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TEKNOLOGI
PETRONAS

FINAL REPORT

Fractional Flow Analysis for Chemical Flooding in Enhanced Oil Recovery

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Table of Content

List of Figures

List of Tables

Abstract

The context of this project is focused on analyzing how fractional flow governs efficiency in enhanced oil recovery and behavior of a reservoir upon chemical flooding. The study of the project is pursued mainly in the sense of manipulation of capillary number; mobility ratio and conformance which is further extrapolated through the calculation of target oil, rate and capillary number, surfactant retention, oil recovery algorithms and production functions. End results of this project are presented with graphical user interface, GUI that provides an efficient screening method of reservoir potentiality and recovery efficiency. Finally, the project is concluded with a detailed list of analysis summary which includes reservoir recovery efficiency as well as cumulative gas, oil and water produced from the reservoir.

1 Introduction

1.1 Background of Study

Conventional water flooding includes injection of water in high pressure making pressure within targeted zone rises which later displaces the oil. However water has low viscosity, which causes fingering effect. Pressure front of water divides as a direct result of fingering effect and hence reduces oil recovery efficiency.

In chemical flooding, polymer/chemical is added to water which raises the viscosity of the flooding medium. Flooding agent later forces oil out as a single pressure front hence increasing oil recovery efficiency.

Contemporary primary and secondary recovery technique can only recover 30% - 50 % of original hydrocarbon in place while tertiary recovery technique can generally recover up to another 35% of hydrocarbon. Chemical flooding is among one of the popular tertiary recovery techniques in enhanced oil recovery, EOR. It involves injection of chemical, surfactant, polymer or alkaline agents into reservoir to increase oil production when secondary recovery process i.e. conventional water flooding is no longer effective.

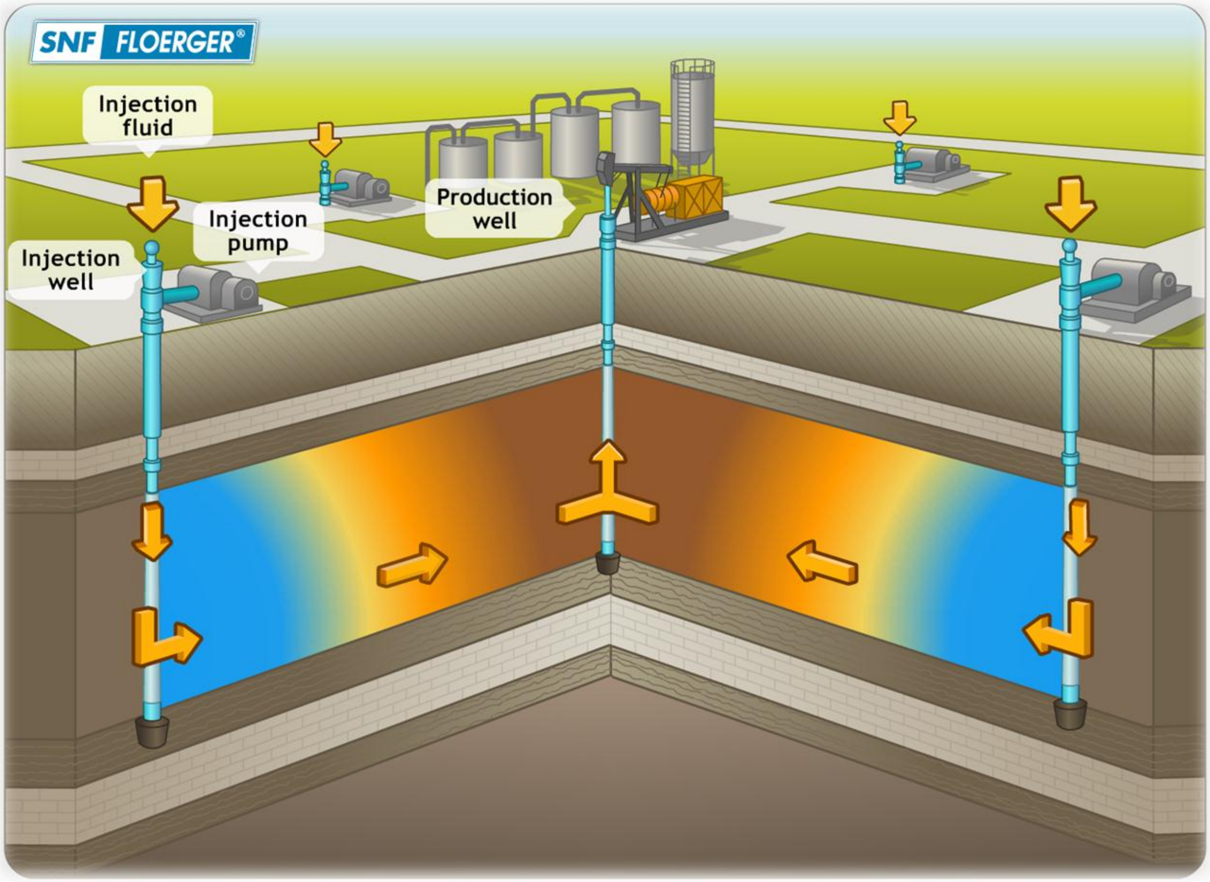


Figure 1: Overview of 5-spot injection process into a reservoir.

The functioning mechanism of chemical flooding can be simplified and broken down into 3 factors:

i) Increasing the capillary number mainly by making the interfacial tension (IFT) between the displacing and the displaced phases small to mobilize residual oil.
ii) Decreasing mobility ratio hence making the mobility of the displacing flood less than or equal to the mobility of the displaced fluid for better sweep efficiency and improving conformance in heterogeneous reservoirs for better sweep efficiency.
iii) Formation of macro and micro-emulsions to improve the mobility ratio through drop entrainment and entrapment.

Other factors such as formation of precipitates, wettability changes, relative permeability shifts surfactant adsorption occurs on the rock surface and changing rock wettability are also taken into consideration

Alkaline flood or caustic-waterflood is generally an extension of chemical flooding concept. It functions by letting sodium hydroxide reacts with naturally occurring acids in crude oil to produce ‘soaps’. As a result of neutralization, altered mobility causes the lowering of interfacial tension between fluids. Wettability changes due to emulsification and entrainment and emulsification with entrapment also promotes fluid mobility and ultimately oil recovery.

1.2 Problem Statement

Despite many works on modeling of chemical flood, they seem to lack a method that is easily accessible and understandable by all to conduct enhanced oil recovery screening. There is also one too many selections of approaches in the modeling and screening of chemical flood. Varying parameters are also focused on different studies.

1.3 Significance of Project

The creation of this project would greatly simplify the task of conducting a reservoirs’ chemical flooding enhanced oil recovery calculation apart from providing an In-situ holistic overview. Engineers would be able to decide on further actions taken unto the reservoir based on the data generated from the project.

1.4 Objectives

The main objective of this study is a direct solution to the problem statement of this study.

i) Study the functioning mechanism of chemical flooding.
ii) Selection, compilation and enhancement of previous model to formulate a simplified chemical flood model based on (Paul et al, 1982) for rapid evaluation and screening for in chemical flooding.

iii) Translate the simplified model into an integrated toolkit with graphical user interface that interpret the data input and perform the solution and post-process retrieval.

1.5 Scope of Study

The project covers the scope of reservoir engineering, in particular the fractional flow theory, chemical flood model and its implementation. Developer's skills are needed as well from theory, development and deployment cycle to commence software architecture, and GUI engineering.

1.6 Relevance of Study

The project can be directly related to the current major the candidate is pursuing in term of Drilling and Production Technology as well as Petroleum Exploration and it relates back to the programming course that have been previously undertaken. Candidate's tasks are then taken a step further as the project incorporates theoretical studies with real time software implementation.

2 Literature Review

The project presents an analytical approach in reservoir screening through the application of various mathematical equations that are used in previous studies and predictive model. It also includes a study of an existing predictive model based on a study presented by Paul and Lake et al, (1982).

Predictive models have been used in literature as a fast way to forecast the EOR processes (Paton, (1969); Paul (1982) and (1984); Giordano, (1987); Lake, (1978); Sayarpour, (2008)) Each EOR process is modeled analytically to include different features of the process. Many had tried to develop analytical models to forecast EOR performance such as production rates, recovery efficiency and economic evaluation to identify reservoir potentiality for desired EOR method.

Patton, (1971) presented an analytical model to predict polymer flood performance (incremental oil recovery) which also provides quick estimate of additional oil recovery by polymer flood. Paul and Lake et al., (1982) developed a predictive model to forecast the chemical flood EOR performance which was used by the Department of Energy for identifying candidate reservoirs for chemical flooding. The model predicts recovery efficiency and oil rate as functions of relevant reservoir and fluid properties.

There are several steps in evaluating EOR methods for field application such as binary screening, forecasting, numerical simulation, pilot and field EOR deployment.

In binary screening, reservoirs are selected on the basis of reservoir average rock and fluid properties. Binary screenings are found to be more consulted for initial determination of EOR applicability. The challenge present in the sense that quick quantitative comparisons and performance predictions of selected EOR processes that are performed in forecasting step of EOR studies are more important and complicated than EOR screening.

In EOR forecasting, we look for ways to get quick and robust quantitative results of the performance of different EOR processes before detailed numerical simulations of the reservoirs under study. This is necessary in screening the potential reservoirs for EOR processes because it is neither possible nor logical to do a detailed engineering study on all of the EOR candidate reservoirs. To reach to these goals we need fast forecasting of the performance of different EOR methods using analytical models that include the relevant aspects of the process and also show the relative advantages of various design scenarios. It is equally important that the models be as alike as possible lest any differences in results be caused by differences in the model rather than differences in the processes.

As mentioned above, a big part of this project is subjected under the influence of the works of Paul and Lake et al, (1982). The final outcome of the project is based on understanding of Paul and Lake et al works and further cross referencing with the works of others to design a screening method that encompass vital factors and parameters.

Numerous works on modeling of chemical flooding have been conducted and in the case of this project, studies incorporate works that ranges from 1978 to 2011. Studies concluded that they are more than one approach in modeling a predictive model for chemical flood. Careful considerations are necessary to ensure parameters incorporated compliments one another.

Larson et al, (1978) created a model that applies fractional flow theory which analyses the physical mechanism in work during surfactant flooding. The model is an extension of Buckley-Leverett analysis to include mass-transfer effect that occurs during chemical flooding. The model was used to investigate the relationship between system parameters (mobility ratio, partition coefficient, adsorption) and performance variable (oil cut, chemical breakthrough, recovery efficiency). The main variables of their model includes adsorption of chemical onto the rock, partitioning of chemical into oleic phases and swelling of oleic phase with water and chemical. Their model assumes homogeneous 1-d system, absence of dispersion, equilibrium mass transfer and constant composition injection (infinite slug). The model predicted that large partition coefficients and high salinity causes retardation of chemical front velocity and delay of oil recovery. The model also predicted that through swelling of residual oleic phase with chemical and water, good recovery could be attained without requiring low value of chemical flood residual oleic phase saturation if the partition coefficient was low enough to avoid retardation of chemical front velocity.

Paul et al, (1982) created a simple predictive model for micellar-polymer flooding. An oil recovery algorithm is developed from theory and the results are depicted in term of numerical simulation. The model contains correlations factors impacting oil recovery to reservoir and process data: capillary number (permeability, depth, spacing), heterogeneity (Dykstra-Parsons coefficient), cross flow (k_v/k_h), surfactant adsorption (clay fraction) and wettability (relative permeability). Oil breakthrough, peak oil rate and project life are estimated from oil-water fractional flow theory, augmented with an effective mobility ratio to represent heterogeneity. The chemical flood predictive model CFPM was developed for sandstone reservoirs, and only two technical constraints were used - formation temperature and salinity (total dissolved solids). Numerical simulation was used to construct and validate the predictive model. The simulations incorporated, among other things, oil-water-surfactant-salinity dependent equilibrium, three-phase relative permeability, capillary pressure, and compositional dependent fluid properties and chemical adsorption.

Their predictive model is governed by five main calculations. They include

- Target Oil Calculation
- Rate and Capillary Number
- Surfactant Retention on Sandstone

- Oil Recovery Algorithms (Displacement Efficiency, Vertical Sweep Efficiency, Mobility Buffer Sweep Efficiency)
- Production Function (Homogeneous Media, Heterogeneous Media, Correction of Cross Flow)

Later, Ramakrishnan et al, (1989) created a fractional flow model that is devoted to caustic-flooding. They incorporated earlier works on fluid-fluid interaction of acidic crude oil caustic system that take into consideration of chemical reaction equilibrium and interfacial tension, IFT. Their model takes into consideration of four main variables namely viscosity ratio, reference capillary number, injected fluid pH and salinity. The paper is aimed at describing chemical equilibria and evaluating IFT at any given composition. The model is able to identify influences of optimum region and identifies over-optimum composition when injected. In the paper, the lowering of IFT is incorporated in identifying oil recovery efficiency assuming water as the wetting medium for all composition. The reason is lowering of IFT alters viscous to capillary force ratio and cause partial or complete mobilization of blobs left behind by ordinary water flooding. In the removal of continuous oil (displacement) as opposed to mobilization of disconnected blobs, enhancement in capillary number can be more effective in reducing ultimate amount of oil trapped. The models assumes simplest condition of secondary and tertiary injection where in secondary the reservoir is only filled with oil and in tertiary only residual oil left by water exist in the reservoir and no adsorption or reactions are considered. Their study concluded that low IFT at intermediate normalized injection of sodium concentration values plays a dominate role in determining oil recovery. As long as viscosity ratio is favorable, dominance of IFT prevails. Other parameters such as injection pH, salinity and overall velocity have little influence in determining recovery.

Hou et al, (2007) proposed a different approach: streamline-based model for potentiality prediction of enhanced oil recovery. Their model is aimed at correcting assumptions and defects made on previous models. The highlighted concern on previous model includes fixed five-point pattern that was used in calculation and the impact of well pattern and formation boundary on the result of the prediction were not considered. At the same time, the mechanisms of diffusion, chemical consumption and variation of relative permeability were neglected. Due to the feature of analytical solution, constant component was supposed to be injected continuously when solving the equations. Errors often occurred in application, especially in the variation tendency of production with time, which directly affect the results of economic evaluation. The usage of streamlined method instead of finite difference method for large-scale reservoir simulation has advantages such as quickness and good convergence. In 1962, Higgins and Leighton proposed approximate stream-tube simulation method. They illustrated that fixed streamline distribution can be adopted to calculate performance of five-point waterflooding pattern through the usage of Buckley-Leverett theory to calculate displacement method. Later Martin and Wegner found that if mobility ratio varies from 0.1 to 10, result of prediction for areal pattern behavior can satisfy the requirement of engineering calculation with assumption of fixed streamline distribution. They too approach modeling of chemical flooding with the phase behavior theory which holds the third micro-emulsion phase. Through usage of a practical mathematical model, a model that satisfies engineering calculation need, fewer input parameters and faster speed is created. It assumes a water-oil only phases and neglecting micro-emulsion phase to fit flooding with low pH values. Five components are considered, namely water, oil, alkaline, surfactant and polymer and no chemical reactions among them. Chemical consumptions are considered including adsorption, chemical degradation, ion exchange and dissolution yet the impacts of ion exchange and dissolution reaction on porosity and permeability are ignored.

Fadili et al, (2009) presented a paper on Smart Integrated Chemical EOR Simulation. They have a very similar approach as Larson et al, yet more detailed research are conducted. Their simulation model utilizes the approach of calculating effective salinites through models of brine, surfactant, foam and alkaline. Their surfactant model encompasses properties such as: surfactant as water phase component, oil and water IFT as a function of surfactant concentration, adsorption (with salinity and permeability dependence), change of wettability as a function of surfactant adsorption and partitioning between the water and oil phases. They stated that oil recovery is closely related to correct balance of capillary, gravity and viscous forces to provide stable front advancement and maximizing contact between EOR agent and reservoir oil. In other words reservoir conformance doesn’t solely depends on the intrinsic properties of EOR agent but also depends on velocities of displacement taking place There is also a strong dependence between EOR agent density and reservoir rock quality distribution even under viscous dominant flow. Early breakthrough of EOR agent translates to poor hydrocarbon sweeping. There is also highlight of surfactant phase regimes and their effects on oil recovery efficiency. Surfactant changes phase regimes depending on surfactant concentration and brine salinity. Low salinity translates to surfactant in aqueous phase while high salinity partitions it to oleic phase. Lowest IFT is achieved during the intermediate phase whereby intermediate salinities generate micro-emulsion in the system and henceforth being the most optimal condition for hydrocarbon recovery. They later proposed that through a smart injection technique that utilizes the same amount of chemical as conventional chemical flood injection technique efficiency could be increased by 10%.

Bataweel et al, (2011) conducted a study on computerized tomography (CT) scan study on fluid flow characterization of chemical flooding. The study is conducted with sandstone cores at room temperature on four different chemical flood processes namely polymer, surfactant, surfactant-polymer (SP) and alkali-surfactant-polymer (ASP). Oil recovery and oil distribution in the core were of main interest for evaluation after chemical flood. During chemical flooding four flow regions are established. They encompass initial two-phase flow at Sorw, oil bank with increase in saturation, two or three phase flow of oil, water and micro-emulsion and single-phase flow of the chasing fluid. They later arrived at the conclusion that ASP and SP flooding yield the best recovery with some residual reduction in permeability caused by usage of polymers. They also mentioned that the lowest recovery was obtained during surfactant flooding, which prove that IFT reduction is highly dependent on mobility control by polymers.

Year	Author	Title	Remarks
1954	R.M.S Reed	Effeciency of Fluid Fisplacement in Water Wet Porous Media as Affected by Interfacial Tension and Pressure	
1978	**R. G. Larson et al**	**Analysis of Physical Mechanism in Surfactant Flooding**	**Investigate the relationship between system parameters and performance variable through partitioning, adsorption and oleic phases.**
1982	**G.W. Paul et al**	**A Simplified Predictive Model for Micellar Polymer Flooding**	**Main literature review, much mathematical calculation are extrapolated based on their study**
1984	J. Hagoort	Measurement of Relative Permeability for Computer Modelling/ Reservoir Simulation	
1989	**T.S. Ramakrishnan et al**	**Fractional Flow Model for High pH Flooding**	**Conducted fractional flow modelling for chemical flooding an relating it to chemical equilibrium properties**
1989	S.M. Farouq Ali et al	The Promise and Problems of Enhanced Oil Recovery Method	
1991	C.U. Okoye et al	An Improved Linear Chemical Model for Alkaline Steamflooding	
1999	S.M. Farouq Ali et al	Micellar Flooding and ASP Chemical Methods for Enhanced Oil Recovery	
2004	A.A. Shapiro et al	A New Method for Analytical Modelling of Chemical Flooding	
2007	**J. Hou et al**	**A Streamlined Based Model for Potentiality Prediction of Enhanced Oil Recovery**	**Proposed streamlined modelling for chemical flooding instead of finite difference method**
2008	A.J.P. Flecthcer et al	Developing A Chemical EOR Pilot Strategy for A Complex, Low Permeability Water Flood	

2009	**A. Fadili et al**	**Smart Integrated Chemical EOR Simulation**	**Conducted study on reservoir conformance based on intrinsic properties of EOR agent and extrinsic properties such as velocity and gravitational forces.**
2010	M. Trujillo et al	Selection Methodology for Screening Evaluation of Enhanced Oil Recovery Methods	
2011	H. Mohan et al	The EOR Potential of United States	
2011	A. Mollaei et al	General Isothermal Enhanced Oil Recovery and Waterflood Forecasting Model	
2011	**M.A. Bataweel et al**	**Fluid Flow Characterization of Chemical EOR Flooding**	**Conducted computerized tomography (CT) scan study on fluid flow characterization of chemical flooding**

Table 2: Tabulated list of literature reviews from 1954 to 2011.

3 Theory

As mentioned above, mobility ratio and capillary number plays an important role in analyzing behavior of oil recovery efficiency.

Mobility ratio is defined as the ratio of displacing fluid mobility over displaced fluid mobility. If M>1, clearly the displacing fluid, e.g., water in a water flood, moves more easily than the displaced liquid, i.e., oil. This is not desirable because the displacing fluid will flow past much of the displaced fluid, displacing it inefficiently. Thus, the mobility ratio influences displacement efficiency. For maximum displacement efficiency, M should be <1, or more generally denoted as 'favorable mobility ratio'. Mobility ratio M can be made smaller or improved, by lowering the viscosity of oil, increasing the viscosity of the displacing fluid, increasing the effective permeability to oil, and decreasing the effective permeability to the displacing fluid.

The capillary number, Nc, is defined as a product displaced fluid viscosity, pore velocity, and interfacial tension (IFT) between the displaced and the displacing fluids. Hagoort (1984) pointed out that the capillary number can be increased, and thereby the residual oil saturation decreased, by reducing oil viscosity, or increasing pressure gradient, but more than anything, by decreasing the IFT. In an earlier work, Reed (1954), showed that residual oil saturation depicts significant decrease during very low IFT's.

Much alike displacement efficiency, areal sweep efficiency as well as conformance (or vertical sweep efficiency) decrease as the mobility ratio increases. In other words, if the displacing fluid flows more readily than oil, the displacement is inefficient.
The following summarizes the theory and mathematical functions that have been chosen and incorporated in commissioning the project.

3.1 Surfactant Retention

Surfactant retention, R_{surf} is composed of surfactant adsorption onto clays, surfactant trapping and other surfactant loss mechanisms. In the project, surfactant retention reflects clay adsorption only, with

$$R_{surf} = 3.3 \times W_{clay}$$

where W_{clay} is the weight fraction of clay. Equation 3.1.1 was developed from literature values for sulfonate surfactant adsorption onto sandstone (DOE, 1980).

In the project, it is more convenient to express surfactant retention, R in units of pore volumes of surfactant injected, $V_{surf,}$

$$V_{surf} = \frac{(1.0 - \phi)}{\phi} \times \frac{\rho R}{\rho S} \times \frac{R_{surf}}{V_{surf'}}$$

where ϕ is porosity, ρR and ρS are the densities (g/ml) of rock and surfactant, respectively, and V_{surf}' is the volume fraction surfactant in the injected slug.

3.2 Target Oil Calculation

In the project, target oil, T_{oil} is defined as the oil remaining in the waterswept portion of the reservoir. It is further reduced by the fraction of the reservoir below bottom water, F_w, and above a gas cap F_g, and a positive value for the original oil-in-place, O_{oil} is provided.

$$T_{oil} = \frac{S_{orw}}{S_{oi} - S_{orw}} \times ((C_{oil} - O_{oil}) \times (\frac{1-B_i}{B_f})) \times (1 - F_w - F_g)$$

If original oil in place specified is less or equals to 0 then,

$$T_{oil} = S_{orw} \times \frac{C_{oil}}{S_{oi} - S_{orw}}$$

where S_{orw} is the residual oil saturation to waters, S_{oi} is the initial oil saturation, S_{wc} is the connate water saturation, C_{oil}, is the cumulative oil produced at the end of waterflooding, and B_i *and* B_f are the initial (pre-waterflood) and final (post-waterflood, pre-chemical flood), oil formation volume factors RB/STB, respectively.

The floodable pore volume V_{flood} for all patterns follows from

$$V_{flood} = T_{oil} \times \frac{B_f}{S_{orw}}$$

and area to be developed, A_{dev} is

$$A_{dev} = \frac{V_{flood} \times T_{pay}}{7758 \times \phi}$$

where T_{pay} is the net reservoir pay thickness.

Number of patterns, n_{pat} can be obtained through

$$n_{pat} = \frac{A_{dev}}{A_{pat}}$$

where A_{pat} is the pattern area.

3.3 Oil Recovery Efficiency

The volume of target oil recoverable, V_{rec} is given by

$$V_{rec} = E \times T_{oil}$$

where E is the tertiary oil recovery efficiency. E may be expressed as the product of the linear (1-D) displacement efficiency, E_{lin}, the vertical sweep efficiency, E_{vert}, and the chase polymer sweep efficiency, E_{poly}

$$E = E_{lin} \times E_{vert} \times E_{poly}$$

3.4 Linear Displacement Efficiency

The 1-D, linear displacement efficiency, E_{lin}, is computed as a function of the capillary number, n_{cap}

$$n_{cap} = (1.97\ X\ 10^{-7} \times K \times C_{inj} \times d) \div (\sqrt[2]{A} \times (5.58 + 0.5 \times \log A))$$

where C_{inj}, is an injectivity coefficient, K, is permeability, d, is reservoir depth, and $A = \frac{A_{pat}}{2}$ is the well spacing. The calculation was developed for confined five-spot patterns (Lake et al, 1979). In the project, the n_{cap} is adjusted as a function of the ratio of relative permeability end-points, R_{perm} as well as to the equivalent n_{cap} for water-wet (Berea) rock.

E_{lin} is then determined from the digitized capillary desaturation curves for Berea (Gupta et al, 1979).

3.5 Vertical Sweep Efficiency

The dimensionless surfactant slug size, D, is the ratio of the pore volumes slug injected, V_{slug}, to V_{surf}, the surfactant retention in pore volumes

$$D = \frac{V_{slug}}{V_{surf}}$$

E_{vert}, vertical sweep efficiency is given by

$$E_{vert} = C_{stor} + D \times (1 - C_{flow})$$

where C_{stor} and C_{flow} are the storage capacity and flow capacity, respectively

$$C_{flow} = \frac{(\frac{E\prime}{D})^{0.5} - Eff\prime}{(1 - E\prime)}$$

$$C_{stor} = \frac{1}{Eff\prime^{(\frac{1}{C_{flow}} - 1)} + 1}$$

Eff' is the effective mobility ratio, introduced to account for heterogeneity in layered reservoirs and is calculated empirically (Paul et al, 1982) from the Dykstra-Parsons coefficient, V_{dp}

$$Eff' = 10^{\frac{V_{dp}}{(1 - V_{dp})^{0.2}}}$$

Eff' is similar to the Koval (1963) "H”-factor which is used to represent the fingers developed in homogeneous media during unstable miscible displacement.

3.6 Polymer Sweep Efficiency

The polymer (mobility buffer) sweep efficiency, *EMB*, is defined as capture efficiency, or volume oil produced over volume oil mobilized.

$$E_{poly} = (1 - V_{dp}{}') \times \left(1 - e^{\frac{-0.4 \times V_{poly}}{Evert^{1.2}}}\right) + V_{dp}{}'$$

where V_{poly} is the pore volumes of polymer slug injected, and

$$V_{dp}{}' = 0.71 - 0.6 \times V_{dp}$$

3.7 Oil Production Curve

The oil production curve, is assumed triangular with base determined by the time of oil breakthrough, t_{break} and time to sweep out to zero oil rate t_{sout}, and the apex by the peak oil rate Q_{peak}, as shown

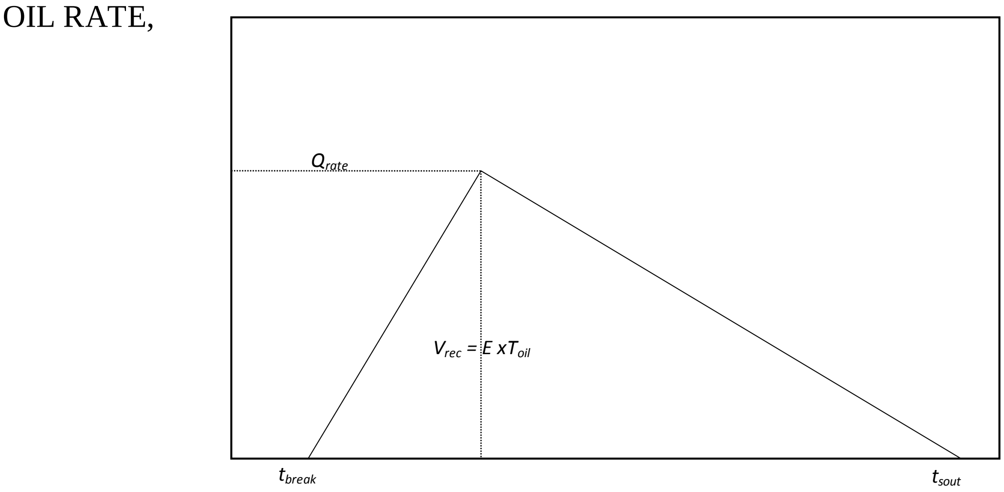


Figure 3: Curve of recovery efficiency versus target oil.

The dimensionless surfactant velocity is

$$v_{surf} = (1 + V_{surf} - S_{orw} \times E_{lin}{}')^{-1}$$

where $E_{lin}{}' = 1 - E_{lin}$.

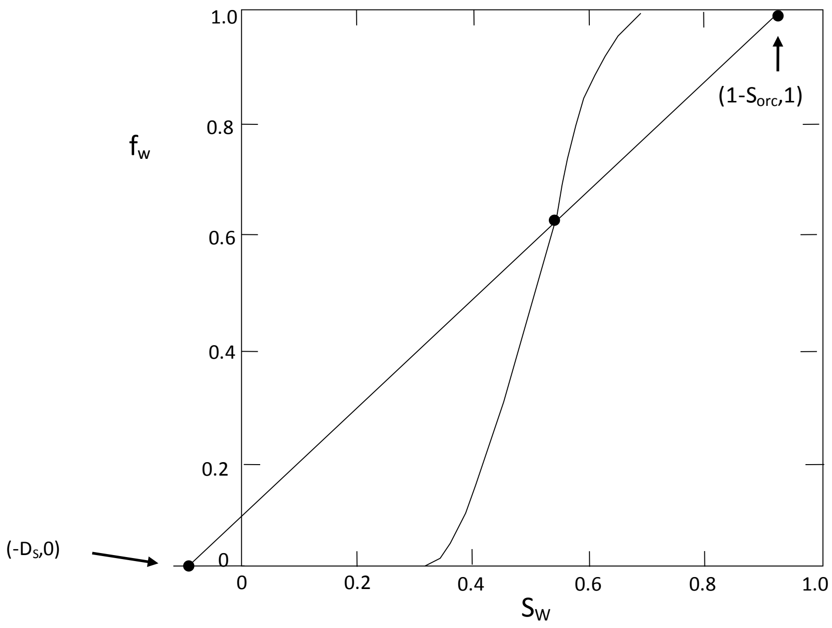


Figure 3.1: Fractional flow diagram.

The model next computes the intersection (*FWB*, *SWB*) of the straight line passing through the points $(f_W = 0, S_W = -V_{surf})$ and $(f_W = 1,\ S_W = 1 - S_{orw} \times E_{lin}')$ with the water-oil fractional flow curve. The stabilized oil bank saturation and fractional flow are S_{ob} and f_{ob} respectively.

The velocity of the oil bank is

$$v_{ob} = \frac{v_{surf} \times f_{ob}}{(S_{ob} - S_{orw})}$$

The dimensionless breakthrough times (fractional pore volumes) of the oil bank, t_{break} and surfactant t_{surf} are then

$$t_{break} = (v_{ob} \times Eff')^{-1}$$

and

$$t_{surf} = (v_{surf} \times Eff')^{-1}$$

The peak oil fractional flow is

$$f_{peak} = f_{ob} \times ff'$$

where

$$ff' = Eff' \times cf' \div (Eff' \times cf' + 1 - cf')$$

and

$$cf' = \left(\frac{1}{v_{surf} \times v_{ob}}\right)^{0.5} - \left(\frac{1}{Eff' - 1}\right)$$

Using the formula for a triangle of $V_{rec} = E\ xT_{oil}$, the dimensionless time at zero oil rate, t_{zero} is

$$t_{zero} = t_{break} + 2 \times E \times \frac{S_{orw}}{f_{peak}}$$

The overall recovery efficiency E is increased to a value E' to account for the effects of crossflow where

$$E' = 0.04 \times \log cf + 0.064 + E$$

where cf is the dimensionless crossflow number, bounded from below by 0.025.

In order to convert the dimensionless production curve to a real-time basis, a steady-state injection/production rate for a five-spot pattern must be estimated. This rate, Q_{ss} may be specified or defaulted from the following equation:

$$Q_{SS} = \frac{0.003541 \times C_{inj} \times K \times d \times T_{pay}}{\mu_{oil} \times 1.25 \times (5.58 + 0.5 \times \log A)}$$

where μ_{oil} is the viscosity of oil.

The peak oil rate is

$$Q_{peak} = Q_{SS} \times \frac{f_{peak}}{B_f}$$

and the times (day) of oil breakthrough, t_{ob} peak oil rate, t_{po} and sweep out, t_{so} are, respectively,

$$t_{ob} = t_{break} \times \frac{V_{pflood}}{Q_{SS}}$$

$$t_{po} = t_{surf} \times \frac{V_{pflood}}{Q_{SS}}$$

and

$$t_{so} = t_{zero} \times \frac{V_{pflood}}{Q_{SS}}$$

where V_{pflood} is the pattern floodable pore volume (MMRB).

3.8 Chemical Injection Schedule

The volume of surfactant slug injected per pattern is

$$V_{spp} = V_{pflood} \times V_{slug}$$

Note that the volume of surfactant slug injected is independent of the surfactant concentration in the slug. The time (year) over which surfactant injection occurs is then

$$t_{sinj} = \frac{V_{spp}}{Q_{SS} \times 365}$$

The polymer (mobility buffer) slug, which follows the surfactant slug, is graded (decreased) in polymer concentration from an initial concentration c_{poly} until the entire polymer has been injected. c_{poly} is calculated internally as a function of mobility (viscosity) ratio and a measure of the wettability,

$$c_{poly} = (\left(111 \times \frac{\mu_{\mathrm{oil}}}{\mu_{\mathrm{water}}}\right) + B)$$

where

$$B = 338 \text{ if } R_{perm} < 0.1$$

$$B = (338.0 + ((R_{perm} - 0.1) \times \frac{1032}{9.9})) \text{ if } 0.10 < R_{perm} < 10$$

and

$$B = 1370 \text{ if } R_{perm} > 10$$

where

$$R_{perm} = \left(\frac{\mathrm{K_{oro}}}{\mathrm{K_{orw}}}\right)$$

μ_{oil} and μ_{water} are the viscosities of oil and water, respectively, and K_{orw} and K_{oro} are the water and oil relative permeability endpoints

4 Methodology

4.1 Project Flow Chart

The flow of this project can be separated into 4 distinct phases.

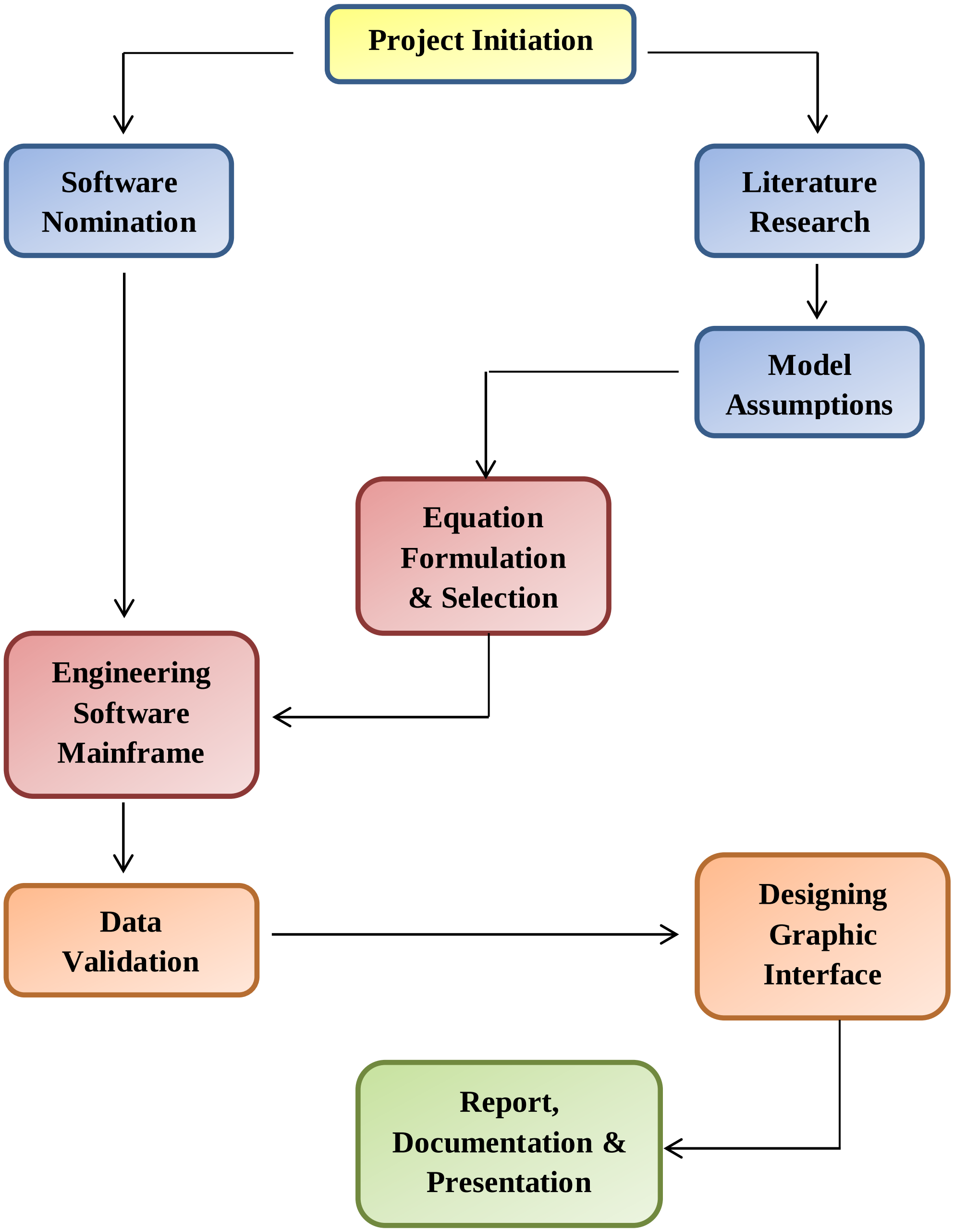


Figure 4: Project execution methodology.

4.2 Screening Program Flow Chart

A more detailed flow of the overall concept of chemical flooding screening and program holistic flow.

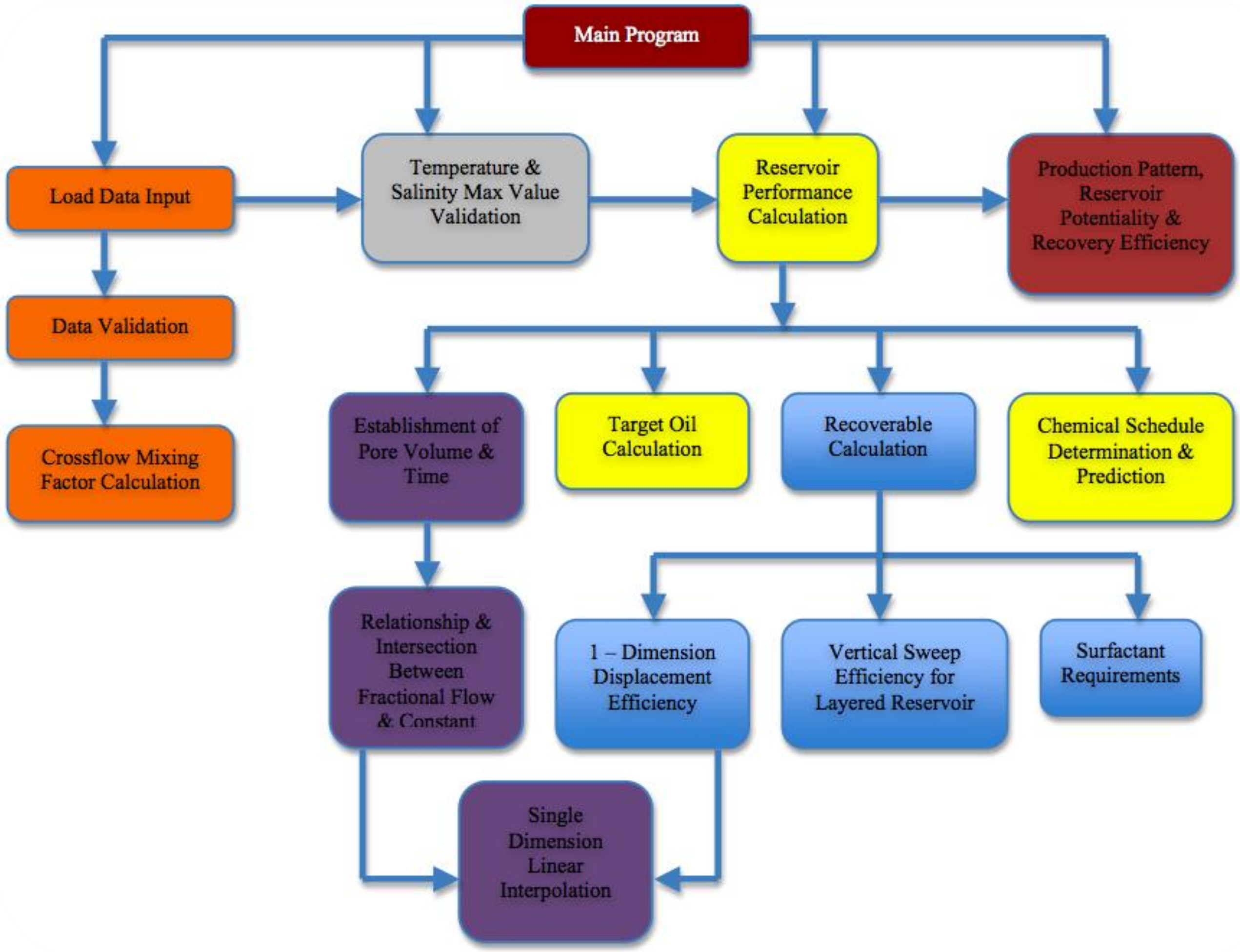
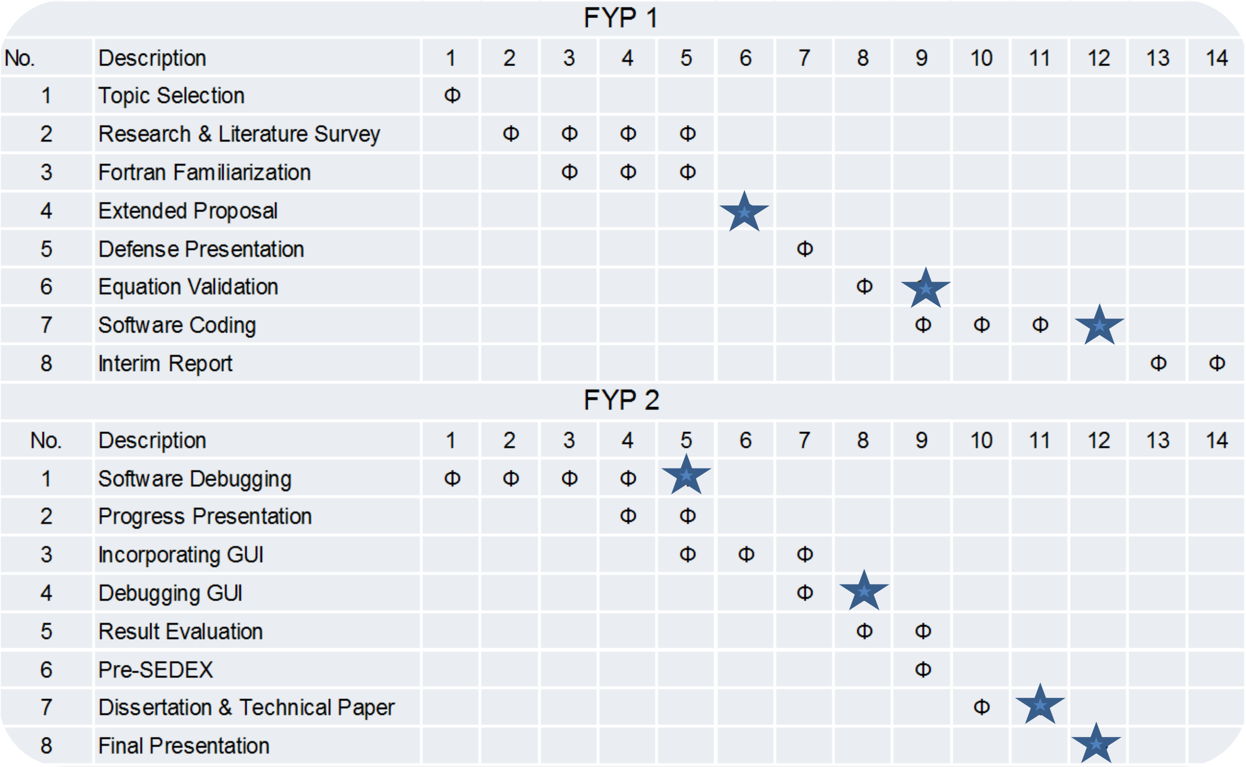


Figure 4.1: Program execution flow.

4.3 Gantt Chart



FYP 1

No.	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Topic Selection	Φ													
2	Research & Literature Survey		Φ	Φ	Φ	Φ									
3	Fortran Familiarization			Φ	Φ	Φ									
4	Extended Proposal						★								
5	Defense Presentation							Φ							
6	Equation Validation								Φ	★					
7	Software Coding									Φ	Φ	Φ	★		
8	Interim Report													Φ	Φ

FYP 2

No.	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Software Debugging	Φ	Φ	Φ	Φ	★									
2	Progress Presentation				Φ	Φ									
3	Incorporating GUI					Φ	Φ	Φ							
4	Debugging GUI							Φ	★						
5	Result Evaluation								Φ	Φ					
6	Pre-SEDEX									Φ					
7	Dissertation & Technical Paper										Φ	★			
8	Final Presentation												★		

Table 4: Gantt Chart

★ **Denotes milestones in Gantt Chart**

4.4 Key Milestones

1) Approval of project feasibility in defense presentation.
2) Equation validation of screening model.
3) Successful coding of VBA mainframe.
4) Incorporation of Graphical User Interface, GUI.
5) Production of program guide.
6) Completion of dissertation and technical paper

5 Model Verification and Discussions

The results generated from the software are cross referenced with actual reservoir generated data to validate accuracy of results obtained. The end results are quite satisfactory. The software is compared with Sloss field test, Nebraska, Big Muddy pilot, Casper, Wyoming and 219-R project at La Selle anticline, Illinois.

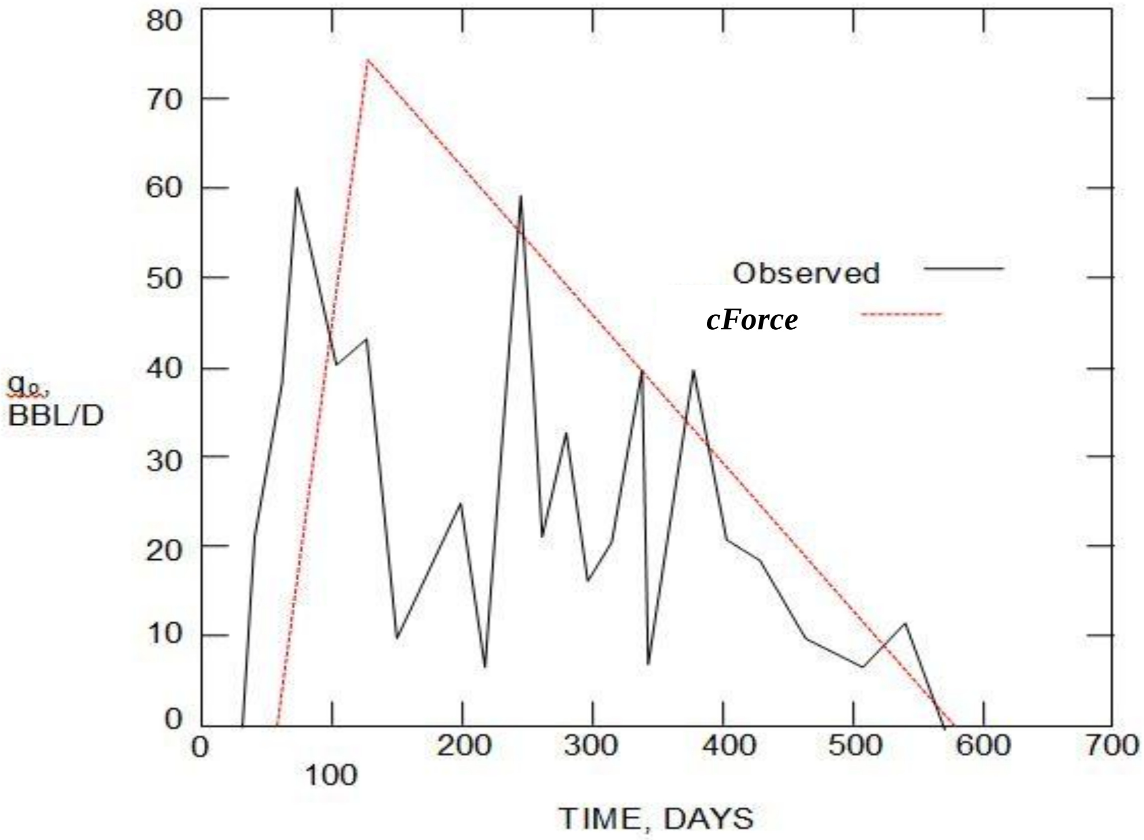


Figure 5: Sloss field test, Nebraska.

For Sloss, the ***cForce*** overestimates oil recovery, perhaps due to productivity problems in the field. When compared with Big Muddy the ***cForce*** is low on recovery, probably because crossflow was not considered. For both these tests, oil timing is predicted well within acceptable limits for economic calculations.

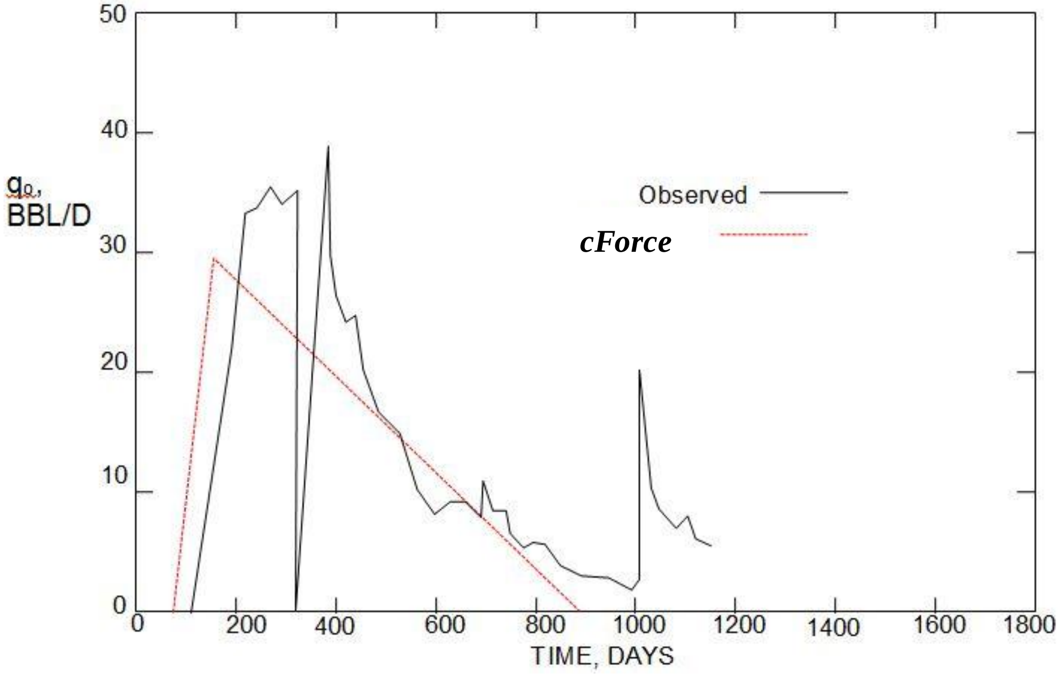


Figure 5.1: Big Muddy pilot, Wyoming.

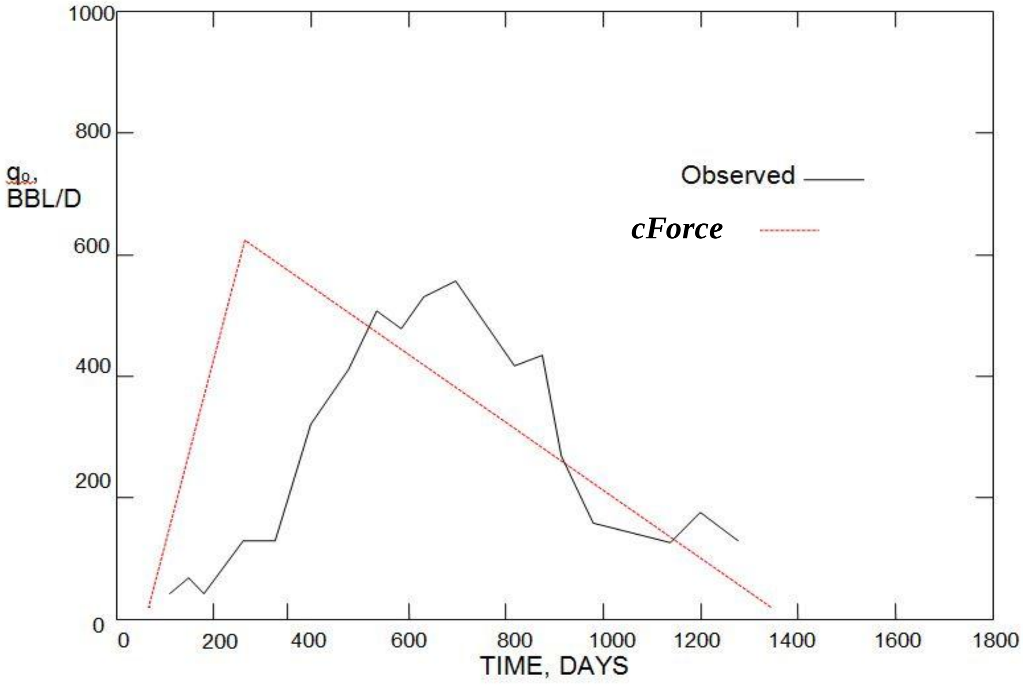


Figure 5.2: 219-R project, La Selle anticline, Illinois.

For 219R, the predicted efficiency of 0.31 agrees well with the field estimate of 0.27 - 0.33. Figure 5.2 shows that the ***cForce*** approximates the magnitude of peak oil rate and project life, but misses on peak rate location and oil breakthrough. There may be several reasons for this:

1. Great uncertainty in the retention and relative permeability data.

2. The simplified fractional flow treatment in the ***cForce*** may be a poor approximation for viscous, relatively high oil content micellar slugs, for which a more specific procedure is available.[11]

3. The symmetrical character of the field curve, with a heterogeneity factor of 0.62, may reflect the effects of high vertical crossflow.

Considering the assumptions made in the development of the ***cForce***, and the uncertainty of much of the data required for its application, the comparative results are good. In addition, the above comparisons indicate that the ***cForce*** might be used as a history matching or design tool to precede more costly, fully compositional simulations.

6 Results

The project presents data in various forms which includes singular calculated results as well as graphed reservoir performance. Calculated results can be grouped into 3 main summary namely, recovery efficiency, analysis summary and production summary.

Recovery Efficiency	Analysis Summary	Production Summary
Field Capillary Number	Total Developed Area	Pattern Surfactant Slug
Displacement Efficiency	No. of Effective Patterns	Initial Polymer Concentration
Cross flow Number	Pattern Floodable Pore	Pattern Polymer
Surfactant Retention	Pattern Target Oil	Dimensionless Surfactant
Dimensionless Surfactant	Project Target Oil	Dimensionless Oil Bank
Surfactant Slug Size	Total Oil Recovery	Oil Breakthrough Pore
Pore Volume Mobility Buffer		Peak Rate Pore Volume
Dykstra-Parsons Coefficient		Sweep Out Pore Volume
Effective Mobility Ratio		Oil Breakthrough Time
Flow Capacity of Layer		Peak Rate Time
Vertical Sweep Efficiency		Total Pattern Life
Mobility Sweep Buffer		Fractional Flow of Oil At Peak
Cross flow Performance		Injectivity Coefficient
Tertiary Oil Recovery		Steady State Pattern Rate
		Oil Rate At Peak
		Water Saturation In Bank
		Water Fractional Flow
		Pattern Spacing
		Starting Oil Saturation
		Project Floodable Pore

Table 6: List of Generated Results.

Results are later graphed to depict reservoir performance and behavior. In this project 7 graphs are plotted namely relative permeability of water and oil, fractional flow curve, derivatives of fractional flow, water production rate, cumulative water production, oil and gas production rate as well as cumulative oil and gas production. Examples of graphs generated are attached as follows.

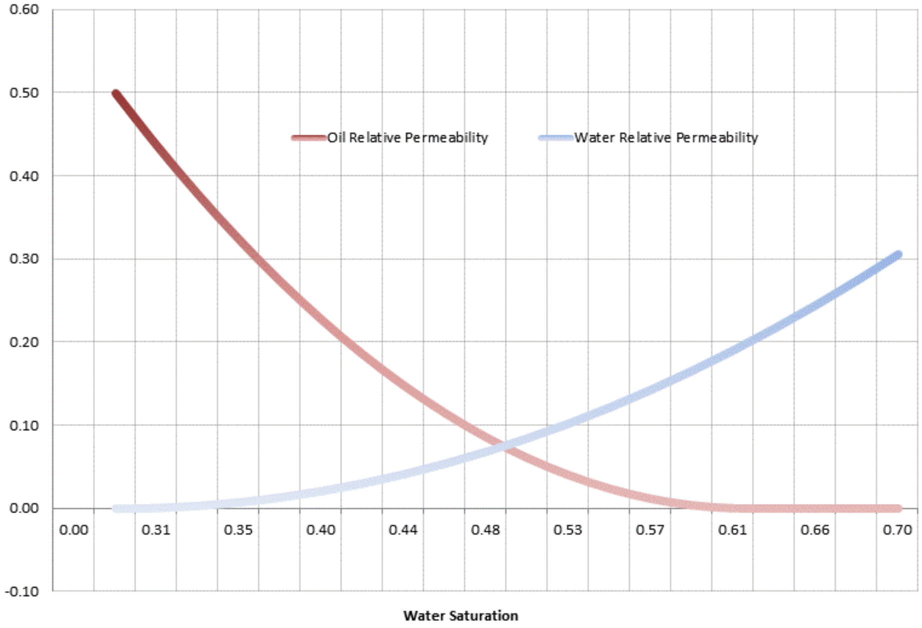


Figure 6: Oil relative permeability vs. water relative permeability.

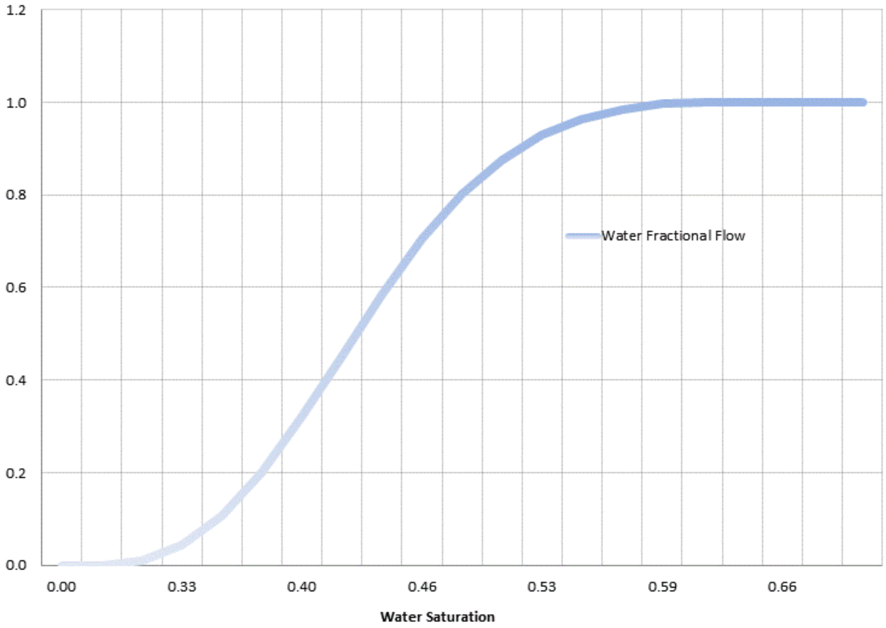


Figure 6.1: Fractional flow of water.

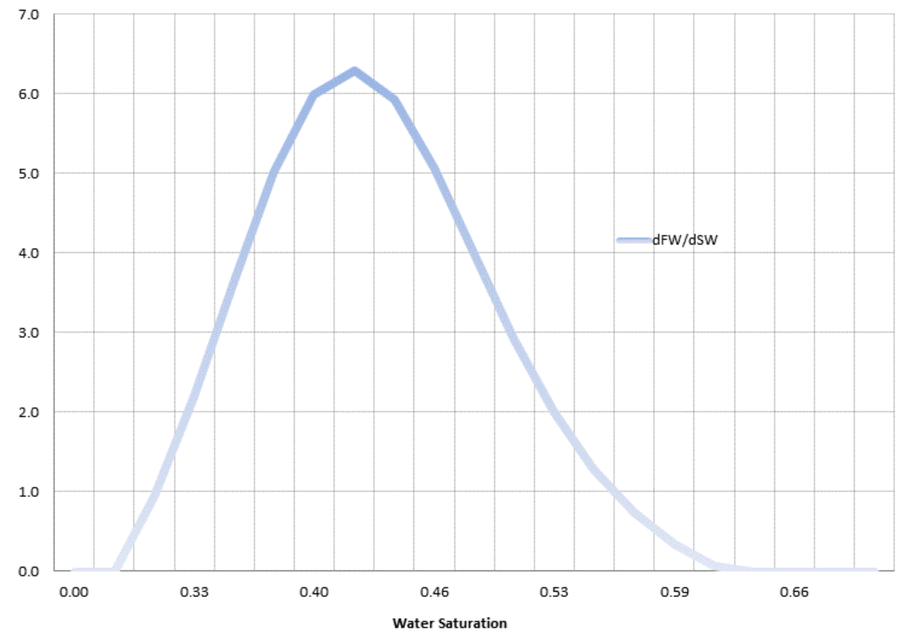


Figure 6.2: Derivatives of fractional flow over saturation of water.

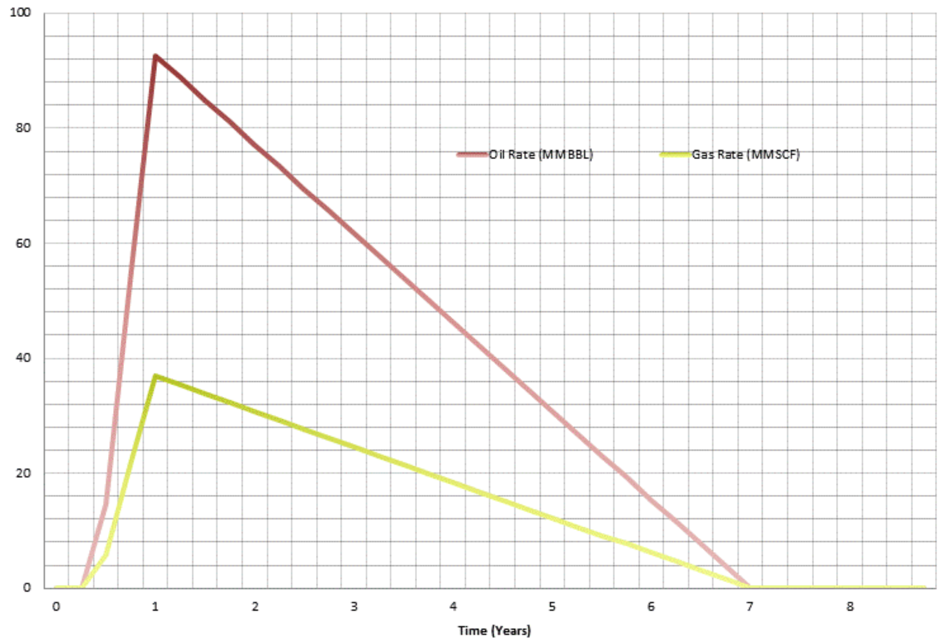


Figure 6.3: Oil and gas production rates.

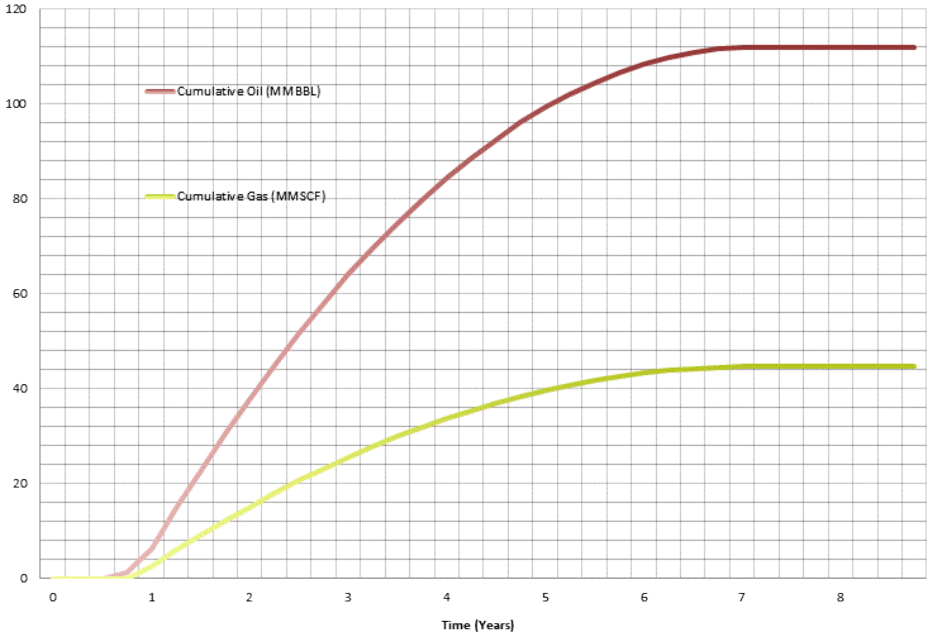


Figure 6.4: Cumulative oil and gas production.

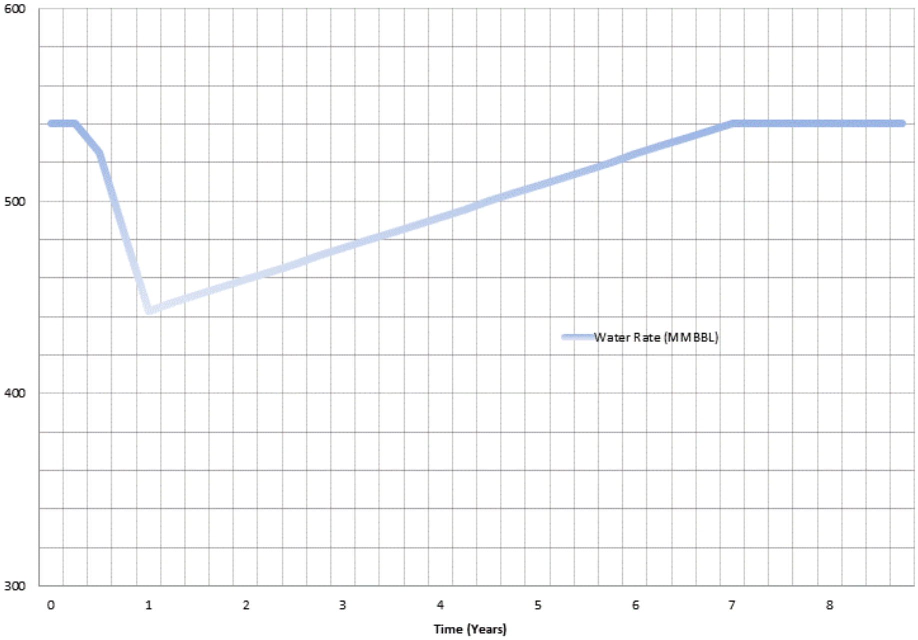


Figure 6.5: Water production rates.

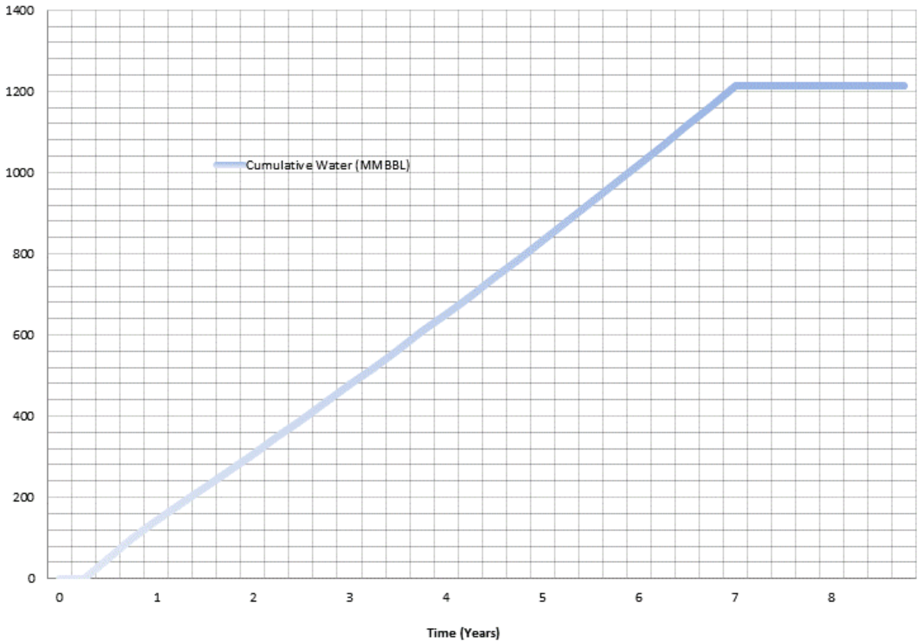


Figure 6.6: Cumulative water production.

The project is later presented in the form of graphical user interface to enhance ease of use and data retrieval. The graphical user interface can be separated into 5 main stages namely loading interface, well data input , pre-processing, solution stage as well as post-processing.

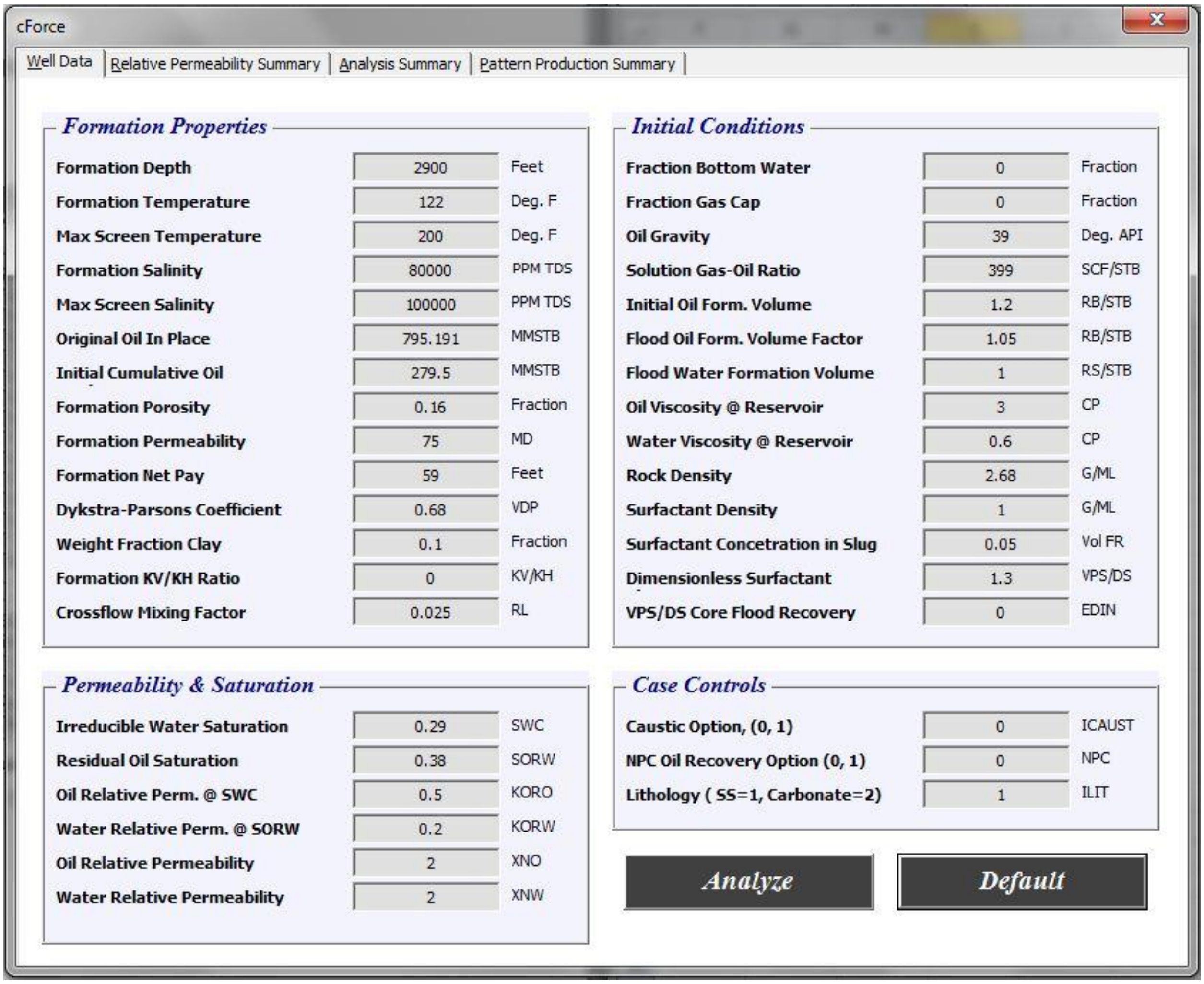
Stage 1 – Loading Interface

Users are greeted with a descriptive interface once the software has been loaded. Clicking RUN would prompt user into the 2nd stage, well data input.

Figure 6.7: Loading interface of chemical flooding predictive module.

Stage 2 – Well Data Input

As mentioned earlier, a loading screen would appear directing users to input well parameters accordingly to formation properties, permeability and saturation, well initial conditions as well as case controls.



Formation Properties

Formation Depth	2900	Feet
Formation Temperature	122	Deg. F
Max Screen Temperature	200	Deg. F
Formation Salinity	80000	PPM TDS
Max Screen Salinity	100000	PPM TDS
Original Oil In Place	795.191	MMSTB
Initial Cumulative Oil	279.5	MMSTB
Formation Porosity	0.16	Fraction
Formation Permeability	75	MD
Formation Net Pay	59	Feet
Dykstra-Parsons Coefficient	0.68	VDP
Weight Fraction Clay	0.1	Fraction
Formation KV/KH Ratio	0	KV/KH
Crossflow Mixing Factor	0.025	RL

Initial Conditions

Fraction Bottom Water	0	Fraction
Fraction Gas Cap	0	Fraction
Oil Gravity	39	Deg. API
Solution Gas-Oil Ratio	399	SCF/STB
Initial Oil Form. Volume	1.2	RB/STB
Flood Oil Form. Volume Factor	1.05	RB/STB
Flood Water Formation Volume	1	RS/STB
Oil Viscosity @ Reservoir	3	CP
Water Viscosity @ Reservoir	0.6	CP
Rock Density	2.68	G/ML
Surfactant Density	1	G/ML
Surfactant Concetration in Slug	0.05	Vol FR
Dimensionless Surfactant	1.3	VPS/DS
VPS/DS Core Flood Recovery	0	EDIN

Permeability & Saturation

Irreducible Water Saturation	0.29	SWC
Residual Oil Saturation	0.38	SORW
Oil Relative Perm. @ SWC	0.5	KORO
Water Relative Perm. @ SORW	0.2	KORW
Oil Relative Permeability	2	XNO
Water Relative Permeability	2	XNW

Case Controls

Caustic Option, (0, 1)	0	ICAUST
NPC Oil Recovery Option (0, 1)	0	NPC
Lithology (SS=1, Carbonate=2)	1	ILIT

Figure 6.8: Well data input.

Stage 3 – pre-Processing

Upon clicking default on well data interface, ***cForce*** would automatically initialize calculation with a set of preloaded data. Users are free to amend details in the well data and re-analyze the calculation. 3 distinct curves are formed in the pre-processing stage namely relative permeability curves, fractional flow curve as well as derivative curve.

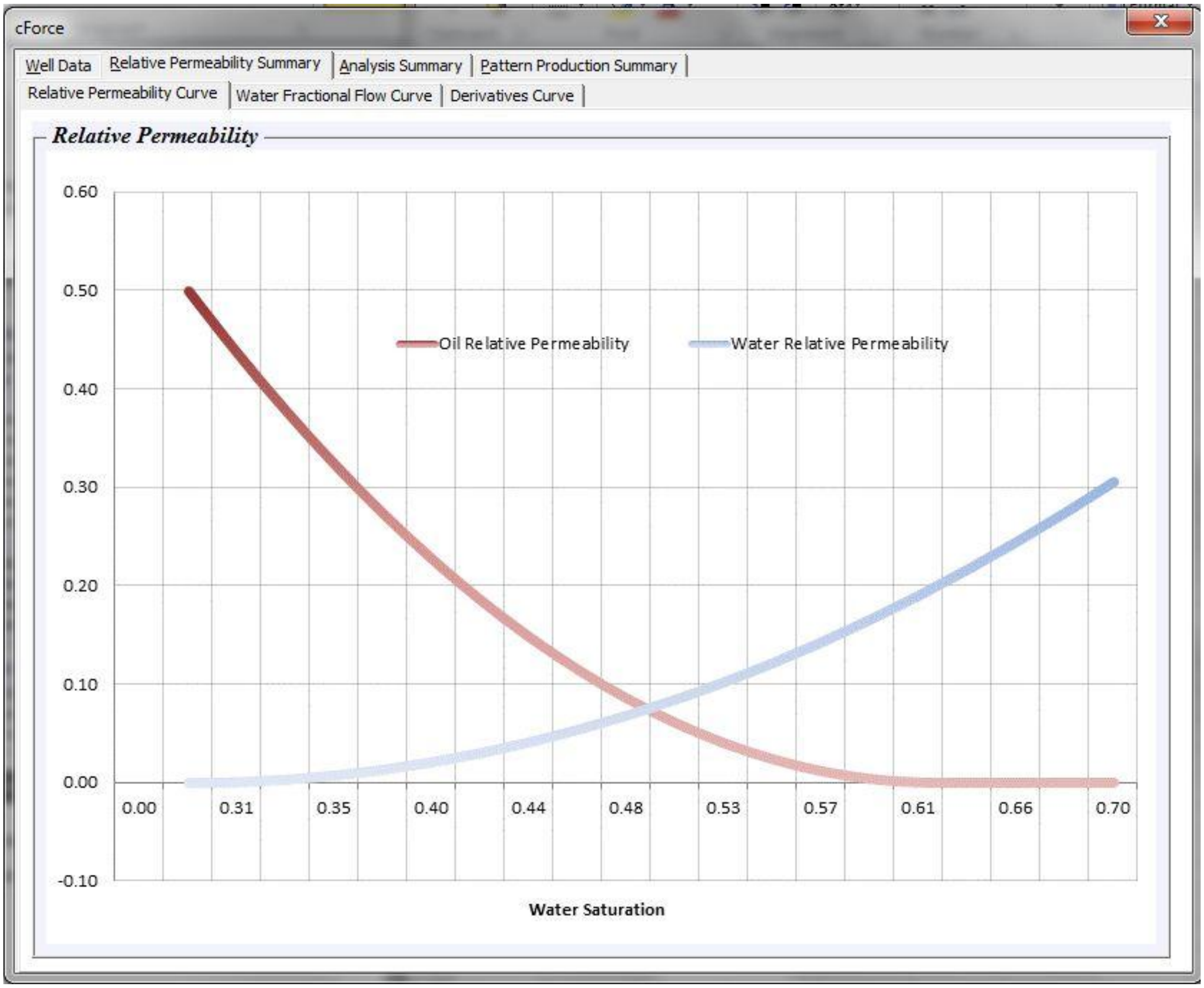
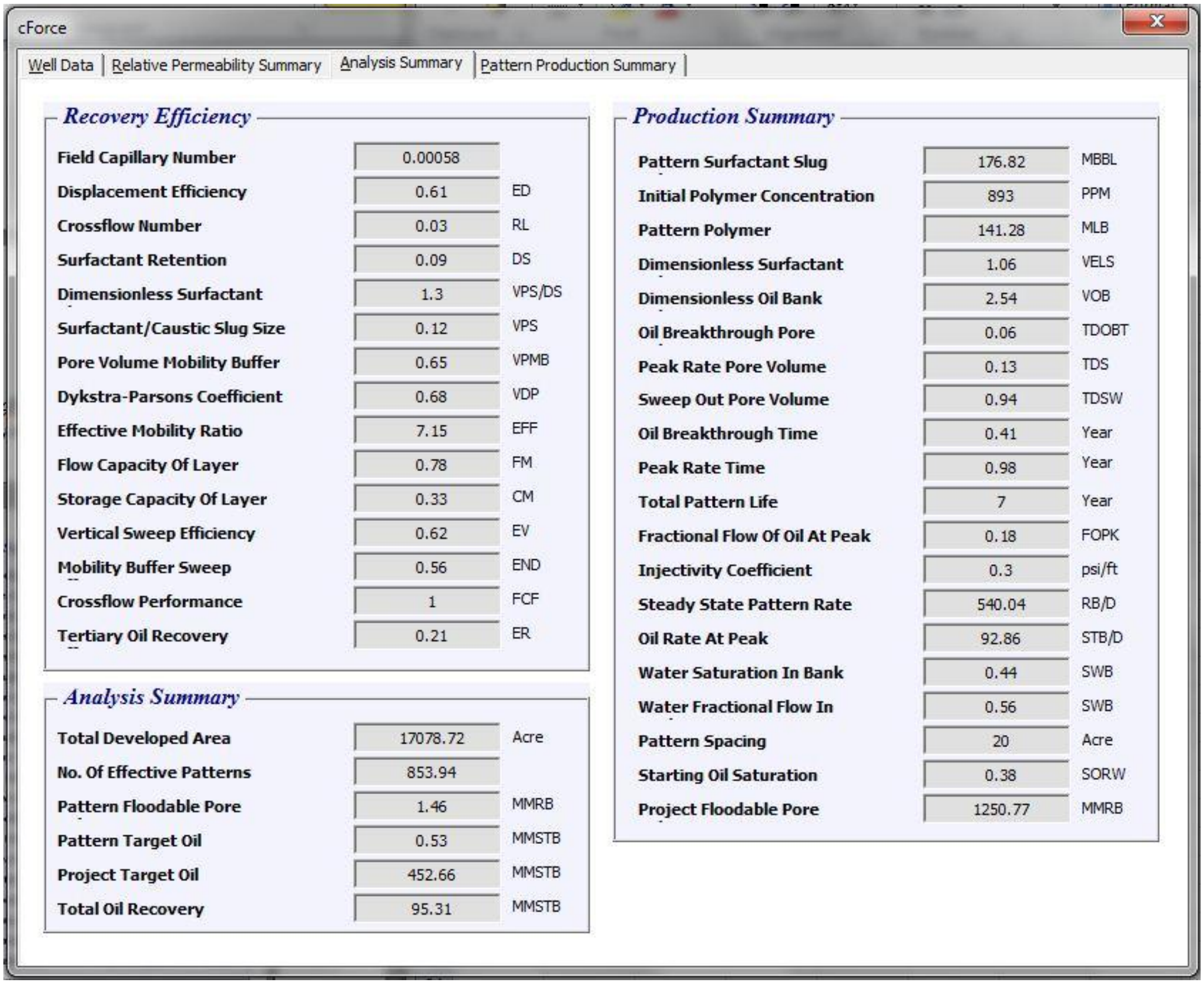


Figure 6.9: Relative permeability curves.

Stage 4 – Solution

Upon completion of pre-processing, numerical solutions of ***cForce*** are presented in an analysis summary interface. Solutions can be separated into recovery efficiency, analysis summary as well as well production summary.



Recovery Efficiency

Field Capillary Number	0.00058	
Displacement Efficiency	0.61	ED
Crossflow Number	0.03	RL
Surfactant Retention	0.09	DS
Dimensionless Surfactant	1.3	VPS/DS
Surfactant/Caustic Slug Size	0.12	VPS
Pore Volume Mobility Buffer	0.65	VPMB
Dykstra-Parsons Coefficient	0.68	VDP
Effective Mobility Ratio	7.15	EFF
Flow Capacity Of Layer	0.78	FM
Storage Capacity Of Layer	0.33	CM
Vertical Sweep Efficiency	0.62	EV
Mobility Buffer Sweep	0.56	END
Crossflow Performance	1	FCF
Tertiary Oil Recovery	0.21	ER

Analysis Summary

Total Developed Area	17078.72	Acre
No. Of Effective Patterns	853.94	
Pattern Floodable Pore	1.46	MMRB
Pattern Target Oil	0.53	MMSTB
Project Target Oil	452.66	MMSTB
Total Oil Recovery	95.31	MMSTB

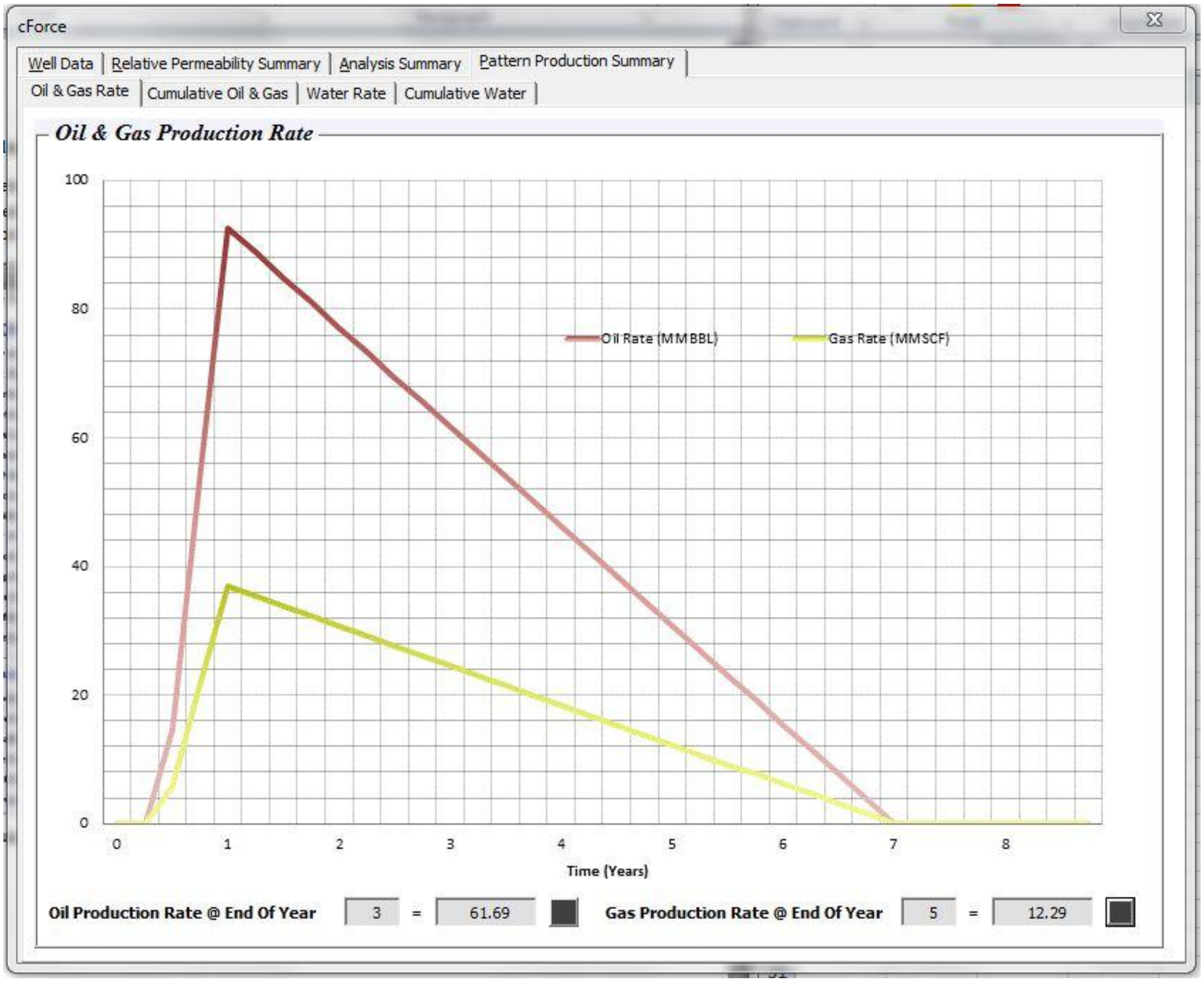
Production Summary

Pattern Surfactant Slug	176.82	MBBL
Initial Polymer Concentration	893	PPM
Pattern Polymer	141.28	MLB
Dimensionless Surfactant	1.06	VELS
Dimensionless Oil Bank	2.54	VOB
Oil Breakthrough Pore	0.06	TDOBT
Peak Rate Pore Volume	0.13	TDS
Sweep Out Pore Volume	0.94	TDSW
Oil Breakthrough Time	0.41	Year
Peak Rate Time	0.98	Year
Total Pattern Life	7	Year
Fractional Flow Of Oil At Peak	0.18	FOPK
Injectivity Coefficient	0.3	psi/ft
Steady State Pattern Rate	540.04	RB/D
Oil Rate At Peak	92.86	STB/D
Water Saturation In Bank	0.44	SWB
Water Fractional Flow In	0.56	SWB
Pattern Spacing	20	Acre
Starting Oil Saturation	0.38	SORW
Project Floodable Pore	1250.77	MMRB

Figure 6.10: Calculated analysis summary.

Stage 5 – post-Processing

A more detailed analysis of ***cForce*** can be found in the pattern production summary interface. Here, respective production rate as well as cumulative production of oil, gas and water can be seen clearly in a graphed manner. Users can even retrieve specific information of production rate or cumulative production on a certain year.



Oil Production Rate @ End Of Year 3 = 61.69

Gas Production Rate @ End Of Year 5 = 12.29

Figure 6.11: Calculated production rates.

7 Conclusion

In conclusion, chemical flooding in enhanced oil recovery is definitely a wide applied tertiary recovery technique that would much attract interest of contemporary engineers. The software based simple screening model proved to be a powerful tool for all to have an initial overview over the reservoir. It provides visualization of In-situ reservoir behavior as well as crucial parameters and deduction for further reservoir development. Users would be able to have an overview through efficiency, predicted production as well as cumulative production and how they relate to each other.

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