents the amount of total pore volume in each grid cell that is inaccessible to the polymer solution. The effect of the dead pore volume within each cell is to cause the polymer solution to travel at a greater velocity than inactive tracers embedded in the water. This chromatographic effect is modeled by assuming that the dead pore space is constant for each rock type.

$$R_K = 1 + (REF - 1)\frac{C_P{}^{a}}{C_P{}^{a\max}} \tag{20}$$

6.5.2.5 Treatment of the non-Newtonian rheology

Two models can be taking into account to understand non-Newtonian rheology behavior reported for polymer solutions. One model targets the shear thinning of polymer that has the effect of reducing the polymer viscosity at higher flow rates. Other model is the Herschel-Bulkey that can be used to model shear thinning and thickening as well as yield stress, dependent on polymer concentration.

The first model assumes that shear rate is proportional to the flow viscosity. This assumption is not valid in general, as for example, a given flow in a low permeability rock will have to pass through smaller pore throats than the same flow in a high permeability rock, and consequently the shear rate will be higher in the low permeability rock. However, for a single reservoir this assumption is probably reasonable. Therefore this model is considered for this project study.

The water flow velocity is calculated by Equation 21 where F_w is the water flow rate in surface units, B_w is the water formation volume factor, Φ is the average porosity of the two cells and A is the flow area between two cells.

$$V_w = B_w \frac{F_w}{\phi A} \tag{21}$$

The reduction in viscosity of the polymer solution is assumed to be reversible as a function of the water velocity. The resulting shear viscosity of the polymer solution is calculated by the Equation 22 where μ_{sh} is the shear viscosity of the polymer solution, $\mu_{w,eff}$ is the effective water viscosity, P is the viscosity multiplier and M is the shear thinning multiplies.

$$\mu_{sh} = \mu_{w,eff} \left[\frac{1+(P-1)M}{P} \right] \tag{22}$$

6.5.3 The Alkaline Model

ECLIPSE provides a simplified model that does not take into account the in-situ surfactant creation and the phase behavior. Alkaline conservation equation is taken into consideration for this model.

6.5.3.1 Alkaline conservation equation

The alkaline is assumed to exist only in the water phase a concentration in a water injector. The distribution of the injected alkaline is modeled by solving a conservation equation which is given in Equation 23 where ρ_w,ρ_r is the water and rock density, C_a is the alkaline concentration, C_a^a is the adsorbed alkaline concentration, μ_{seff} is the effective viscosity of the salt, D_z is the cell center depth, B_w B_r is the water and rock formation volume respectively, T is the transmissibility, k_{rw} is the water relative permeability, S_w is the water saturation, V is the block pore volume, P_w is the water pressure and g is the gravity acceleration.

$$\frac{d}{dt}\left(\frac{VS_w C_a}{B_r B_w}\right)+\frac{d}{dt}\left(V\rho_r C_a{}^a\frac{1-\phi}{\phi}\right)=\sum\left[\frac{Tk_{rw}}{B_w\mu_{seff}}(\delta P_w-\rho_w g D_z)\right]C_a+Q_w C_a \tag{23}$$

6.5.3.2 Treatment of adsorption

The adsorption of alkaline is assumed to be instantaneous. The isotherm adsorption is specified as either a look-up table of adsorbed alkaline as a function of alkaline concentration using the ALKADS keyword or by a generic analytical adsorption model using the ADSORP keyword.

If desorption is prevented then the adsorbed alkaline concentration may not decrease with time. If desorption is allowed then each grid block retraces the adsorption isotherm as the alkaline concentration falls in the cell.

6.5.3.3 Alkaline effect on water-oil surface tension

The effect of alkaline on the water-oil surface tension is modeled by a combination effect with surfactant. The modification is done by the water-oil surface tension which is given in Equation 24.

$$\sigma_{wo}=\sigma_{wo}C_{surf}A_{st}C_{alk} \tag{24}$$

Where $\sigma_{wo}C_{surf}$ is the surface tension at surfactant concentration as well as zero alkaline concentration and $A_{st}C_{alk}$ is the surface tension multiplier at alkaline concentration.

6.5.3.4 Alkaline effect on surfactant/polymer adsorption

The alkaline can reduce the adsorption of both surfactant and polymer on the rock surface. This is modeled by modifying the mass of adsorbed surfactant or polymer which is given in Equation 25 where V is the pore volume of the cell, Φ is the porosity, ρ_r is the mass density of the rock, $C^a{}_{s,p}$ is the surfactant/polymer adsorbed concentration and $A_{ad}C_{alk}$ is the adsorption multiplier at alkaline concentration.

$$\text{Mass of adsorbed surfactant} = V\rho_r C^a{}_{s,p}\frac{1-\phi}{\phi}A_{ad}C_{alk} \tag{25}$$

6.6 Significant keywords to activate ASP Model in Eclipse 100

There are some major keywords which are very fundamental to activate ASP Model in Eclipse 100, some are optional. The Polymer keyword as well as the Surfactant keyword should be active with alkaline keyword. The keyword has shown in Table 5, should include in the RUNSPEC section and SCHEDULE section to activate ASP model in the Norne E-segment data file which is obligatory. The keyword include in the RUNSPEC section sets the concentration of surfactant, polymer and alkaline in a water injector. Table 6 shows the keywords are used in the PROPS section in the ASP model [36].

Table 5: Important keyword for ASP model with Eclipse.

RUNSPEC	SCHEDULE
POLYMER **SURFACT** **ALKALINE**	**WSURFACT** **WALKALIN** **WPOLYMER**

Table 6: ASP Keywords in the PROPS section .

Keyword	Description
SURFST	Water-oil surface tension in the presence of surfactant
SURFVISC	Modified water viscosity
SURFCAPD	Capillary de-saturation data
SURFADS	Adsorption isotherm
SURFROCK	Rock properties and adsorption model indicator
PLYADS	Polymer adsorption isotherms.
ADSORP	Analytical adsorption isotherms with salinity and permeability dependence.
PLYMAX	Polymer/salt concentrations for mixing calculations.
PLYROCK	Specifies the polymer-rock properties.
PLYSHEAR	Polymers shear thinning data.
PLYVISC	Polymer solution viscosity function.
PLYVISCS	Polymer/salt solution viscosity function.
RPTPROPS	Controls output from the PROPS section.
SALTNODE	Salt concentration nodes for polymer solution viscosity.
TLMIXPAR	Todd-Longstaff mixing parameter.
ALSURFST	Table of oil/water surface tension as a function of alkaline concentration
ALSURFAD	Table of surfactant adsorption as a function of alkaline concentration
ALPOLADS	Table of polymer adsorption as a function of alkaline concentration
ALKADS	Table of adsorption functions
ALKROCK	Specifies alkaline-rock properties

Chapter 7

Result of Simulations

7.1 ASP Synthetic Model in Eclipse

A synthetic model of dimension 15, 15, 5 in I, J and K directions respectively, has been done by using Eclipse100. Two wells, one producer and one injector have been created in grids 15, 15, 5 and 1, 1, 5 respectively. This is a homogenous and flat reservoir which is shown in Figure 41. All properties such as fluid properties, rock properties and reservoir properties, have been used in this model is from Norne reservoir dataset. But the properties of surfactant, polymer and alkali is used from the previous thesis work which is done by Simulation has been run for 600 days starting from 1 Jan, 2011.

The following cases were simulated;

- Base case with only water flooding
- Effect of Continuous ASP flooding.
- Effect of ASP slug injection
- Effect of Adsorption
- Comparison between vertical and horizontal well;

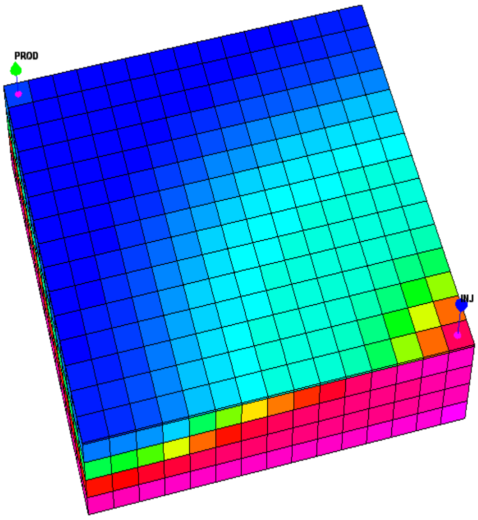


Figure 41: Synthetic model for ASP flooding simulation.

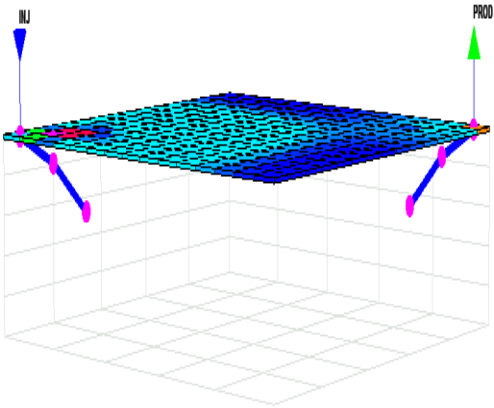


Figure 42: Horizontal well placed for continuous ASP flooding.

Figure 42 shows the schematic of synthetic model when horizontal well was placed instead vertical well. It is obvious that, vertical well has perform better than horizontal well because few layers considered in this model. Therefore, It can be conclude that for few layers reservoir vertical well is sufficient than horizontal well. Figure 43 shows the effect of continuous ASP flooding into the synthetic model. The black line represents the ASP flooding whereas red line represents the base case. Figure 43 illustrates that the recovery factor goes to 94% for the ASP flooded reservoir where as base case with no alkaline-surfactant-polymer flooding (only water flooding) gives only 76% recovery factor. Thus, from the fore-going, it is obvious that the eclipse surfactant option works in recovery of residual oil. Thus this model will be applied to the Norne E segment.

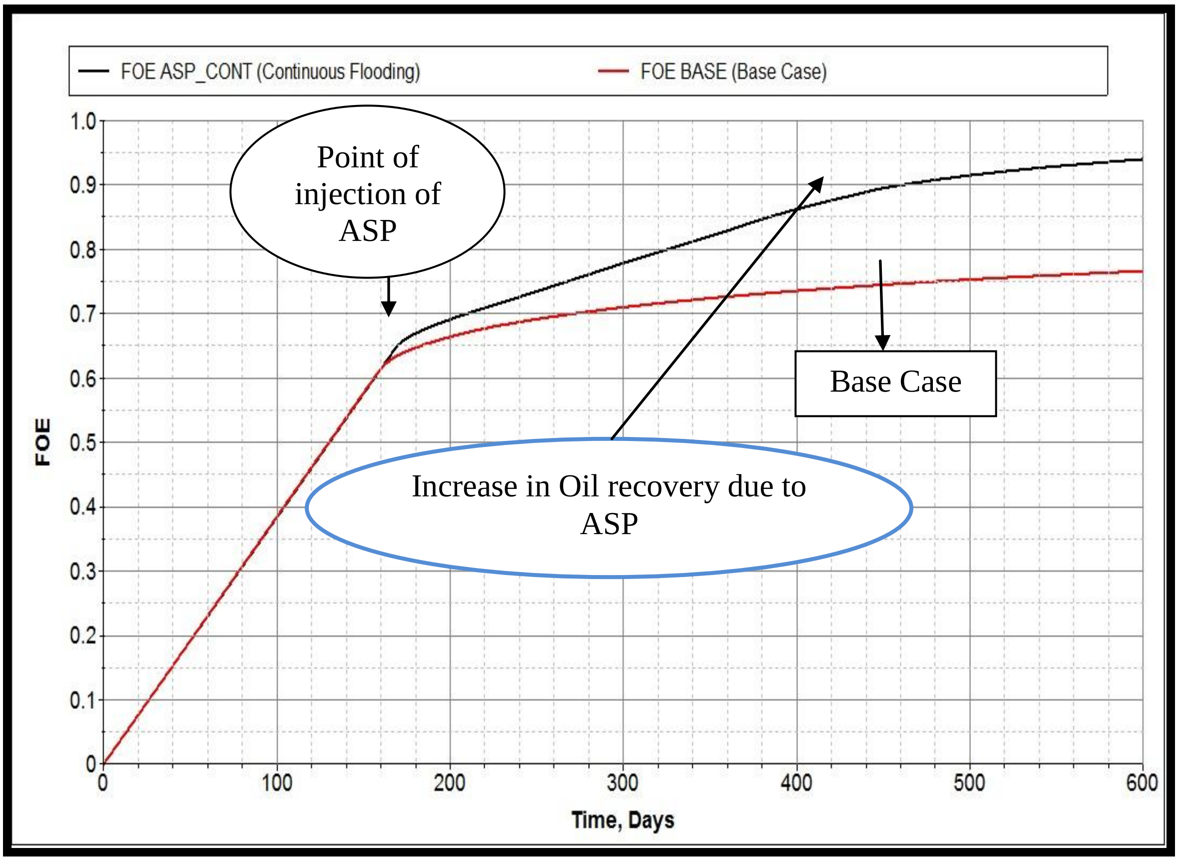


Figure 43: Effect of continuous ASP flooding on oil efficiency.

Figure 44 through 48 shows the effect of ASP continuous flooding on oil production rate, oil production total, water production rate, water cut and pressure.

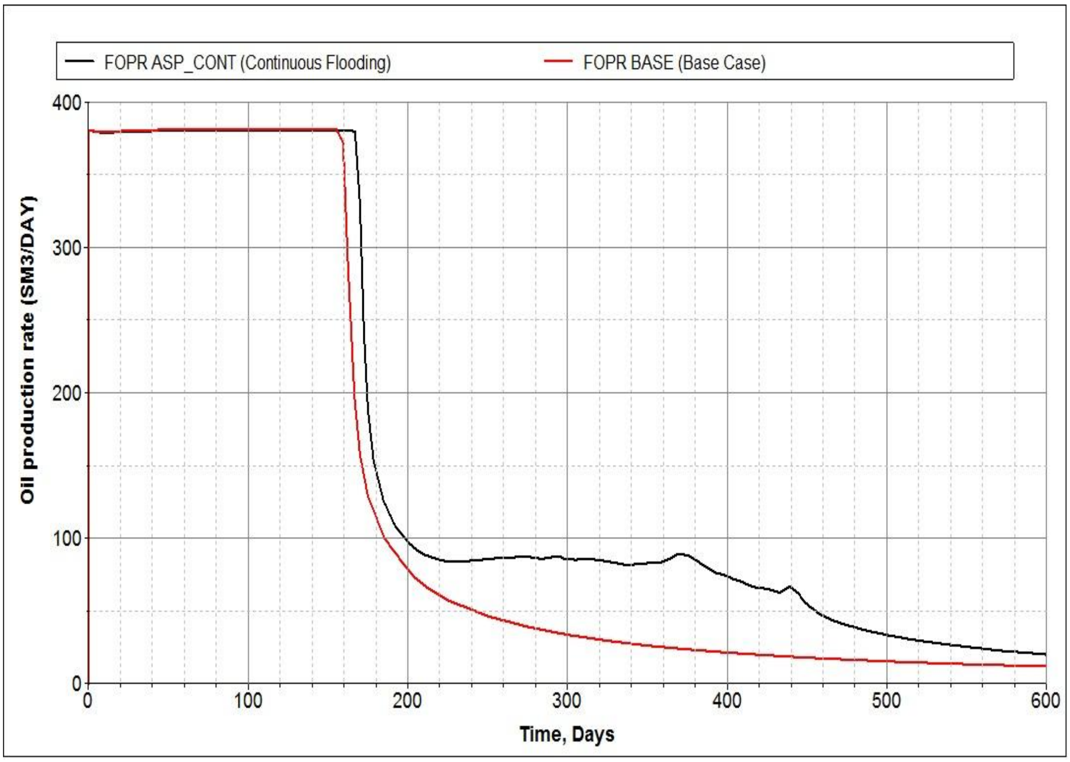


Figure 44: Effect of continuous ASP flooding on Oil Production.

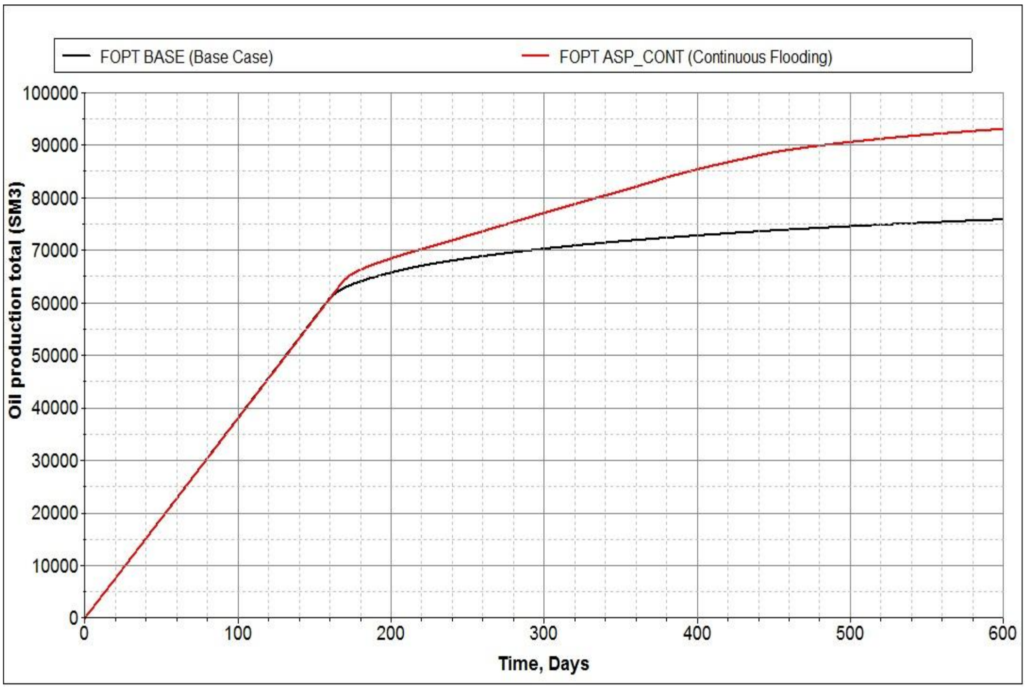


Figure 45: Effect of continuous ASP flooding on cumulative Oil Production.

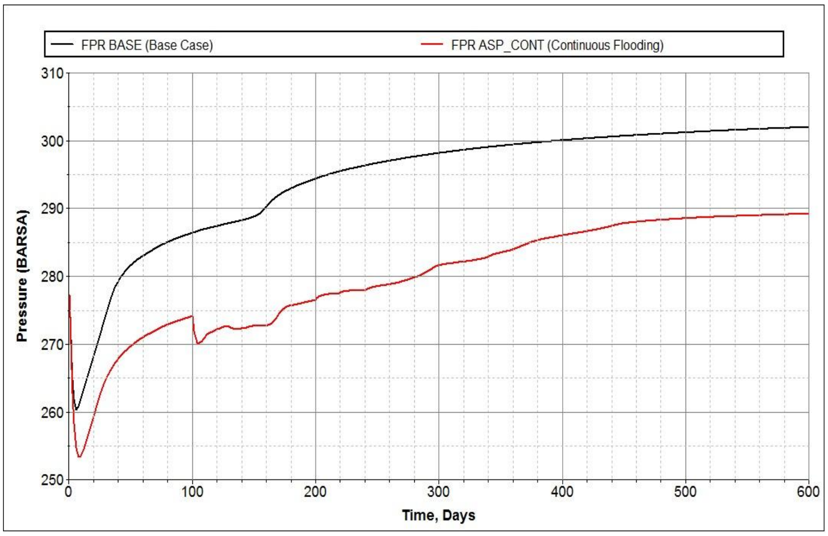


Figure 46: Effect of continuous ASP flooding on Reservoir Pressure.

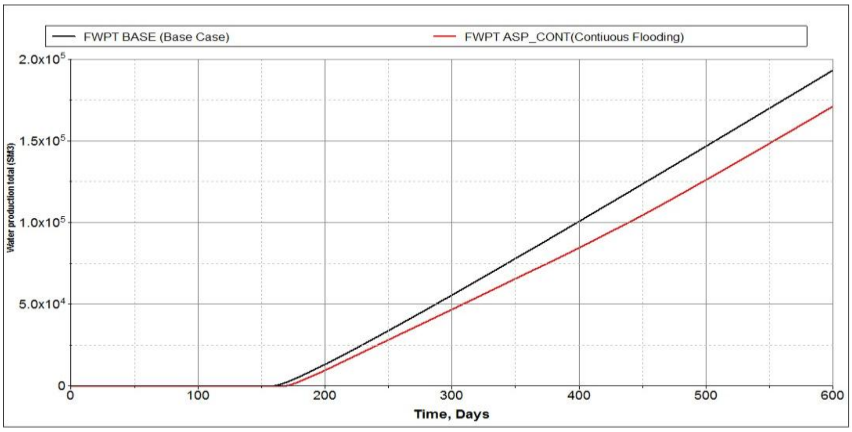


Figure 47: Effect of continuous ASP flooding on Cumulative Water Production.

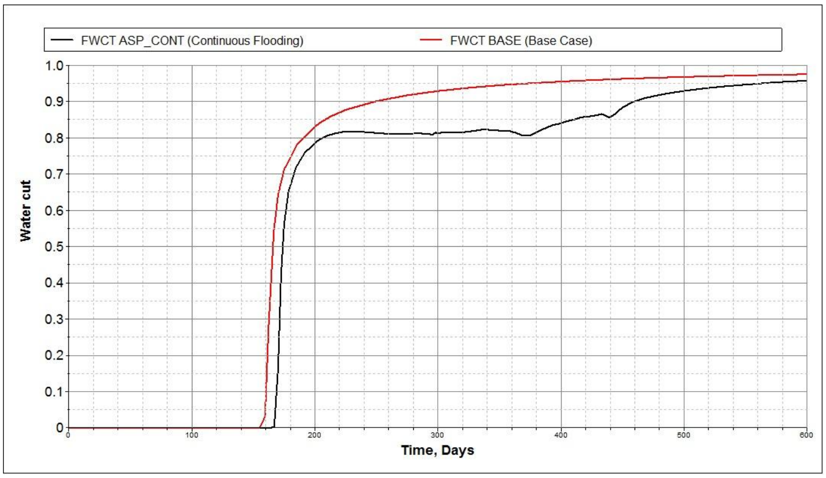


Figure 48: Effect of continuous ASP flooding on Water Cut.

7.2 ASP Model at Norne E-segment

The Norne data provided by Statoil ASA are made available through the Center for Integrated Operations in the Petroleum Industry (IO Center), which includes several research program with its center located at NTNU/SINTEF in Trondheim.

As Norne field drive mechanism is water flooding and there is no study available of the properties of alkali, surfactant and polymer which are compatible with Norne reservoir. As a matter of fact the chemical (alkali, surfactant and polymer) properties used in this model are not the real data. It is assumed that the chemical properties are compatible with the reservoir and fluid properties. Also, all chemicals are injected with pure water and there is no salinity effect.

Again modeling the injection of ASP into an oil reservoir should be a systematic process due to the high cost of chemical. For example, if slug injection of surfactant could give the same increased oil recovery as continuous injection, then the latter becomes unnecessary as this will give rise to increased expenditure. In this thesis, there is a step by step modeling of what method of ASP injection to use. Several cases were examined ranging from continuous surfactant injection with different periods of injection, to slug injection with different intervals. Also, the appropriate surfactant concentration was determined and the most profitable well configurations were examined.

7.2.1 Continuous ASP Flooding

In continuous ASP injection, two cases were considered; injection of ASP continuously for five years starting from 2010 and injection of ASP continuously for seven years, also starting in 2010. The concentration of alkali is 2 Kg/m^3, polymer is 0.4 Kg/m^3 and surfactant is 5 Kg/m^3.The aim was to ascertain which would give a better recovery.

A figure 49 shows the oil production rate for the two cases. All ASP cases gave better oil production rates compare with the base case. The next challenge was to examine which period is more viable: seven or five years. From the study it can be seen that it is rather wasteful to inject chemical (alkali, surfactant and polymer) for seven years because the incremental oil produced is not encouraging. Also, flooding for seven years led to a high quantity of chemical like surfactant injected into the reservoir, which resulted in very high quantities of surfactant, undermining the expensive nature of the chemical. From Figure 50, the total surfactant injected into the E-Segment is shown to be about 146 million kg for 7 years and about 110 million kg for 5 years. Thus, injecting ASP for five years is better than seven years. As surfactant is expensive, here surfactant is only shown by the graph and consider for comparative study. It is required more polymer and alkali for injection into the reservoir for 7 years than 5 years. However, the volume and the cost of ASP needed for five years is still a considerable amount because chemicals are relatively expensive.

Next, we looked at ASP slug injection and compared it with continuous ASP injection.

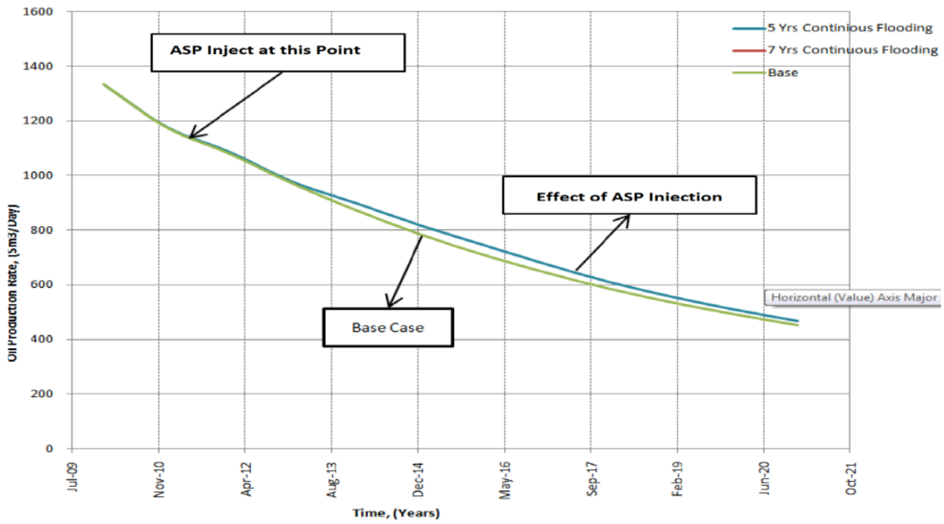


Figure 49: Oil production rate for continuous surfactant flooding for five and seven years.

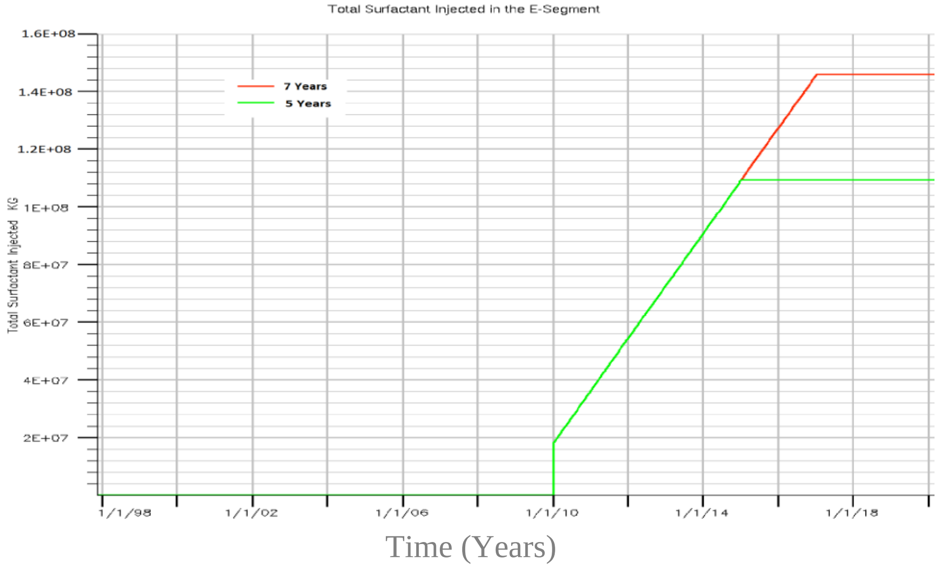


Figure 50: Total surfactant injected for five and seven years continuous flooding.

7.2.2 ASP Slug Injection

ASP slug injection involves injecting a certain volume of alkali, surfactant and polymer for a period of time followed by water. Two cases were modeled; injecting with four month intervals and injection with two month interval (Figures 51 – 55). The concentration of alkali is 2 Kg/m^3, polymer is 0.4 Kg/m^3 and surfactant is 5 Kg/m^3. Again as surfactant is an expensive chemical rather than polymer and alkali, surfactant injection is compared to take the discussion which would give the better result.

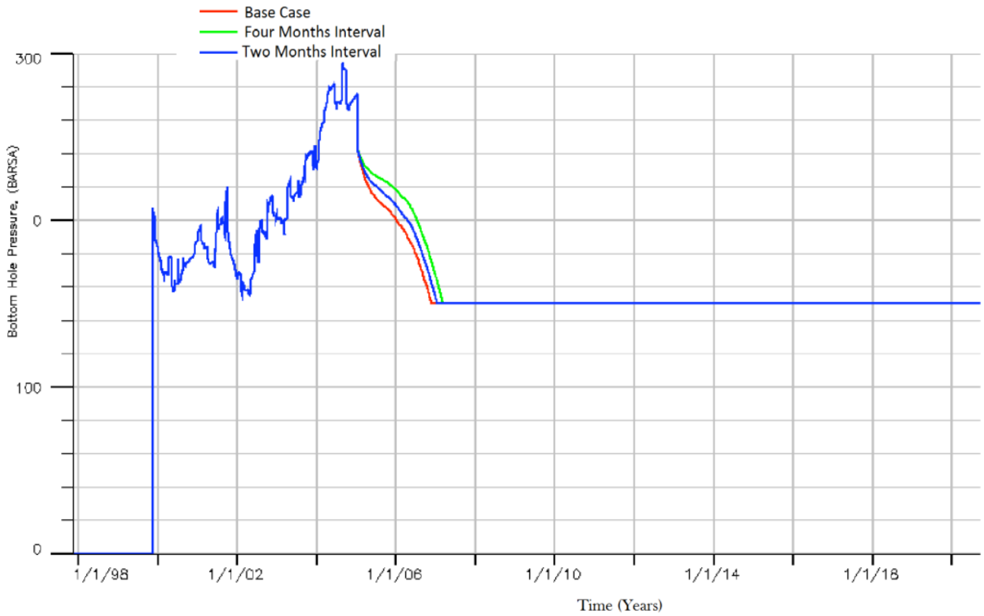


Figure 51 : Bottom hole pressure vs. time for the base case against the four month interval case and the two month interval case.

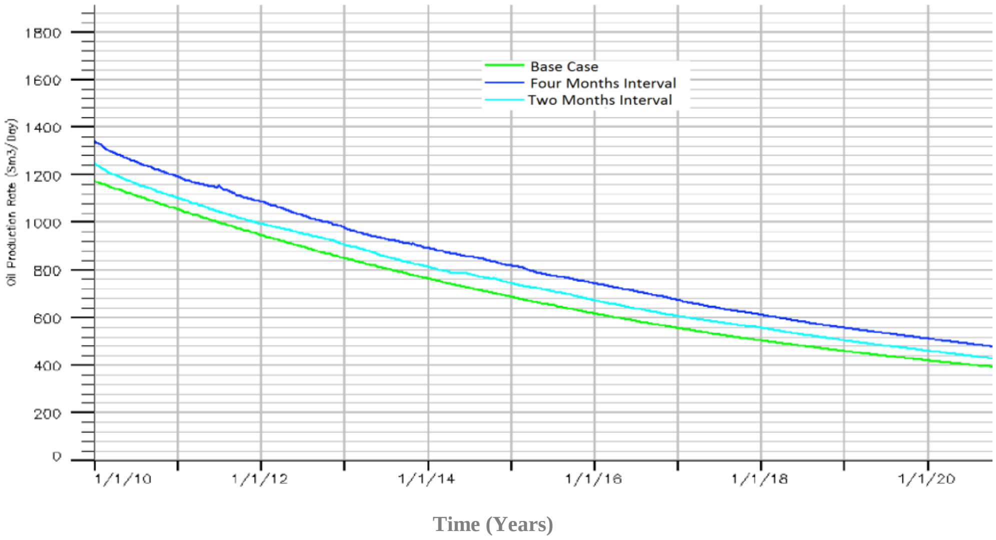


Figure 52 : Oil production rate vs. time for the base case against the four month interval case and the two month interval case.

Figure 51 show the bottom hole pressure variations for ASP slug compared to the base case. Pressure is increasing with ASP injection into the reservoir. Using 4 month intervals gave a better pressure increase that using 2 month intervals.

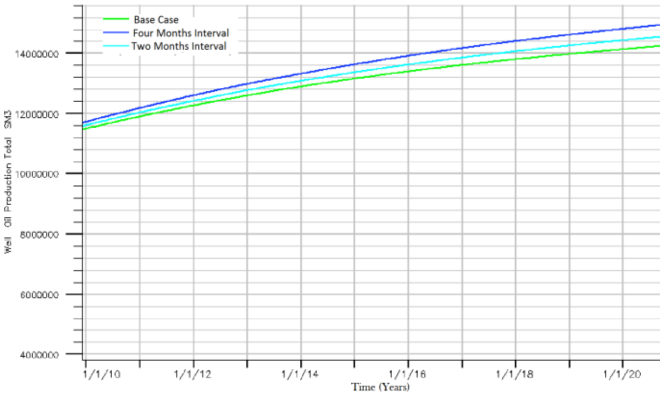


Figure 53 : Total oil production vs. time for the base case, four month interval case and two month interval case.

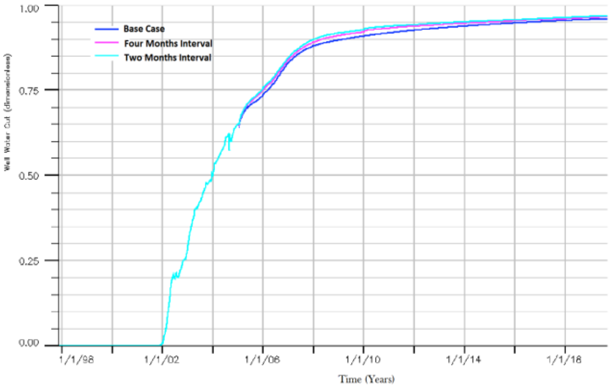


Figure 54: Well water cut vs. time for the base case, four month interval case and two months interval case.

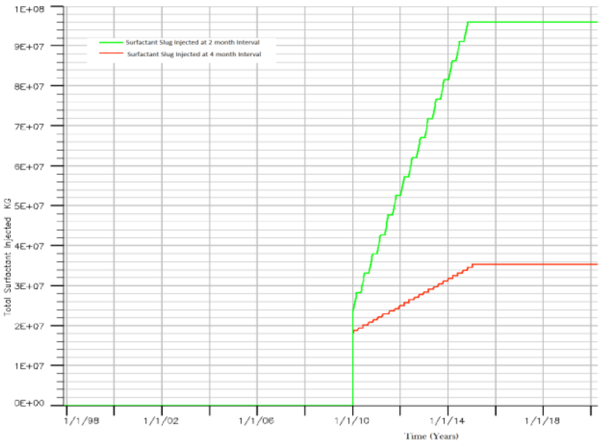


Figure 55: Total surfactant injected for 4 month intervals and 2 month intervals.

Figures 52 and 53 describe the oil production rate and the total oil production for ASP slug injection at four months and two months interval compared to the base case (with a two months break for both cases). After injection of ASP in 2010 followed by water, there is a significant increase in oil production rate compared to base case at first, but with a subsequent decrease. The same scenario can be observed from the total oil production.

Two month intervals give a better result than the other case. Looking at the total mass of surfactant needed for both 4 months injection period and 2 months injection period, it can be seen that about 95 million kg is required for 2 months while about 35 million kg is required for 4 months intervals.

Figure 54 show the water cut with the time. As expected the water cut decreases with increasing oil production. This is because some of the injected water is displacing the oil, and therefore reduces the amount of water produced.

From all studies, it was discovered that injecting ASP every four months is the better solution than every two months, and injecting every 6 months is not necessarily better than injecting every 4 months.

The next step is to compare the continuous ASP injection of five years with the slug injection of two months interval over a period of five years.

7.2.3 Comparison Between Continuous and Slug Injection

Figure 56 and 57 show the comparison between ASP slug and continuous ASP injection over a five year period. Figure 56 show the production rate for the cyclic to be about 1190 Sm3/day in 2010 while for continuous ASP flooding the production rate is about 1400 Sm3/day at the same period. Though continuous injection shows to give the best increase in oil production, cyclic will be a better economical choice because total chemical needed for cyclic injection is less than for continuous injection in the same period of time. As an example surfactant needed for continuous flooding is about 47 million Kg and 29 million Kg for Cyclic. Therefore, by all analysis, the option of ASP slug for injection into the reservoir for a five year period at intervals of four months is the most appropriate.

The next step was to model for different concentration.

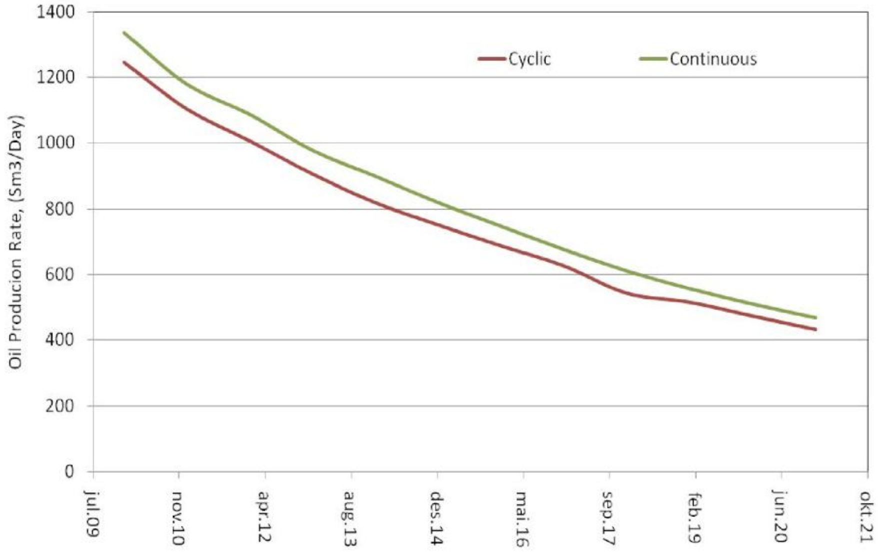


Figure 56: Oil production rate vs. time for the cyclic and continuous case.

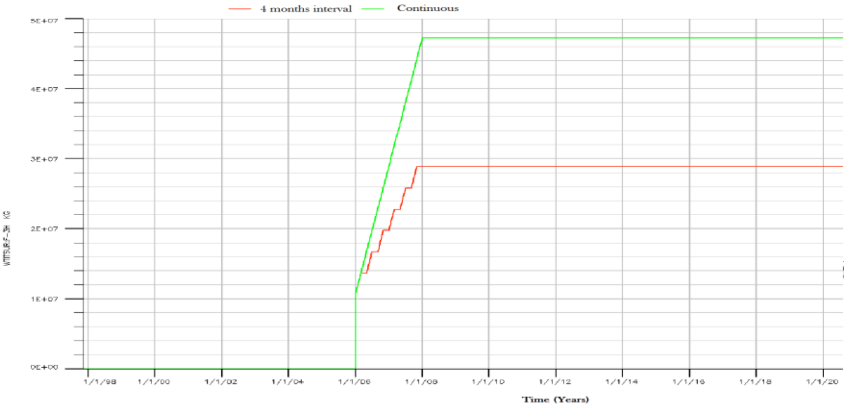


Figure 57: Total surfactant injected over a five year period in a continuous and a cyclic process.

7.2.4 Appropriate ASP concentration

From modeling in the previous sections, it was discovered that flooding pattern should be for 5 months Interval for 5 years. The chemical concentration used during the modeling was: alkali-2 kg/m3, polymer-0.4 Kg/m^3 and surfactant-5Kg/m^3. However, it is not certain if this are the best chemical concentration that would reduce residual oil to the barest minimum while ensuring that maximum profit is obtained.

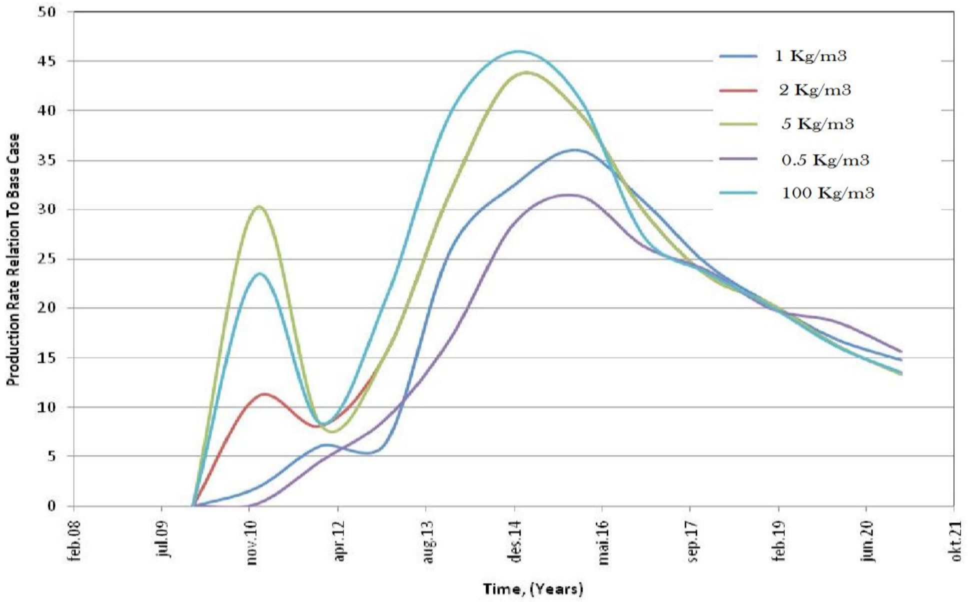


Figure 58: Production rate in relation to the base case for different concentrations.

Based on previous studies, several concentrations were tested on Norne E-segment by trial and error method in order to come up with the right amount of chemical that would give a profitable recovery and thereby reducing residual oil saturation to the possible minimum. For this reason, chemical concentration is optimized. For the optimization, different concentration is used. As an example: concentration of alkali was 2 Kg/m^3 and 5 Kg/m^3 while polymer concentration was 0.2 Kg/m^3, 0.4 Kg/m^3, 0.5 Kg/m^3, 0.7 Kg/m^3 and 1 Kg/m^3 and surfactant concentration is used 0.5 Kg/m^3, 1 Kg/m^3, 2 Kg/m^3, 5 Kg/m^3 and 10 Kg/m^3. Finally by fixing alkali and polymer concentration, surfactant concentration is changed. Concentration of alkali is used here 2 Kg/m^3, while polymer concentration is 0.5 Kg/m^3. Figure 60 shows the production rate in relation to the base case with time when the injection starts in 2010 and lasts for five years. It can be seen that increasing surfactant concentrations led to increase in the production rate. 0.5 kg/m^3, 1 kg/m^3, 2 kg/m^3, 5 kg/m^3 and 10 kg/m^3 were the concentrations considered and modeled, WOPR, WOPT among other plots made indicated 1 kg/m^3 as good concentration. Figure 58 show the production rate in relation to the base case

7.2.5 Effect of No. of Well

In the beginning of this project, one of the scenarios we wanted to look at was what difference it would make to inject in only one well compared to injecting in both wells. We know that injecting in one well would be problematic due to the use of seabed templates in the Norne field. Since we didn’t know enough about the practical circumstances of ASP injection, we want to include the result, which we suspected would give a more profitable result. We compared injection in one well vs. both wells using 4 month interval injections for five years (Figure 59).

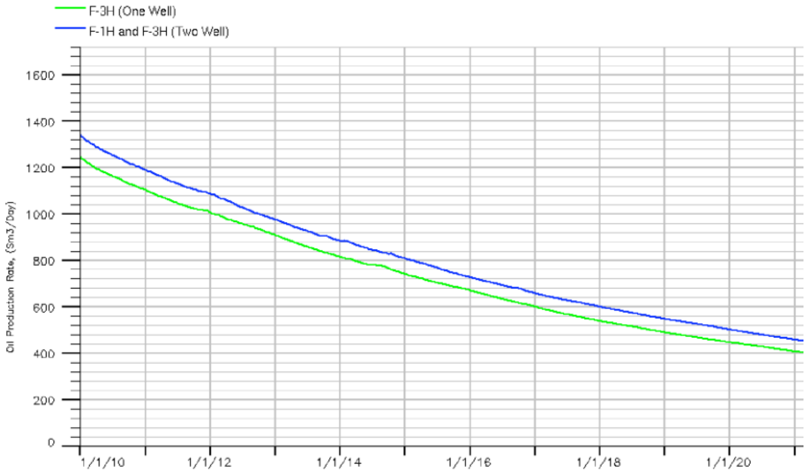


Figure 59: Oil production rate vs. time for the one and two well case.

ASP injection in only F-3H gave a better economic result. We observed the highest recovery using both injectors, but this was less profitable considering the amount of chemical needed for both wells. We carried out optimization on the injection rate and noted that 8000 Sm3/day was good for F-1H while 5000 Sm3/day was good for F-3H.

7.3 Effect of Additional Well in the Norne E-segment

To see the effect of additional well with the existing into the reservoir, a new well which is named by E-1H (Figure 61) is taken into consideration and optimized the rate, location etc. Then further investigate the various cases to get the better one. Figure 60 shows the total field production with and without new oil.

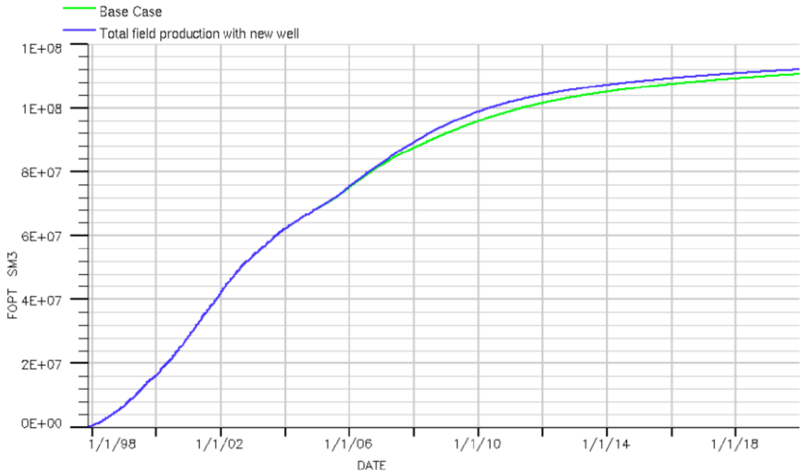


Figure 60: Total field production rate for base case and new well case.

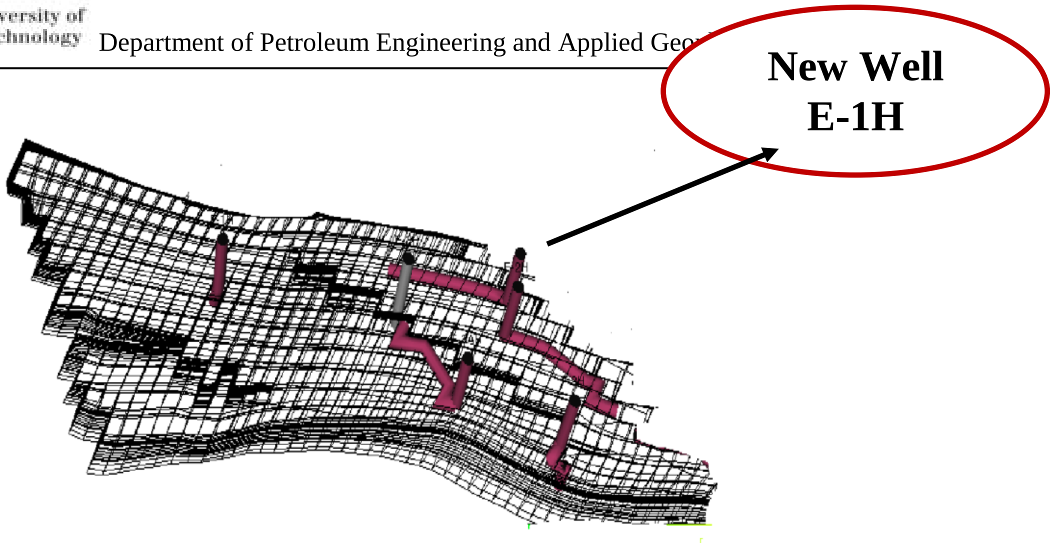


Figure 61: Schematic of Norne E-segment with new oil.

7.3.1 Effect of ASP flooding on new well

Injecting ASP for the new well case has the same injectors as the old case. Several scenarios were tried out, both continuous and cyclic injection. Figure 62 shows the oil production rate for new well to see the effect of the new oil.

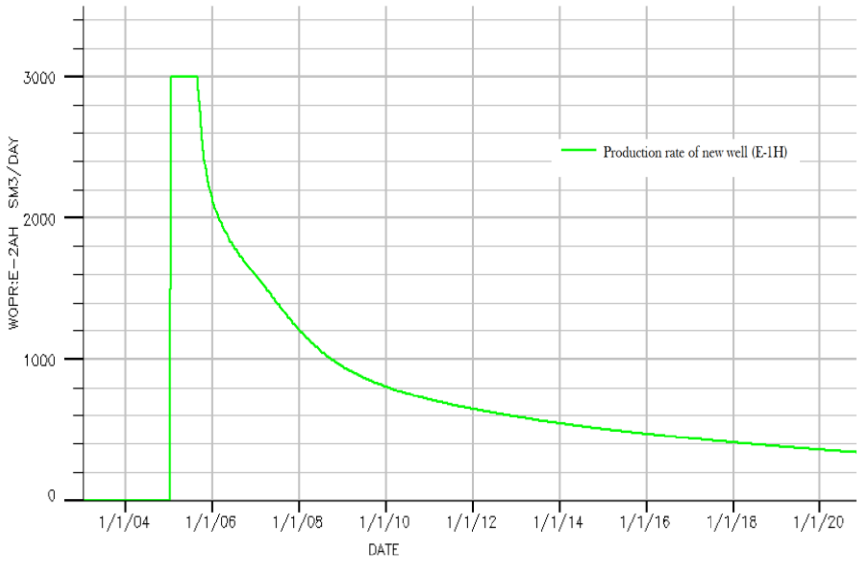


Figure 62: Production rate for new well, E-1H.

7.3.2 Continuous ASP injection in new well

In continuous ASP injection for the new well only one scenario was considered, four year injection, starting in 2010. Figure 63 shows four year continuous injection for four different concentrations, alkali-2 Kg/m^3, polymer-0.2 Kg/m^3 and surfactant- 0.3 Kg/m^3; alkali-2 Kg/m^3, polymer-0.2 Kg/m^3 and surfactant- 0.5 Kg/m^3; alkali-2 Kg/m^3, polymer-0.2 Kg/m^3 and surfactant- 1 Kg/m^3; alkali-2 Kg/m^3, polymer-0.2 Kg/m^3 and surfactant- 5 Kg/m^3 . All rates are compared to a base case for the same period of time without ASP injection. As you see from the figure, injecting 5 kg/m^3 may not be any better solution than injecting 1 kg/m^3 or 0.5 kg/m^3. Since surfactant is expensive and doubling concentrations does not double the production rate. Therefore it is not required to consider the high concentration of chemical. From Figure 64, it is obvious that the total amount of surfactant injected in well F-1H is about 147 million kg for a concentration of 1 kg/m^3 and 80 million Kg for a concentration of 0.5 Kg/m^3.

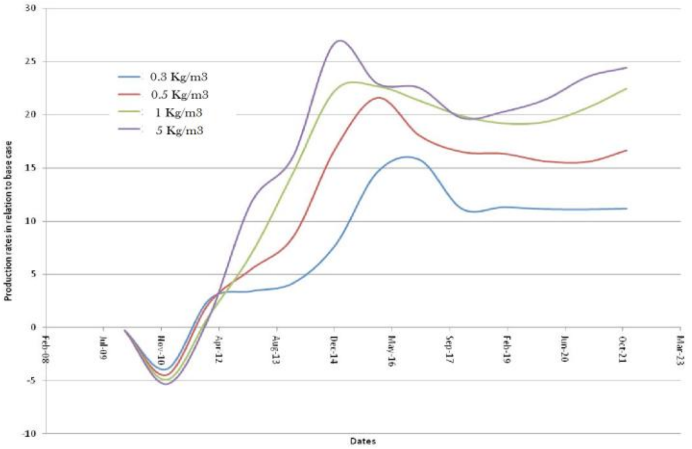


Figure 63: Production rates in relation to base case when injection starts in 2010 and last for four years.

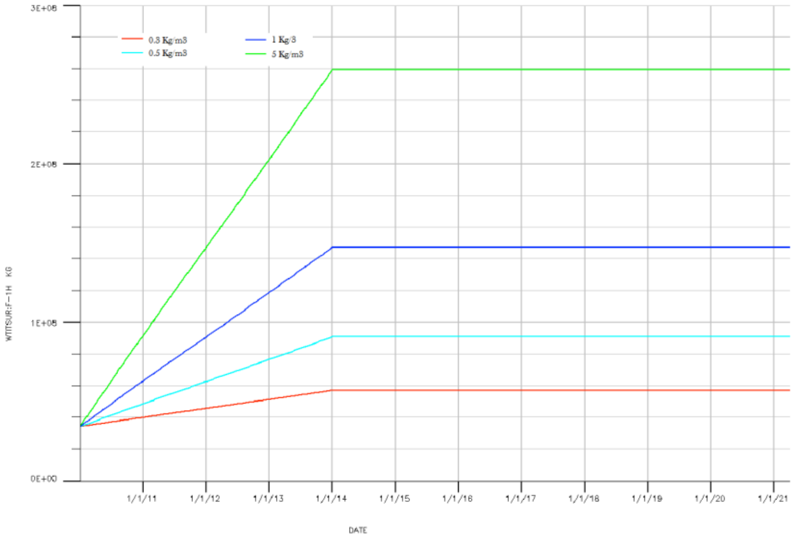


Figure 64: Total amount of surfactant injected in well F-1H for the four different injection cases in 2010.

7.3.3 Time of injection

Injecting 0.5 kg/m^3 surfactant for a two year period in 2006, 2010 and 2015 gave different production rates and cumulative production for the new well. Since Norne field

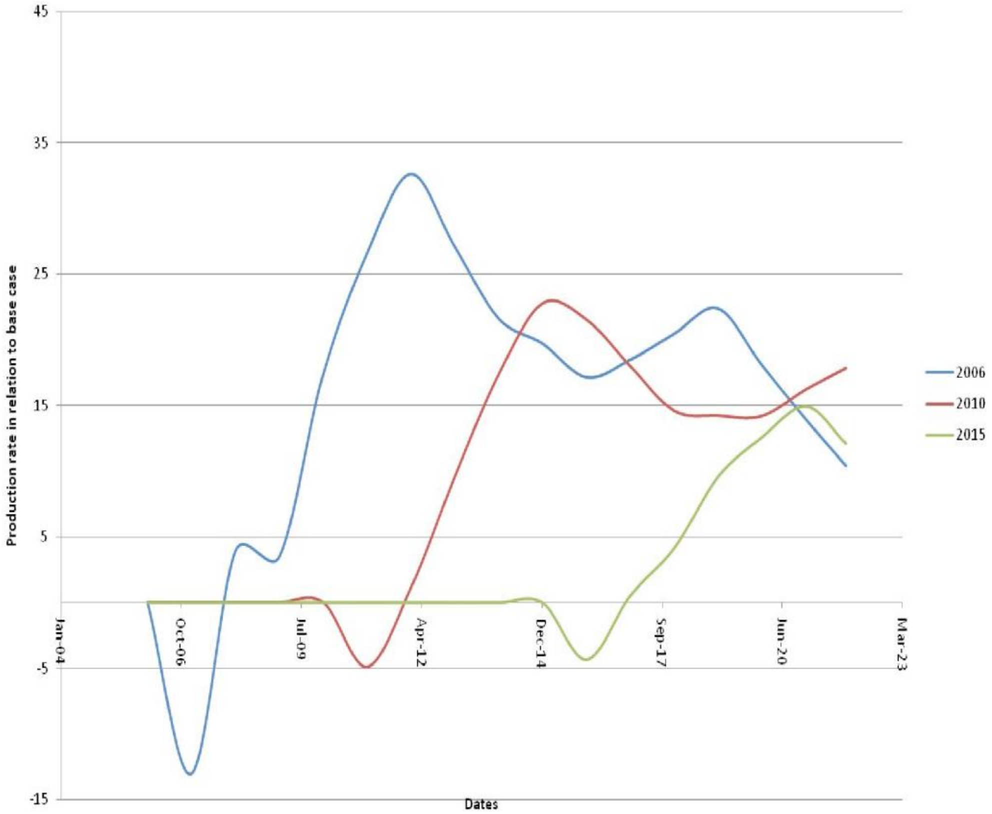


Figure 65: Production rate in relation to base case with different start time for injection of 2 year slug.

is scheduled to be shut down in 2022 it is most profitable to inject ASP earlier such as in 2006. As we see from Figure 65 the production rate will be highest for injection in 2006, followed by 2010 and 2015 as the least good result.

7.3.4 Effect of No.of Well

In Norne E-segment both F-1H and F-3H are injection wells. Looking at the effect of injecting ASP followed by water flooding in only F-3H, indicates a decrease in oil production rate as seen in Figure 66. Injector F-3H was chosen since this is the well with best communication to the new producer E-1H. By removing F-1H as an injector for ASP injection, which has a high injection rate, an extensive use of chemicals could be neglected. This implies that chemical should only inject in well F-3H for this scenario may be a good option for the most profitable solution.

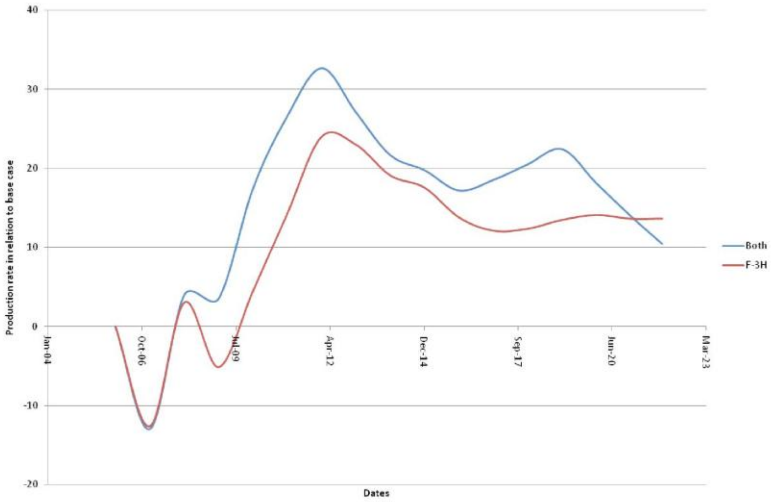


Figure 66: Effect of production rate in relation to base case by only using F-3H or both injectors.

7.3.5 Cyclic vs. continuous injection

By using cycles when injecting you may not decrease the production rate significantly, but save the amount of chemical used drastically. Using a cyclic rate of two months of injection with ASP and two months of injection without will reduce the amount of chemical used by half. As you see from Figure 67 the decrease in production rate is not significant for a cyclic injection process. The difference in total oil produced will be about 160000 bbl, while amount saved surfactant will be about 47 million kg for a cycle of two years. Therefore it will not be profitable to inject continuous compared with cyclic injection.

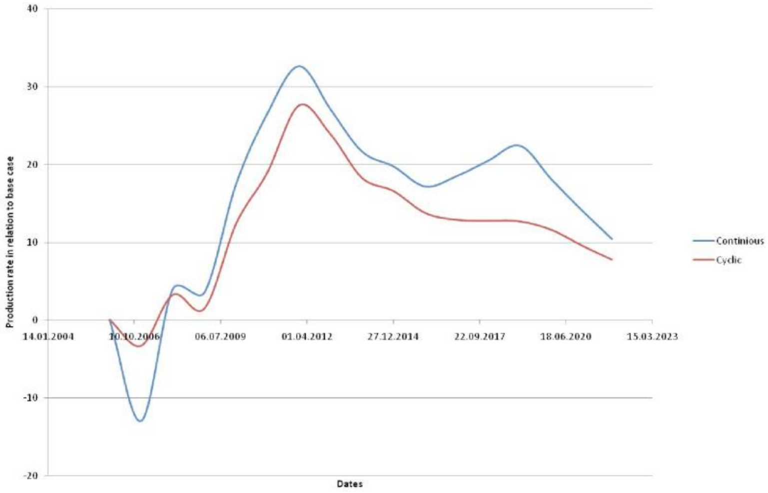


Figure 67: The effect of using continuous injection or cyclic injection in relation to base Case.

We therefore chose to look at injection in only well F-3H from 2006 with cyclic injection. The lengths of cycles were set to be either two or four years; the concentration of alkaline to be 2 kg/m^3, polymer 0.2 kg/m^3 and surfactant 0.5 kg/m^3 or alkaline 2 kg/m^3, polymer 0.2 kg/m^3 and surfactant 1 kg/m^3. Four simulation cases have studied for this purpose

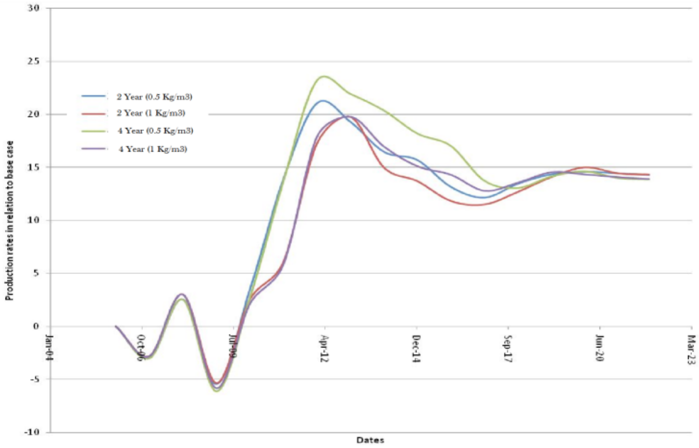


Figure 68: Different cyclic injection scenarios in relation to base case.

with different amount of chemicals injected over various periods of time. As from Figure 68, it can be observe that the case with four year injection gave the highest oil production rate for the longest time period. But injection 1 kg/m3 over a period of four years with an injection rate of 5000 Sm3/day will lead to large amount of chemical injected compared to the increase in oil recovered.

The difference of injecting surfactant for a two or four year period does not show significant increase in total oil produced. For a concentration of 1 kg/m^3 over two and four years the difference in total oil recovered is about 80000 bbl, while for a concentration of 0.5 kg/m^3 over difference is about 67000 bbl.

In comparison with the base case the most profitable solution for the new well case seems to be a two year cyclic injection period with a concentration of 1 kg/m3. In this case the increase from the base case is 211.000 bbl. This case is also the case which demands the least amount of chemicals such as the total surfactant consumption of about 19 million kg.

Chapter 8

Economic Evaluation

8.1 Prediction of oil price

The price of a barrel of oil is the result of a number of competing factors; how much oil is available; how much oil is demanded by consumers; how much it costs to get oil from the ground to the consumer; the price of dollars and the potential that oil speculators see for the price to rise or fall.

Many of the long-term global trends point to steady increases in the price of oil. Reserves are finite so the commodity is slowly becoming scarcer, something that pushes the price up. The explosion of development in countries like China and India has created more demand as those and other developing regions industrialize. They build more roads and increase manufacturing, all of which requires oil.

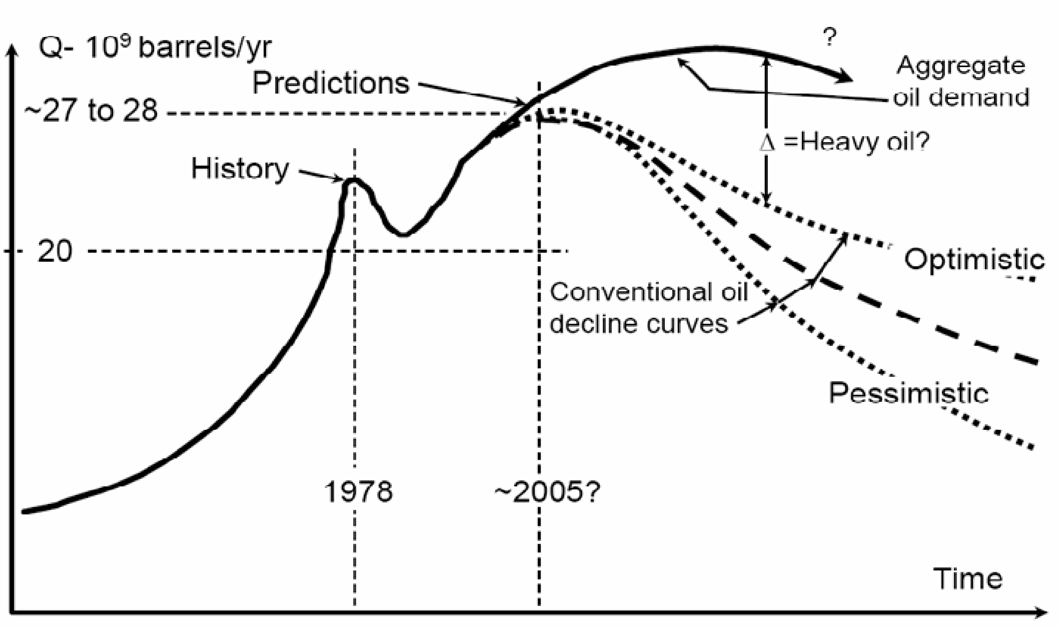


Figure 69: The future for oil production, expectations in 2005

The bearish argument is that technological new energy developments (solar, wind, etc.) should begin to reduce the world's dependence on oil. Supply is fettered by the countries that export it. The Organization of the Petroleum Exporting Countries (OPEC) meets regularly to set the amount they are willing to release onto the market. OPEC oil accounts for approximately 35 million of the 80 million barrels released onto the global market each day.

OPEC can reduce output as a means to push prices higher and can increase it to meet greater demand. It is tempting to think that all the producers are motivated simply by a high price. In fact, for some countries it may be beneficial to have a lower price if it means they can maintain, or increase, the volumes they sell. Oil is priced in dollars so movements in that currency also impacts on crude. The weaker the dollar, the higher the dollar price of oil because it takes more dollars to buy a barrel.

8.2 Reserves and production

The long term ability of the oil market to meet demand depends on the magnitude of available reserves. An important category of reserves are proved reserves. Proved reserves are those quantities that geological and engineering analysis suggests can be recovered with high probability under existing technological and economic conditions.

Figure 70: Oil price history 1987–2011.

Proved reserves can be augmented through exploration and development of new discoveries, through technological improvements, as well as through the existence of more favorable economic conditions. In the past, all of these factors have contributed to augmenting the proved reserve base. Whether the proved reserve base grows over time or not depends in part on the level of production. As production proceeds, the level of proved reserves declines. Before new reserves are fully considered, the recovery methods in declining reserves are being enhanced such as polymer, surfactant and foam flooding. As new oil discoveries are made, recovery technologies improve, or as the price of oil rises, the stock of proved reserves increases.

8.3 Economy Evaluation

To make an economical evaluation of the surfactant injection a simple NPV evaluation was made. NPV of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values of the individual cash flows (Equation 26) [59].

NPV compares the value of a dollar today to the value of the same dollar in the future, taking inflation and returns into account. If the NPV of a project is positive, it should be accepted. However, if the NPV is negative, the project should probably be rejected because cash flow will also be negative. Many oil companies work with high discount rates, and a rate between 5-10 % is reasonable. 8% discount rate is used in the calculation of NPV.

$$NPV = \sum_{i=1}^{t} \frac{R_t}{(1+r)^t} - R_o \qquad (26)$$

This implies that the oil price, alkali chemical cost (alkali, surfactant and polymer) and discount rate play a very important role in the economical evaluation. In addition, operational cost and surfactant facilities costs must be considered. An economical evaluation of injection of ASP shows that long injection periods are not the best solution. High volumes of chemicals over a long time does not increase the oil production with a significantly amount compared to shorter time periods. As seen from the economic evaluation even five year periods are highly dependent on chemical costs and oil price. Very few cases will be profitable with a surfactant price of 3 \$/kg, Alkaline price 1.5 \$/kg and polymer price 4 \$/kg unless the oil price is correspondingly high. If the oil price is about 100 \$/bbl and chemical like surfactant would be 1 \$/Kg and polymer price decrease to 2 \$/Kg then both 0.5 kg/m3 and 1 kg/m3 concentrations for 5 years will result in a positive NPV. But reducing the oil price to 60 \$/bbl only gives a positive NPV for 5 year injection with 1 kg/m3. For the new well case the best surfactant results came when injecting high amounts of surfactant in both wells over a four year period. This however, will not be the best economical solution when chemical are very expensive. The cases where cyclic injection is in only well F-3H will give the lowest chemical cost, and still a good increase in oil recovery. For the case where 1 kg/m3 is injected in a two month cycle for two years it will give positive results for a low chemical price and high oil price. For injection in 2006 this gave a positive NPV result of \$ 5.39 million. While injecting same amount in 2010 gave a positive NPV of \$ 4,36 million. It seems the price of chemical plays a more important role than the oil price. Reducing the oil price to \$

60/bbl still gives positive results for NPV calculations, while increasing the chemical cost requires a oil price of $ 130/bbl, the oil price exceeds 100 $/bbl.

Another scenario that was discussed and simulated was the effect of doing cyclic injection compared with continuous injection. By using cyclic injections of i.e. two months instead of continuous flooding, surfactant required will be reduced. This is a good alternative since it did not reduce the production drasticly, but reduced the need of chemicals. This allows a higher chemical cost. For a two year injection period in 2006 both two weeks and two months cycles gave a positive NPV result.

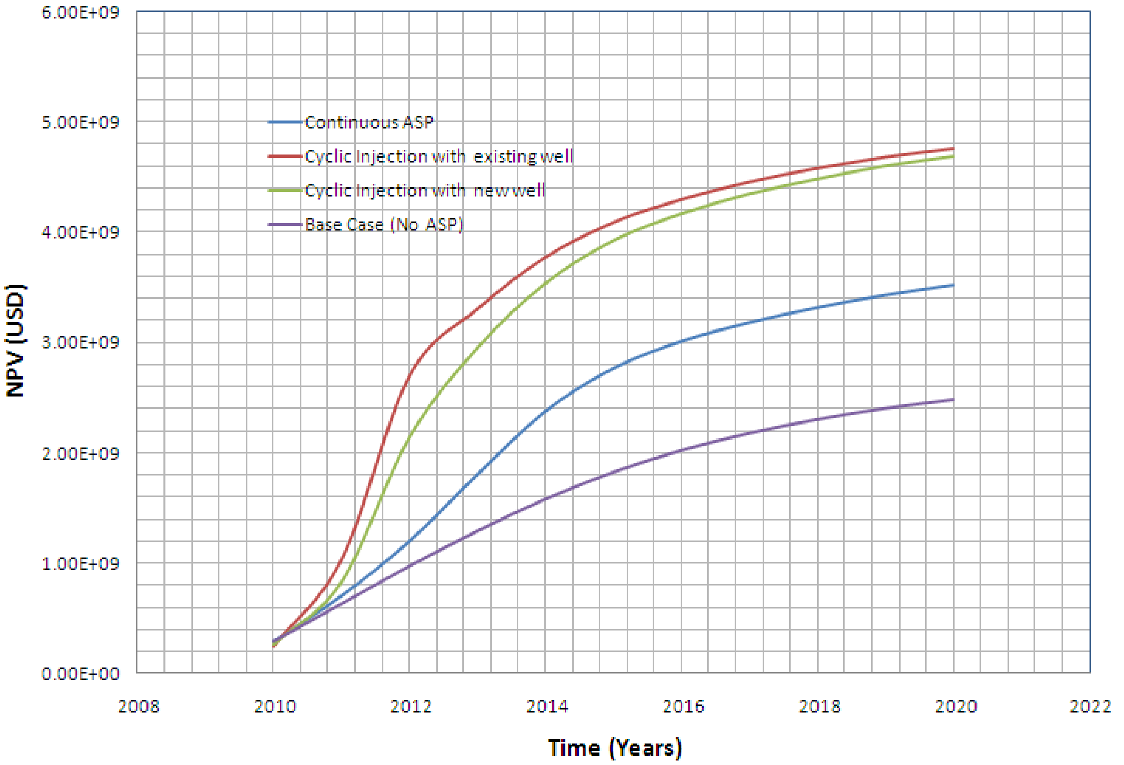


Figure 71: Plot of NPV for different scenario.

Figure 71 shows the plot of NPV for various scenario. It can be shown from the figure that chemical flooding like ASP is the good option for the trapped oil and it would be economical. As alkali reduces the amount of surfactant, therefore the chemical cost drastically reduces. So, ASP flooding is a good option rather than surfactant flooding though ASP flooding is a very complex process.

It is important to note that this is a simple economic analysis and that some costs are excluded. We have not calculated with tax on income and depreciation of investments, which in Norway are set to 78 % for both cases. This analysis therefore only give an idea of potential revenue and not profit by surfactant flooding.

Chapter 9

Discussion and Conclusion

9.1 Discussion

Chemical EOR technology is dramatically better than 30 years ago due to more experience, better understanding, better modeling, better enabling technologies and better chemicals at lower cost adjusted for inflation. However, Chemical EOR, especially ASP, is a complex technology requiring a high level of expertise and experience to successfully implement in the field

In this project, the effect of chemical flooding which is ASP (alkali, surfactant and polymer) flooding in the Norne E-segment for various scenario was investigate. Though the results were good but not as expected, and this deviation was traced to fairly good reservoir model.

Injecting different concentrations in both F-1H and F-3H showed that an increase in amount of chemical did not necessarily give a corresponding increase in oil production. Higher concentrations gave higher oil production rate and higher cumulative oil production, but it did not prove to be profitable due to the cost of chemicals (alkali, surfactant and polymer). Applying a concentration between 0.5–10 kg/m^3 seems to be the best alternative for ASP injection.

Using both injectors also lead to a much higher total injection rate. In case of this, it would therefore be a good alternative to only inject in one well, and F-3H is the best alternative. This is because F-1H is set at a higher injection rate in an area with low oil saturation. More chemicals (alkali, surfactant and polymer) will therefore spread out into the aquifer instead of attacking the residual oil.

Furthermore, an attempt was made to compare continuous flooding with cyclic flooding. But before this, duration of injection was looked into, two cases were considered; injection of ASP continuously for five years starting from 2010 and injection of ASP continuously for seven years also starting at 2010. The results showed, as expected, zero deviation between the two cases the first five years. Further, the increase in oil production for the seven year case was not noticeable in relation to the five year case.

The five year injection was therefore selected as the best option of these two. Furthermore, comparison between continuous and cyclic was done. By using cyclic injection, It is given more time to attack the residual oil to the chemicals and a more precise amount of chemicals can be injected. Another advantage with cyclic injection is that the total amount of chemicals would be reduced. Cyclic injection will therefore be a much better alternative, even though it does not produce equally high amount of oil as continuous.

In addition of a new well also increase the field oil production total with a great amount. The results presented a good effect of oil production due to the ASP flooding, with an increase in oil production rate between 20–30 m^3/day for the best cases. And F-3H also showed up as a better alternative for injection than F-1H. Different injection times were also tried out, and there were indications that ASP injection should be commenced at an early stage for an increased in oil production rate over longer time period. Injection at a later stage will not give the chemicals sufficient time to attack the residual oil, and the rise in oil production rate will affect the total production by a minimum.

From the economic evaluation it is seen that ASP cost and oil price are very important by taking consideration of the chemicals. The cases with high chemicals concentration was not profitable.

Shorter time periods, and also cyclic injection were much more beneficial than continuous and long period injections. It is also important to note that this is a simple evaluation, and that very few cases will show up to be profitable when all development and operational costs have been taken into account.

As this project has completed from Bangladesh, therefore limitation of software availability and the scarcity of expertise was the main barrier and made it difficult to complete the project. Therefore recompletion of existing well has not done in this project. It may be the good option to get the good oil recovery. Also ASP flooding followed by polymer also be the good choice to get the higher recovery.

There was no laboratory data available for the chemicals which would be compatible with the Norne Field. Therefore, the properties of the chemicals were assumed for the simulation.

9.2 Conclusion

Continuous simulation gave the best recovery, but it was far from the most profitable solution. Longer injection periods did not prove to be significant better than shorter periods, and cyclic slug injection will be the best solution for ASP (Alkaline, Surfactant, Polymer) flooding. From the simulation studies, using both injectors is not the best solution. If using one well for ASP flooding, injector F-3H is a better choice than F-1H. But in reality, the constraint of using subsea templates makes using only one well for ASP flooding impossible.

Introducing a new producer well is the good option for getting the higher recovery.

The economic evaluation indicates that profitability is highly dependent on oil price and chemicals (alkali, surfactant and polymer) cost. With reasonably high oil price and not unrealistic chemical costs, ASP flooding may be a good alternative for enhanced oil recovery in the Norne E-segment.

Due to the work on ASP flooding in the E-segment, some further options would be recommended.

The best option to inject ASP would be in the layers where residual oil can be found, and not in the aquifer. As injection wells are not re-completed, much of the chemicals will be spread out in the aquifer. Further investigation of ASP flooding in the Norne E-segment is recommended, and also in other fields, to inject the ASP so it attacks a more specific target area.

Further, more ASP injections can be done to sweep most of the oil in new target areas. Since time is needed for the surfactant bank to be formed, ASP flooding is recommended to commence as early as possible for a better sweep efficiency.

Extra costs associated to ASP injection such as boat rental (and other transportation costs) should be considered in the NPV analysis.
ASP Flood can start at any time in the life of the field and good engineering design is vital to success.

At current oil prices, oil companies operating in WY can make a high rate of return using chemical EOR methods. Many of the mature oil fields in WY appear to be suitable candidates for chemical flooding but operators should screen reservoirs by doing SWCTT to measure SOR and test process in-situ.

Many ASP floods made money even at $20/Bbl oil but were under designed for current oil prices

Operators can both increase oil recovery and make more profit by using

-larger amounts of surfactant and polymer;
-better geological characterization;
-better reservoir modeling and engineering design;
-better well technologies;
-better monitoring and control similar to what evolved over many decades with steam drives and CO2 floods.

9.3 Uncertainties

- Reservoir model and history matching of reservoir model;
- The ASP Model;
- The chemicals (alkali, surfactant and polymer) properties;
- Consideration of operation costs as sunk costs;
- Oil and chemicals (alkali, surfactant and polymer) prices;
- Total unrecoverable reserves;
- Laboratory data of crude and reservoir rock under reservoir conditions.

9.4 Recommendation

It is recommended to build a good chemical EOR laboratory to provide the support to small independent operators as well as doing research. It is necessary to study reservoir data to identify good candidates and also ask for crude oil samples to do chemical screening.

Simulations must be done by students and/or staff who have done chemical EOR experiments and who will integrate geology, petrophysics, process engineering and reservoir engineering with the simulation and design.

It is necessary to send the students to the field to work with the operators for better understanding.

It is also recommended to do more research regarding the ASP flooding followed by polymer. Better result may come.

It is also recommended to form a working team with the field engineers for each specific field after doing the screening studies

Nomenclature

ϕ	porosity
σ	interfacial tension between the displaced and the displacing fluids
ρ_r	mass density of the rock formation
υ	pore velocity
$\mu_{a,eff}$	effective viscosity of the water (a=w), polymer (a=p) and salt (a=s).
$\mu s,eff$	effective viscosity of salt
μw	Water viscosity
μws	Water-surfactant solution viscosity
μ_s	Surfactant viscosity
$\mu_{w,eff}$	effective water viscosity
μ_{sh}	shear viscosity of the polymer solution (water + polymer)
μ	displaced fluid viscosity
T	transmissibility
S_{dpv}	dead pore space within each grid cell
R_k	relative permeability reduction factor for the aqueous phase due to polymer retention
λ	Mobility
Q_w	water production rate
ω	Todd-Longstaff mixing parameter
D_x	cell center depth
C_P^a	polymer adsorption concentration
C_a	alkaline concentrations
$C^a_{s,p}$	surfactant/polymer adsorbed concentration
C_PC_n	polymer and salt concentrations respectively in the aqueous phase
C_a^a	alkaline adsorption concentration
	adsorption multiplier at alkaline concentration
	pore volume
ASP	Alkaline, surfactant and polymer
CDC	Capillary Desaturation Curve
CMC	Critical Micelle Concentration
C_{unit}	A unit constant
$CA(C_{surf})$	Adsorption as a function of local surfactant concentration
EOR	Enhanced oil recovery
IEA	International Energy Agency
IFT	Interfacial Tension
K	Permeability
MD	Mass Density
N_C	Capillary Number
NPD	Norwegian Petroleum Directory
NPV	Net Present Value
P	Potential
P_{cow}	Capillary pressure
$P_{cow}(S_{w)}$	Capillary pressure from the initially immiscible curve scaled according to the end points
P_{ref}	Reference pressure
PORV	Pore volume in a cell
S_{orw}	Residual oil saturation after water flooding
ST	Surface tension
$ST(C_{surf})$	Surface tension with present surfactant concentration
$ST(C_{surf})=0$	Surface tension with no surfactant present

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Appendices

A ASP Model with Eclipse100

A.1 ASP Data Input File

```
-- water injection rate of F-1, F-2, and F-3 by 50
---------------------------------------------------------------------------
-- Ny model July 2004 build by marsp/oddhu
-- New grid with sloping faults based on geomodel xxx
------------------------------------
RUNSPEC
--LICENSES
--'NETWORKS' /
--/
DIMENS
 46 112 22   /
--NOSIM
--
-- Allow for multregt, etc. Maximum number of regions 20.
--
GRIDOPTS
 'YES' 0 /
OIL
WATER
GAS
SURFACT
POLYMER
ALKALINE
DISGAS
VAPOIL
METRIC
-- use either hysteresis or not hysteresis
--NOHYST
HYST
START
 06  'NOV' 1997 /
EQLDIMS
 5  100  20 /
EQLOPTS
 'THPRES'  /   no fine equilibration if swatinit is being used
REGDIMS
-- ntfip  nmfipr  nrfreg  ntfreg
   22      4      1*      20    /
TRACERS
--  oil  water  gas  env
   1*    10    1*    1*   /
```

```
WELLDIMS
--ML  40  36  15  15 /
 130  36  15  84 /
--WSEGDIMS
-- 3  30  3 /
LGR
-- maxlgr maxcls mcoars mamalg mxlalg lstack interp
2*   693 /
TABDIMS
--ntsfun ntpvt nssfun nppvt ntfip nrpvt ntendp
    110     2     33     60   16    60 /
-- WI_VFP_TABLES_080905.INC = 10-20
VFPIDIMS
 30    20   20 /
-- Table no.
-- DevNew.VFP        = 1
-- E1h.VFP           = 2
-- AlmostVertNew.VFP = 3
-- GasProd.VFP       = 4
-- NEW_D2_GAS_0.00003.VFP = 5
-- GAS_PD2.VFP = 6
-- pd2.VFP           = 8 (flowline south)
-- pe2.VFP           = 9 (flowline north)
-- PB1.PIPE.Ecl  = 31
-- PB2.PIPE.Ecl  = 32
-- PD1.PIPE.Ecl  = 33
-- PD2.PIPE.Ecl  = 34
-- PE1.PIPE.Ecl  = 35
-- PE2.PIPE.Ecl  = 36
-- B1BH.Ecl = 37
-- B2H.Ecl  = 38
-- B3H.Ecl  = 39
-- B4DH. Ecl= 40
-- D1CH.Ecl = 41
-- D2H.Ecl  = 42
-- D3BH.Ecl = 43
-- E1H.Ecl  = 45
-- E3CH.Ecl = 47
-- K3H.Ecl  = 48
VFPPDIMS
 19  10  10  10  0  50 /
FAULTDIM
10000 /
PIMTDIMS
1  51 /
NSTACK
 30 /
UNIFIN
```

```
UNIFOUT
--RPTRUNSPEC
OPTIONS
77* 1 /
------------------------------------------------------
--
--        Input of grid geometry
--
------------------------------------------------------
GRID
NEWTRAN
GRIDFILE
  2  /
-- optional for postprocessing of GRID
MAPAXES
 0.  100.  0.  0.  100.  0.  /
GRIDUNIT
METRES  /
-- do not output GRID geometry file
--NOGGF
-- requests output of INIT file
INIT
MESSAGES
 8*10000  20000 10000 1000 1* /
PINCH
 0.001 GAP  1* TOPBOT TOP/
NOECHO
------------------------------------------------------
--
--        Grid and faults
--
------------------------------------------------------
--
-- Simulation grid, with slooping faults:
--
-- file in UTM coordinate system, for importing to DecisionSpace
INCLUDE
 './INCLUDE/GRID/IRAP_1005.GRDECL' /
--  '/project/norne6/res/INCLUDE/GRID/IRAP_0704.GRDECL' /
--
INCLUDE
 './INCLUDE/GRID/ACTNUM_0704.prop' /
--
-- Faults
--
--
INCLUDE
 './INCLUDE/FAULT/FAULT_JUN_05.INC' /
```

```
-- Alteration of transmiscibility by use of the 'MULTFLT' keyword
--
INCLUDE
 './INCLUDE/FAULT/FAULTMULT_AUG-2006.INC' /
--  '/project/norne6/res/INCLUDE/FAULT/FAULTMULT_JUN_05.INC' /
-- Additional faults
--Nord for C-3 (forlengelse av C_10)
EQUALS
  MULTY  0.01   6  6 22 22  1 22  /
/
-- B-3 water
EQUALS
  'MULTX'  0.001  9 11 39 39  1 22 /
  'MULTY'  0.001  9 11 39 39  1 22 /
  'MULTX'  0.001  9  9 37 39  1 22 /
  'MULTY'  0.001  9  9 37 39  1 22 /
/
-- C-1H
EQUALS
  'MULTY'  0.001     26 29 39 39  1 22 /
/
-------------------------------------------------------
--
--        Input of grid parametres
--
-------------------------------------------------------
INCLUDE
 './INCLUDE/PETRO/PORO_0704.prop' /
--
INCLUDE
 './INCLUDE/PETRO/NTG_0704.prop' /
--
INCLUDE
 './INCLUDE/PETRO/PERM_0704.prop' /
-- G segment north
EQUALS
  PERMX  220  32  32  94  94   2   2 /
  PERMX  220  33  33  95  99   2   2 /
  PERMX  220  34  34  95  97   2   2 /
  PERMX  220  35  35  95  98   2   2 /
  PERMX  220  36  36  95  99   2   2 /
  PERMX  220  37  37  95  99   2   2 /
  PERMX  220  38  38  95 100   2   2 /
  PERMX  220  39  39  95 102   2   2 /
  PERMX  220  40  40  95 102   2   2 /
  PERMX  220  41  41  95 102   2   2 /
/
-- C-1H
```

```
MULTIPLY
 PERMX   4  21  29  39  49  16  18 /
 PERMX  100  21  29  39  49  19  20 /
/
COPY
  PERMX PERMY /
  PERMX PERMZ /
/
-- Permz reduction is based on input from PSK
-- based on same kv/kh factor
-- ******************************************
-- CHECK! (esp. Ile & Tofte)
-- ******************************************
MULTIPLY
  'PERMZ' 0.2    1 46 1 112  1  1 /    Garn 3
  'PERMZ' 0.04   1 46 1 112  2  2 /    Garn 2
  'PERMZ' 0.25   1 46 1 112  3  3 /    Garn 1
  'PERMZ' 0.0    1 46 1 112  4  4 /    Not      (inactive anyway)
  'PERMZ' 0.13   1 46 1 112  5  5 /    Ile 2.2
  'PERMZ' 0.13   1 46 1 112  6  6 /    Ile 2.1.3
  'PERMZ' 0.13   1 46 1 112  7  7 /    Ile 2.1.2
  'PERMZ' 0.13   1 46 1 112  8  8 /    Ile 2.1.1
  'PERMZ' 0.09   1 46 1 112  9  9 /    Ile 1.3
  'PERMZ' 0.07   1 46 1 112 10 10 /    Ile 1.2
  'PERMZ' 0.19   1 46 1 112 11 11 /    Ile 1.1
  'PERMZ' 0.13   1 46 1 112 12 12 /    Tofte 2.2
  'PERMZ' 0.64   1 46 1 112 13 13 / Tofte 2.1.3
  'PERMZ' 0.64   1 46 1 112 14 14 / Tofte 2.1.2
  'PERMZ' 0.64   1 46 1 112 15 15 / Tofte 2.1.1
  'PERMZ' 0.64   1 46 1 112 16 16 / Tofte 1.2.2
  'PERMZ' 0.64   1 46 1 112 17 17 / Tofte 1.2.1
  'PERMZ' 0.016  1 46 1 112 18 18 /Tofte 1.1
  'PERMZ' 0.004  1 46 1 112 19 19 /Tilje 4
  'PERMZ' 0.004  1 46 1 112 20 20 /Tilje 3
  'PERMZ' 1.0    1 46 1 112 21 21 /  Tilje 2
  'PERMZ' 1.0    1 46 1 112 22 22 /  Tilje 1
/
--------------------------------------------------------
--
--     Barriers
--
--------------------------------------------------------
-- MULTZ multiplies the transmissibility between blocks
-- (I, J, K) and (I, J, K+1), thus the barriers are at the
-- bottom of the given layer.
-- Region barriers
--
--
```

```
INCLUDE
 './INCLUDE/PETRO/MULTZ_HM_1.INC' /
--
-- Field-wide barriers
--
EQUALS
  'MULTZ'    1.0      1  46  1 112   1   1  / Garn3       - Garn 2
  'MULTZ'    0.05     1  46  1 112  15  15  / Tofte 2.1.1 - Tofte 1.2.2
  'MULTZ'    0.001    1  46  1 112  18  18  / Tofte 1.1   - Tilje 4
  'MULTZ'    0.00001  1  46  1 112  20  20  / Tilje 3     - Tilje 2
-- The Top Tilje 2 barrier is included as MULTREGT = 0.0
/
-- Local barriers
--
INCLUDE
 './INCLUDE/PETRO/MULTZ_JUN_05_MOD.INC' /
-- 20 flux regions generated by the script Xfluxnum
--
INCLUDE
 './INCLUDE/PETRO/FLUXNUM_0704.prop' /
-- modify transmissibilites between fluxnum using MULTREGT
--
INCLUDE
 './INCLUDE/PETRO/MULTREGT_D_27.prop' /
NOECHO
MINPV
  500 /
EQUALS
'MULTZ'   0.00125  26  29  30  37  10  10  /  better WCT match for B-2H
'MULTZ'   0.015    19  29  11  30  8  8    /  better WCT match for D-1CH
'MULTZ'   1        6   12  16  22  8  11  / for better WCT match for K-3H
'MULTZ'   .1       6   12  16  22  15 15  / for better WCT match for K-3H
/
COARSEN
-- I1 I2 J1 J2 K1 K2 NX NY NZ
 6 29 11 44  1  3 1 1  3/
 6 29 11 44  5 22 1 1 18 /
16 19 45 67  1  3 1 1  3 /
16 19 45 67  5 22 1 1 18 /
20 25 45 67  1  3 1 1  3 /
20 25 45 67  5 22 1 1 18 /
26 29 45 67  1  3 1 1  3 /
26 29 45 67  5 22 1 1 18 /
30 41 63 75  1  3 1 1  1 /
30 41 63 75  5 20 1 1 16 /
30 41 63 75 22 22 1 1  1 /
30 41 76 93  1  3 1 1  1 /
30 41 76 93  5  9 1 1  5 /
```

```
30 41 76 93 12 20 1 1  9 /
30 41 76 93 22 22 1 1  1 /
30 37 58 62  1  3 1 1  1 /
30 37 58 62  5 22 1 1 18 /
30 34 54 57  1  3 1 1  1 /
30 34 54 57  5 18 1 1 14 /
30 34 54 57 20 22 1 1  3 /
30 32 51 53  1  3 1 1  1 /
30 32 51 53  5 22 1 1 18 /
30 30 48 48  1  3 1 1  1 /
30 30 50 50  1  3 1 1  1 /
30 30 48 48  5 22 1 1 18 /
30 30 50 50  5 22 1 1 18 /
33 33 52 53  1  3 1 1  1 /
33 33 52 53  5 22 1 1 18 /
35 36 57 57  1  3 1 1  1 /
35 36 57 57  5 22 1 1 18 /
38 38 59 60  1  3 1 1  1 /
38 38 59 60  5 22 1 1 18 /
38 39 61 62  1  3 1 1  1 /
38 39 61 62  5 22 1 1 18 /
17 19 68 85  1  3 1 1  1 /
17 19 68 85  5 22 1 1 18 /
17 19 86 89  1  3 1 1  1 /
17 19 86 89  5 22 1 1 18 /
22 25 68 70  1  3 1 1  1 /
26 29 68 70  1  3 1 1  1 /
20 21 68 70  5 22 1 1 18 /
20 21 68 69  1  3 1 1  1 /
22 25 68 69  5 22 1 1 18 /
26 29 68 69  5 22 1 1 18 /
10 15 45 51  1  3 1 1  3 /
10 15 45 51  5 22 1 1 18 /
13 15 52 57  1  3 1 1  3 /
13 15 52 57  5 22 1 1 18 /
11 12 52 54  1  3 1 1  3 /
11 12 52 54  5 22 1 1 18 /
12 12 55 56  1  3 1 1  3 /
12 12 55 56  5 22 1 1 18 /
10 10 52 53  1  3 1 1  3 /
10 10 52 53  5 22 1 1 18 /
13 15 58 59  1  3 1 1  3 /
13 15 58 59  5 22 1 1 18 /
14 15 60 61  1  3 1 1  3 /
14 15 60 61  5 22 1 1 18 /
15 15 62 64  1  3 1 1  3 /
15 15 62 64  5 22 1 1 18 /
16 16 68 69  1  3 1 1  3 /
```

```
16 16 68 69  5 22 1 1 18 /
 8  9 45 46  1  3 1 1  3 /
 8  9 45 46  5 22 1 1 18 /
 9  9 47 48  1  3 1 1  3 /
 9  9 47 48  5 22 1 1 18 /
31 41 94 95  1  3 1 1  1 /
31 41 94 95  5 22 1 1 18 /
34 41 96 97  1  3 1 1  1 /
34 41 96 97  5 22 1 1 18 /
36 41 98 99  1  3 1 1  1 /
36 41 98 99  5 22 1 1 18 /
39 41 100 102  1  3 1 1  1 /
39 41 100 102  5 22 1 1 18 /
/
RPTGRID
/
EDIT
--------------------------------------------------------------------------------
-- modification related to HM of G-segment aug-2006
MULTIPLY
'TRANX' 0.1 30 46 72 112 2 2 /
'TRANX'  0.1 30 46 72 112 3 3 /
'TRANY' 5 30 46 72 112 2 2 /
'TRANY'  10 30 46 72 112 3 3 /
--
'TRANX' 10 29 29 67  70 1 3 /
'TRANY' 10 30 41 67  67 1 3 /
--
'TRANX' 0.05 34 34 76  95 1 3 /
'TRANY' 0.001 30 41 67 67 1 3 / Open against the main field
--
'TRANY' 0.5 30 30 90 93 1 3 / Increase TRANY against the well
'TRANY' 0.5 31 32 94 94 1 3 / Increase TRANY against the well
--
--
'TRANY' 0.5 31 31 87 93 1 3 /
--
--
'TRANY' 0.5 30 30 85 89 1 1 /
'TRANY' 2 30 30 72 82 1 3 /
'TRANY' 0.8 30 30 82 93 1 3 /
--
--
'TRANX' 10 34 34 92 95 1 3 / Increase TRANX trough the fault against the well
'TRANX' 0 34 34 90 91 1 3 /
'TRANX' 2 34 38 88 89 1 3/
--'TRANX' 2 35 36 93 95 1 3 /
'TRANX' 0.1 35 36 90 91 1 3 /
```

```
'TRANX' 10 35 38 95 98 1 3 /
'TRANX' 5 31 31 91 92 1 3 / Increase TRANX against the well
--
--
'TRANX' 2 31 33 92 95 1 3 /
--
'TRANY' 2 30 31 79 86 3 3 /
'TRANY' 3 30 30 86 86 2 2 /
--
--
'TRANY' 0.7 34 41 72 80 1 3 /
'TRANX' 2 31 31 87 94 1 3 /
--
'TRANY' 0.0004 37 41 71 71 1 3 /
'TRANY' 2 30 31 87 93 2 3 /
'TRANX' 5 34 34 88 90 1 3 /
--
'TRANY' 1.5 33 35 94 96 2 3 /
--
'TRANX' 2 30 41 68 70 1 3 /  Increase trans around F-4H
--
/
EQUALS
'TRANY' 20 31 31 85 85 1 3 /  SET TRANY ulik 0 trougth the fault
'TRANY' 30 30 30 93 93 2 2 /
'TRANY' 30 32 32 84 84 1 3 /
'TRANY' 30 30 30 93 93 3 3 /
--
--
'TRANY' 30 31 32 95 95 2 3 /
'TRANY' 30 31 32 94 94 1 1 /
'TRANY' 20 33 33 96 96 2 3 /
'TRANY' 20 34 34 97 97 2 3 /
--
--
'TRANX' 0 33 33 71 81 1 3 / set the fault tight
'TRANX' 0 34 34 76 85 1 3 /
--
'TRANY' 0 33 33 71 81 1 3 / Set the fault tigt
'TRANY' 0 34 34 76 85 1 3 /
--
'TRANY' 0 33 36 71 71 1 3 /
'TRANX' 0 34 41 71 71 1 3 /
--
'TRANY' 0 33 33 71 72 1 3 / Decrease TRANY trougth the fault
--
'TRANX' 0 34 34 73 75 1 3 / Set the fault tight
'TRANY' 0 34 34 71 75 1 3 /
```

```
--
/
-------------------------------------------------------------------------------
PROPS
-------------------------------------------------------------------------------
--
--    Input of fluid properties and relative permeability
--
---------------------------------------------------------
NOECHO
-- Input of PVT data for the model
-- Total 2 PVT regions (region 1 C,D,E segment, region 2 Gsegment)
--
INCLUDE
 './INCLUDE/PVT/PVT-WET-GAS.DATA' /

TRACER
  'SEA'  'WAT'  /
  'HTO'  'WAT'  /
  'S36'  'WAT'  /
  '2FB'  'WAT'  /
  '4FB'  'WAT'  /
  'DFB'  'WAT'  /
  'TFB'  'WAT'  /
/
---------------------------------------------------------
--
-- initialization and relperm curves: see report blabla
--
---------------------------------------------------------
-- rel. perm and cap. pressure tables --
--
INCLUDE
 './INCLUDE/RELPERM/HYST/swof_mod4Gseg_aug-2006.inc' /
--  '/project/norne6/res/INCLUDE/RELPERM/HYST/swof.inc' /
--Sgc=10 0.000000or g-segment
--
INCLUDE
 './INCLUDE/RELPERM/HYST/sgof_sgc10_mod4Gseg_aug-2006.inc' /
--  '/project/norne6/res/INCLUDE/RELPERM/HYST/sgof_sgc10.inc' /
--
--INCLUDE
--'./INCLUDE/RELPERM/HYST/waghystr_mod4Gseg_aug-2006.inc' /
--  '/project/norne6/res/INCLUDE/RELPERM/HYST/waghystr.inc' /
INCLUDE
'./INCLUDE/ASP.inc' /
--RPTPROPS
-- 1 1 1 5*0 0 /
```

```
------------------------------------------------------------------------------
REGIONS
--
INCLUDE
 './INCLUDE/PETRO/FIPNUM_0704.prop' /
--
INCLUDE
 './INCLUDE/PETRO/SATNUM_0704.prop' /
SURFNUM
113344*89 /
--113344*88 /
MISCNUM
113344*1 /
EQUALS
'SATNUM'  102  30 41  76 112  1 1 /
'SATNUM'  103  30 41  76 112  2 2 /
'SATNUM'  104  30 41  76 112  3 3 /
/
--
INCLUDE
 './INCLUDE/PETRO/IMBNUM_0704.prop' /
EQUALS
'IMBNUM'  102  30 41  76 112  1 1 /
'IMBNUM'  103  30 41  76 112  2 2 /
'IMBNUM'  104  30 41  76 112  3 3 /
/
--
INCLUDE
 './INCLUDE/PETRO/PVTNUM_0704.prop' /
EQUALS
'PVTNUM'  1  1 46   1 112    1 22  /
/
--
INCLUDE
 './INCLUDE/PETRO/EQLNUM_0704.prop' /
-- extra regions for geological formations and numerical layers
INCLUDE
 './INCLUDE/PETRO/EXTRA_REG.inc' /
RPTREGS
'FIPNUM' 'SATNUM' 'SURFNUM'   /
-------------------------------------------------------------------------------
SOLUTION
RPTRST
BASIC=2 /
RPTSOL
'FIP=3' 'SURFBLK' 'SURFADS' 'FIPTR=2' 'TBLK' 'PBLK' 'FIPSURF=2' 'FIPPLY=2'
'PLYADS' /
-------------------------------------------------------------------------------
```

```
-- equilibrium data: do not include this file in case of RESTART
--
--
--INCLUDE
--'./INCLUDE/PETRO/E3.prop' /
-- restart date: only used in case of a RESTART, remember to use SKIPREST
RESTART
'../BASE_CASE_NORNE/BASE_CASE_NORNE' 196    /   AT TIME 2552.0 DAYS    (
1-NOV-2004)
THPRES
  1 2 0.588031 /
  1 3 0.787619 /
  1 4 7.00083  /
/
-- initialise injected tracers to zero
TVDPFSEA
1000   0.0
5000   0.0 /
TVDPFHTO
1000   0.0
5000   0.0 /
TVDPFS36
1000   0.0
5000   0.0 /
TVDPF2FB
1000   0.0
5000   0.0 /
TVDPF4FB
1000   0.0
5000   0.0 /
TVDPFDFB
1000   0.0
5000   0.0 /
TVDPFTFB
1000   0.0
5000   0.0 /
-------------------------------------------------------------------------------
SUMMARY
RUNSUM
SEPARATE
EXCEL
--
INCLUDE
 './INCLUDE/SUMMARY/summary.data' /
RPTSMRY
1 /
--------------------------------------------------------------------------------
SCHEDULE
```

```
NOWARN
-- use SKIPREST in case of RESTART
SKIPREST
-- No increase in the solution gas-oil ratio?!
DRSDT
 0  /
-- Use of WRFT in order to report well perssure data after first
-- opening of the well. The wells are perforated in the entire reservoir
-- produce with a small rate and are squeesed after 1 day. This pressure
-- data can sen be copmared with the MDT pressure points collected in the
-- well.
NOECHO
------------------------------------------------
--=======Production Wells========--
------------------------------------------------
--
INCLUDE
 './INCLUDE/VFP/DevNew.VFP' /
--
INCLUDE
 './INCLUDE/VFP/E1h.VFP' /
--
INCLUDE
 './INCLUDE/VFP/NEW_D2_GAS_0.00003.VFP' /
--
INCLUDE
 './INCLUDE/VFP/GAS_PD2.VFP' /
--
INCLUDE
 './INCLUDE/VFP/AlmostVertNew.VFP' /
--
INCLUDE
 './INCLUDE/VFP/GasProd.VFP' /
-- 01.01.07 new VFP curves for producing wells, matched with the latest well tests in
Prosper. lmarr
--
INCLUDE
 './INCLUDE/VFP/B1BH.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/B2H.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/B3H.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/B4DH.Ecl' /
--
```

```
INCLUDE
 './INCLUDE/VFP/D1CH.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/D2H.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/D3BH.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/E1H.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/E3CH.Ecl' /
--
INCLUDE
 './INCLUDE/VFP/K3H.Ecl' /
------------------------------------------
--=======Production Flowlines========--
------------------------------------------
--
-- 16.5.02 new VFP curves for southgoing PD1,PD2,PB1,PB2 flowlines -> pd2.VFP
--
INCLUDE
 './INCLUDE/VFP/pd2.VFP' /
--
-- 16.5.02 new VFP curves for northgoing PE1,PE2 flowlines -> pe2.VFP
--
INCLUDE
 './INCLUDE/VFP/pe2.VFP' /
-- 24.11.06 new matched VLP curves for PB1 valid from 01.07.06
--
INCLUDE
 './INCLUDE/VFP/PB1.PIPE.Ecl' /
--24.11.06 new matched VLP curves for PB2 valid from 01.07.06
--
INCLUDE
 './INCLUDE/VFP/PB2.PIPE.Ecl' /
--24.11.06 new matched VLP curves for PD1 valid from 01.07.06
--
INCLUDE
 './INCLUDE/VFP/PD1.PIPE.Ecl' /
--24.11.06 new matched VLP curves for PD2 valid from 01.07.06
--
INCLUDE
 './INCLUDE/VFP/PD2.PIPE.Ecl' /
--24.11.06 new matched VLP curves for PE1 valid from 01.07.06
--
```

```
INCLUDE
 './INCLUDE/VFP/PE1.PIPE.Ecl' /
--24.11.06 new matched VLP curves for PE2 valid from 01.07.06
--
INCLUDE
 './INCLUDE/VFP/PE2.PIPE.Ecl' /
 -------------------------------------------
--=======INJECTION FLOWLINES 08.09.2005     ========--
-------------------------------------------
-- VFPINJ nr. 10 Water injection flowline WIC
--
INCLUDE
 './INCLUDE/VFP/WIC.PIPE.Ecl' /
-- VFPINJ nr. 11 Water injection flowline WIF
--
INCLUDE
 './INCLUDE/VFP/WIF.PIPE.Ecl' /
-------------------------------------------
--=======   INJECTION Wells 08.09.2005      ========--
-------------------------------------------
-- VFPINJ nr. 12 Water injection wellbore Norne C-1H
--
INCLUDE
 './INCLUDE/VFP/C1H.Ecl' /
-- VFPINJ nr. 13 Water injection wellbore Norne C-2H
--
INCLUDE
 './INCLUDE/VFP/C2H.Ecl' /
-- VFPINJ nr. 14 Water injection wellbore Norne C-3H
--
INCLUDE
 './INCLUDE/VFP/C3H.Ecl' /
-- VFPINJ nr. 15 Water injection wellbore Norne C-4H
--
INCLUDE
 './INCLUDE/VFP/C4H.Ecl' /
-- VFPINJ nr. 16 Water injection wellbore Norne C-4AH
--
INCLUDE
 './INCLUDE/VFP/C4AH.Ecl' /
-- VFPINJ nr. 17 Water injection wellbore Norne F-1H
--
INCLUDE
 './INCLUDE/VFP/F1H.Ecl' /
-- VFPINJ nr. 18 Water injection wellbore Norne F-2H
--
INCLUDE
 './INCLUDE/VFP/F2H.Ecl' /
```

```
-- VFPINJ nr. 19 Water injection wellbore Norne F-3 H
--
INCLUDE
 './INCLUDE/VFP/F3H.Ecl' /
-- VFPINJ nr. 20 Water injection wellbore Norne F-4H
--
INCLUDE
 './INCLUDE/VFP/F4H.Ecl' /
TUNING
1 10  0.1  0.15  3  0.3  0.3  1.20  /
5*   0.1   0.0001   0.02  0.02  /
--2* 40 1* 15 /
/
-- only possible for ECL 2006.2+ version
ZIPPY2
'SIM=4.2' 'MINSTEP=1E-6' /
/
--WSEGITER
--/
-- PI reduction in case of water cut
--
INCLUDE
 './INCLUDE/PI/pimultab_low-high_aug-2006.inc' /
-- History and prediction --
--
INCLUDE
'./INCLUDE/BC0407_ASP.SCH'/
END
```

A.2 ASP Include File

```
--ALKALINE KEYWORDS
--Water/oil surface tension multipliers as a function of alkaline --concentration
ALSURFST
--Alkaline      Water/oil Surface
--conc          Tension Multiplier
--Kg/m3
0.0                   1.0
6.0                   0.5
15.0                  0.3
20.0                  0.1
30.0                  0.0 /
/
--Alkaline multipliers for polymer adsorption
ALPOLADS
--Alkaline      Adsorption
--conc          Multiplier
--Kg/m3
0.0                   1.0
```

```
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 / --10
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
```

```
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 / --20
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
3.0             0.7
6.0             0.5
9.0             0.3 /
0.0             1.0
```

```
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 / --30
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
```

```
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 / --40
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
3.0                      0.7
6.0                      0.5
9.0                      0.3 /
0.0                      1.0
```

```
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 / --50
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 / --60
0.0                 1.0
```

```
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 / --70
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
```

```
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 / --80
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
```

```
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 / --90
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.3 /
0.0                     1.0
```

```
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 / --100
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.3 /
0.0                 1.0
```

```
3.0                  0.7
6.0                  0.5
9.0                  0.3 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.3 / --110

--Alkaline multipliers for surfactant adsorption
ALSURFAD
--Alkaline    Adsorption
--conc        Multiplier
--Kg/m3
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
9.0                  0.0 /
0.0                  1.0
3.0                  0.7
6.0                  0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --10
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --20
0.0                 1.0
3.0                 0.7
6.0                 0.5
```

```
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 / --30
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --40
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
```

```
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 / --50
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
9.0                     0.0 /
0.0                     1.0
3.0                     0.7
6.0                     0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --60
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --70
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --80
0.0                 1.0
3.0                 0.7
6.0                 0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --90
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --100
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
```

```
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 /
0.0                 1.0
3.0                 0.7
6.0                 0.5
9.0                 0.0 / --110
--Alkaline adsorption
ALKADS
--Alkaline     Alkaline Adsorbed
--conc         on rock
--Kg/m3             (kg/kg)
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
```

```
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --10
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
```

```
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --20
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
```

```
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --30
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
```

```
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --40
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
```

```
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --50
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
```

```
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --60
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
```

```
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --70
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
```

```
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 / --80
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
```

```
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 /
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
10.0                0.000009 / --90
0.0                 0.000000
3.0                 0.000005
6.0                 0.000007
9.0                 0.000008
```

```
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 /
0.0                     0.000000
3.0                     0.000005
6.0                     0.000007
9.0                     0.000008
10.0                    0.000009 / --100
0.0                     0.000000
3.0                     0.000005
```

```
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 /
0.0                  0.000000
3.0                  0.000005
6.0                  0.000007
9.0                  0.000008
10.0                 0.000009 / --110
```

```
-- No desorption
ALKROCK
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --10
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --20
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --30
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --40
2 /
2 /
2 /
2 /
2 /
2 /
```

```
2 /
2 /
2 /
2 / --50
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --60
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --70
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --80
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --90
2 /
2 /
2 /
2 /
```

```
2 /
2 /
2 /
2 /
2 /
2 / --100
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 /
2 / --110
--- Surfactant Keywords
SURFST
0               30.0E-03
0.1             10.0E-03
0.25            1.60E-03
0.5             0.40E-03
1.0             0.07E-03
2.0             0.01E-03
3.0             0.006E-03
5.0             0.004E-03
10.0            0.006E-03
15.0            0.008E-03
20.0            0.01E-03 /
/
--Water viscosity
SURFVISC
0.0   0.42
5.0   0.449
10.0  0.503
15.0  0.540
20.0  0.630 /
/
--Surfactant Adsorption by rock
SURFADS
0.0             0.00000
1.0             0.00017
5.0             0.00017
10.0            0.00017 /
0.0             0.00000
1.0             0.00017
5.0             0.00017
10.0            0.00017 /
```

```
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 / -10
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
```

```
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 / -20
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
0.0         0.00000
1.0         0.00017
5.0         0.00017
10.0        0.00017 /
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -30
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -40
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -50
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -60
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -70
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -80
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -90
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
```

```
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -100
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 /
0.0          0.00000
1.0          0.00017
5.0          0.00017
10.0         0.00017 / -110
```

```
--Capillary De-saturation curve
SURFCAPD
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
```

```
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
0               1.0
```

```
5          1.0
10         1.0/
-8         0.0
-7         0.0
-6         0.0
-5.0       0.0
-2.5       1.0
0          1.0
5          1.0
10         1.0/
-8         0.0
-7         0.0
-6         0.0
-5.0       0.0
-2.5       1.0
0          1.0
5          1.0
10         1.0/
-8         0.0
-7         0.0
-6         0.0
-5.0       0.0
-2.5       1.0
0          1.0
5          1.0
10         1.0/
-8         0.0
-7         0.0
-6         0.0
-5.0       0.0
-2.5       1.0
0          1.0
5          1.0
10         1.0/
-8         0.0
-7         0.0
-6         0.0
-5.0       0.0
-2.5       1.0
0          1.0
5          1.0
10         1.0/
-8         0.0
-7         0.0
-6         0.0
-5.0       0.0
-2.5       1.0
0          1.0
```

```
5                 1.0
10                1.0/
-8                0.0
-7                0.0
-6                0.0
-5.0              0.0
-2.5              1.0
0                 1.0
5                 1.0
10                1.0/
-8                0.0
-7                0.0
-6                0.0
-5.0              0.0
-2.5              1.0
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10                1.0/
-8                0.0
-7                0.0
-6                0.0
-5.0              0.0
-2.5              1.0
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-8                0.0
-7                0.0
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-5.0              0.0
-2.5              1.0
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-8                0.0
-7                0.0
-6                0.0
-5.0              0.0
-2.5              1.0
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-8                0.0
-7                0.0
-6                0.0
-5.0              0.0
-2.5              1.0
0                 1.0
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5               1.0
10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
-2.5            1.0
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-8              0.0
-7              0.0
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-5.0            0.0
-2.5            1.0
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-5.0            0.0
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-5.0            0.0
-2.5            1.0
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-5.0            0.0
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-5.0       0.0
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-5.0       0.0
-2.5       1.0
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-5.0            0.0
-2.5            1.0
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-5.0              0.0
-2.5              1.0
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-2.5            1.0
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-5.0            0.0
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10              1.0/
-8              0.0
-7              0.0
-6              0.0
-5.0            0.0
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10              1.0/
-8              0.0
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-5.0            0.0
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5               1.0
10              1.0/
-8              0.0
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-5.0            0.0
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-8              0.0
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-5.0            0.0
-2.5            1.0
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-8              0.0
-7              0.0
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-5.0            0.0
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5               1.0
10              1.0/
-8              0.0
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--POLYMER KEYWORDS
--PLYSHEAR
--Polymer shear thinning data
-- Wat. Velocity            Visc reduction
-- m/day            CP
--0.0                       1.0
--2.0                       1.0      /
-- Polymer solution Viscosity Function
PLYVISC
-- Ply conc.        Wat. Visc. mult.
-- kg/m3
0.0                         1.0
0.1                         1.55
0.3                         2.55
0.5                         5.125
```

```
0.7                     8.125
1.0                     21.2  /
/
-- Polymer Adsorption Function
PLYADS
-- Ply conc.            Ply conc.
--                      Adsorbed by rock
-- kg/m3                kg/kg
0.0                          0.0
0.5                          0.0000017
1.0                          0.0000017 /
0.0                          0.0
0.5                          0.0000017
1.0                          0.0000017 /
0.0                          0.0
0.5                          0.0000017
1.0                          0.0000017 /
0.0                          0.0
0.5                          0.0000017
1.0                          0.0000017 /
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0.5                          0.0000017
1.0                          0.0000017 /
0.0                          0.0
0.5                          0.0000017
1.0                          0.0000017 /
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0.5                     0.0000017
1.0                     0.0000017 /
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0.0                     0.0
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0.5                 0.0000017
1.0                 0.0000017 /
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TLMIXPAR
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-- Polymer-Salt concentration for mixing
-- maximum polymer and salt concentration
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-- Ply conc.          Salt conc.
-- kg/m3              kg/m3
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--Polymer-Rock Properties
PLYROCK
--dead          residual                  mass          Ads.           max.
--pore          resistance                densityIndex           Polymer
--space         factor                                 adsorption
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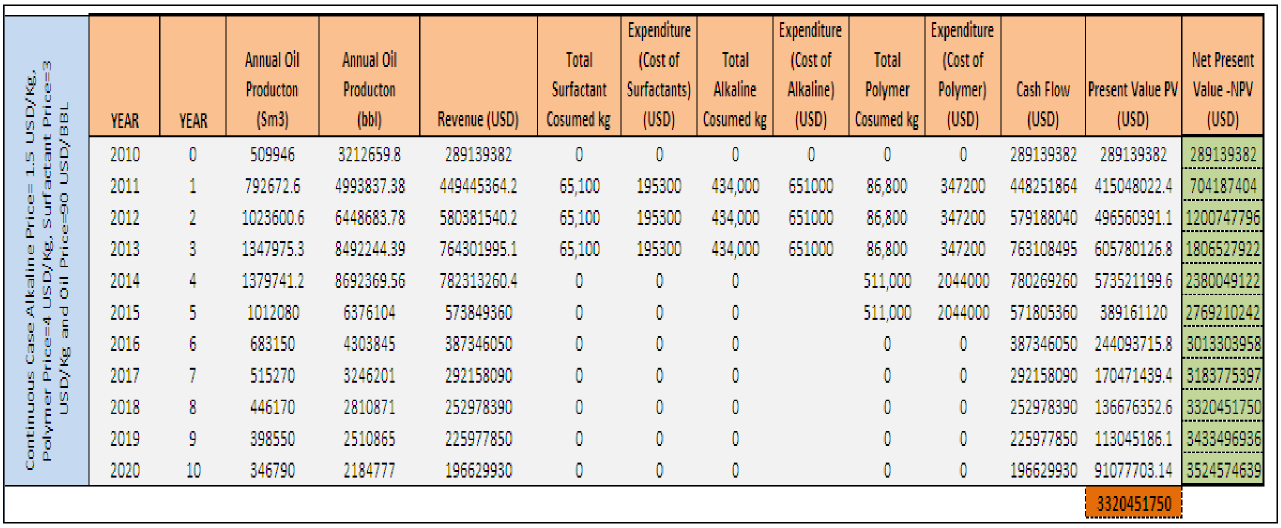
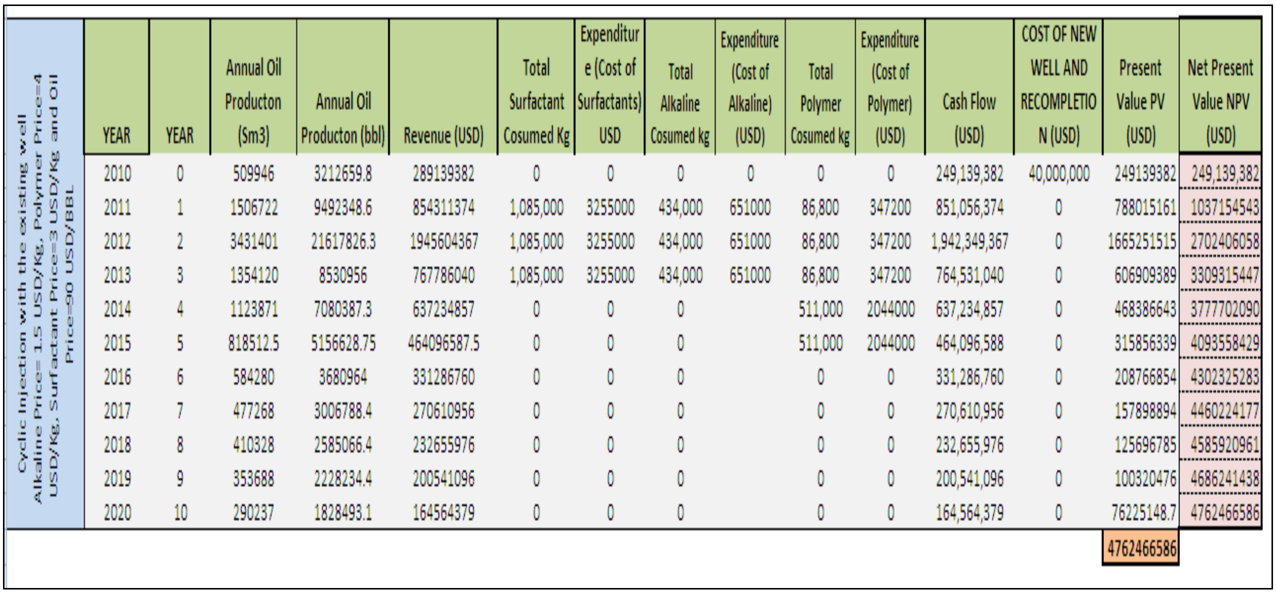
B Economic Model

B.1 Continuous Injection



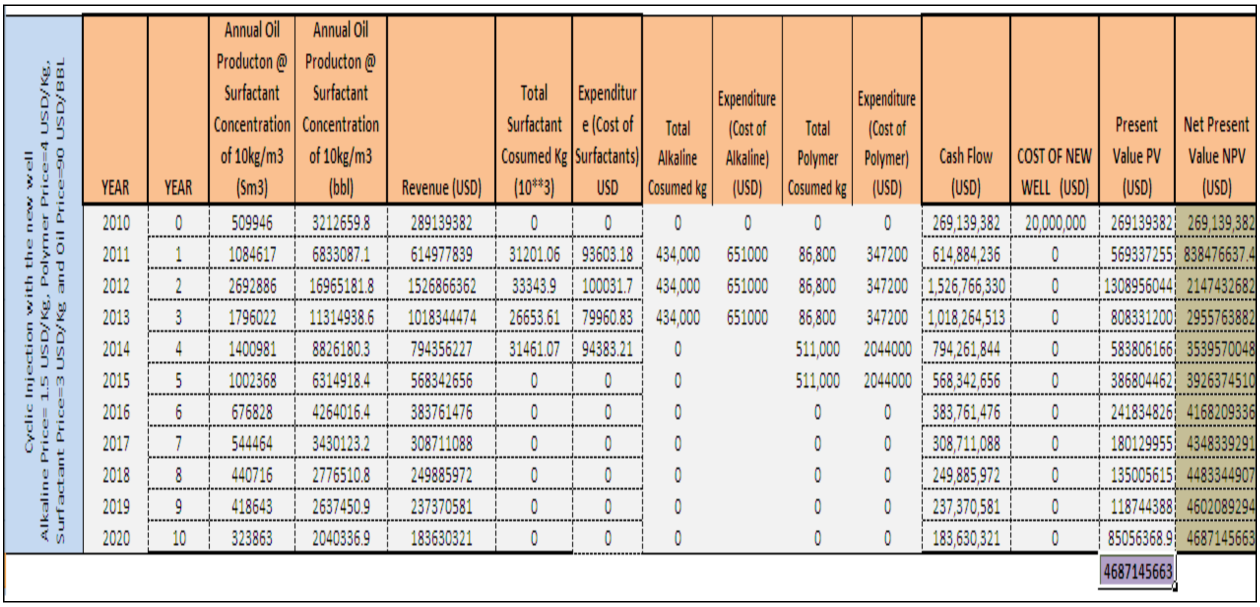
	YEAR	YEAR	Annual Oil Producton (Sm3)	Annual Oil Producton (bbl)	Revenue (USD)	Total Surfactant Cosumed kg	Expenditure (Cost of Surfactants) (USD)	Total Alkaline Cosumed kg	Expenditure (Cost of Alkaline) (USD)	Total Polymer Cosumed kg	Expenditure (Cost of Polymer) (USD)	Cash Flow (USD)	Present Value PV (USD)	Net Present Value -NPV (USD)
Continuous Case Alkaline Price= 1.5 USD/Kg, Polymer Price=4 USD/Kg, Surfactant Price=3 USD/Kg and Oil Price=90 USD/BBL	2010	0	509946	3212659.8	289139382	0	0	0	0	0	0	289139382	289139382	289139382
	2011	1	792672.6	4993837.38	449445364.2	65,100	195300	434,000	651000	86,800	347200	448251864	415048022.4	704187404
	2012	2	1023600.6	6448683.78	580381540.2	65,100	195300	434,000	651000	86,800	347200	579188040	496560391.1	1200747796
	2013	3	1347975.3	8492244.39	764301995.1	65,100	195300	434,000	651000	86,800	347200	763108495	605780126.8	1806527922
	2014	4	1379741.2	8692369.56	782313260.4	0	0	0		511,000	2044000	780269260	573521199.6	2380049122
	2015	5	1012080	6376104	573849360	0	0	0		511,000	2044000	571805360	389161120	2769210242
	2016	6	683150	4303845	387346050	0	0	0		0	0	387346050	244093715.8	3013303958
	2017	7	515270	3246201	292158090	0	0	0		0	0	292158090	170471439.4	3183775397
	2018	8	446170	2810871	252978390	0	0	0		0	0	252978390	136676352.6	3320451750
	2019	9	398550	2510865	225977850	0	0	0		0	0	225977850	113045186.1	3433496936
	2020	10	346790	2184777	196629930	0	0	0		0	0	196629930	91077703.14	3524574639
													3320451750	

B.2 Cyclic injection in existing well



	YEAR	YEAR	Annual Oil Producton (Sm3)	Annual Oil Producton (bbl)	Revenue (USD)	Total Surfactant Cosumed Kg	Expenditure (Cost of Surfactants) USD	Total Alkaline Cosumed kg	Expenditure (Cost of Alkaline) (USD)	Total Polymer Cosumed kg	Expenditure (Cost of Polymer) (USD)	Cash Flow (USD)	COST OF NEW WELL AND RECOMPLETION (USD)	Present Value PV (USD)	Net Present Value NPV (USD)
Cyclic Injection with the existing well Alkaline Price= 1.5 USD/Kg, Polymer Price=4 USD/Kg, Surfactant Price=3 USD/Kg and Oil Price=90 USD/BBL	2010	0	509946	3212659.8	289139382	0	0	0	0	0	0	249,139,382	40,000,000	249139382	249,139,382
	2011	1	1506722	9492348.6	854311374	1,085,000	3255000	434,000	651000	86,800	347200	851,056,374	0	788015161	1037154543
	2012	2	3431401	21617826.3	1945604367	1,085,000	3255000	434,000	651000	86,800	347200	1,942,349,367	0	1665251515	2702406058
	2013	3	1354120	8530956	767786040	1,085,000	3255000	434,000	651000	86,800	347200	764,531,040	0	606909389	3309315447
	2014	4	1123871	7080387.3	637234857	0	0	0		511,000	2044000	637,234,857	0	468386643	3777702090
	2015	5	818512.5	5156628.75	464096587.5	0	0	0		511,000	2044000	464,096,588	0	315856339	4093558429
	2016	6	584280	3680964	331286760	0	0	0		0	0	331,286,760	0	208766854	4302325283
	2017	7	477268	3006788.4	270610956	0	0	0		0	0	270,610,956	0	157898894	4460224177
	2018	8	410328	2585066.4	232655976	0	0	0		0	0	232,655,976	0	125696785	4585920961
	2019	9	353688	2228234.4	200541096	0	0	0		0	0	200,541,096	0	100320476	4686241438
	2020	10	290237	1828493.1	164564379	0	0	0		0	0	164,564,379	0	76225148.7	4762466586
														4762466586	

B.3 Cyclic injection in a new well



Cyclic Injection with the new well Alkaline Price= 1.5 USD/Kg, Polymer Price=4 USD/Kg, Surfactant Price=3 USD/Kg and Oil Price=90 USD/BBL	YEAR	YEAR	Annual Oil Producton @ Surfactant Concentration of 10kg/m3 (Sm3)	Annual Oil Producton @ Surfactant Concentration of 10kg/m3 (bbl)	Revenue (USD)	Total Surfactant Cosumed Kg (10**3)	Expenditure (Cost of Surfactants) USD	Total Alkaline Cosumed kg	Expenditure (Cost of Alkaline) (USD)	Total Polymer Cosumed kg	Expenditure (Cost of Polymer) (USD)	Cash Flow (USD)	COST OF NEW WELL (USD)	Present Value PV (USD)	Net Present Value NPV (USD)
	2010	0	509946	3212659.8	289139382	0	0	0	0	0	0	269,139,382	20,000,000	269139382	269,139,382
	2011	1	1084617	6833087.1	614977839	31201.06	93603.18	434,000	651000	86,800	347200	614,884,236	0	569337255	838476637.4
	2012	2	2692886	16965181.8	1526866362	33343.9	100031.7	434,000	651000	86,800	347200	1,526,766,330	0	1308956044	2147432682
	2013	3	1796022	11314938.6	1018344474	26653.61	79960.83	434,000	651000	86,800	347200	1,018,264,513	0	808331200	2955763882
	2014	4	1400981	8826180.3	794356227	31461.07	94383.21	0		511,000	2044000	794,261,844	0	583806166	3539570048
	2015	5	1002368	6314918.4	568342656	0	0	0		511,000	2044000	568,342,656	0	386804462	3926374510
	2016	6	676828	4264016.4	383761476	0	0	0		0	0	383,761,476	0	241834826	4168209336
	2017	7	544464	3430123.2	308711088	0	0	0		0	0	308,711,088	0	180129955	4348339291
	2018	8	440716	2776510.8	249885972	0	0	0		0	0	249,885,972	0	135005615	4483344907
	2019	9	418643	2637450.9	237370581	0	0	0		0	0	237,370,581	0	118744388	4602089294
	2020	10	323863	2040336.9	183630321	0	0	0		0	0	183,630,321	0	85056368.9	4687145663
														4687145663	