A FRAMEWORK TO DESIGN AND OPTIMIZE CHEMICAL FLOODING PROCESSES

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by
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ABSTRACT

The goal of this proposed research is to provide an efficient and user friendly simulation framework for screening and optimizing chemical/microbial enhanced oil recovery processes. The framework will include (1) a user friendly interface to identify the variables that have the most impact on oil recovery using the concept of experimental design and response surface maps, (2) UTCHEM reservoir simulator to perform the numerical simulations, and (3) an economic model that automatically imports the simulation production data to evaluate the profitability of a particular design. Such a reservoir simulation framework is not currently available to the oil industry.

The objectives of Task 1 are to develop three primary modules representing reservoir, chemical, and well data. The modules will be interfaced with an already available experimental design model. The objective of the Task 2 is to incorporate UTCHEM reservoir simulator and the modules with the strategic variables and developing the response surface maps to identify the significant variables from each module. The objective of the Task 3 is to develop the economic model designed specifically for the chemical processes targeted in this proposal and interface the economic model with UTCHEM production output. Task 4 is on the validation of the framework and performing simulations of oil reservoirs to screen, design and optimize the chemical processes.

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INTRODUCTION

In this report, we detail our progress on Tasks 1 and 2 for the first half of the first year of the project. We have initiated the development of the framework with three modules for uncertainty and optimization of reservoir properties, well placement, and chemical data. We have performed several surfactant flooding simulations with different permeability and permeability heterogeneities, surfactant concentration and slug size to identify the key variables that control the project life and oil recovery.

The experimental design module was then used to design the simulations varying the primary variables such as surfactant and polymer concentration and slug size and the provided range for each.

EXECUTIVE SUMMARY

Reservoir simulation has become an increasingly widespread and important tool for analyzing and optimizing the oil recovery projects. Although reservoir simulation software is currently available but there are still many obstacles to widespread use in the upstream oil and gas industry, in particular for small and medium sized companies. The goal of this proposed research is to provide an efficient and user-friendly framework for optimizing chemical enhanced oil recovery processes adequate for desktop computers. We have developed UTCHEM simulator over many years with the support of the Department of Energy and it is clearly the most versatile reservoir simulator for chemical EOR processes. Here, we are in the process of developing an easy to use framework suitable for desktop computers using experimental design concept to reduce the number of UTCHEM simulations required to achieve a level of confidence in uncertainty of the key variables and performing economic analysis to aid in an economically optimal design for a particular oil reservoir.

The objectives of Task 1 are to develop three primary modules representing reservoir, chemical, and well data. The modules will be interfaced with an already available experimental design model. The objective of the Task 2 is to incorporate UTCHEM reservoir simulator and the modules with the strategic variables and developing the response surface maps to identify the significant variables from each module.

The objective of the Task 2 is to perform a certain number of flow simulations using UTCHEM in order to determine the "response surface" of the simulator in the space of predominant uncertain parameters. The simulation results will then be analyzed and recovery data as a function of designed variables will be stored. These simulation results will then be ported to Design-Expert software to plot the responses versus each parameter.

Here we report on our initial efforts on Tasks 1 and 2. A platform called Integrated Reservoir Simulation Platform (IRSP) is designed and developed that is a combination of several softwares and hardwares to solve various oil reservoir engineering problems. Several window based commercial packages are used to analyze the results by IRSP.

In order to use the distributive and parallel features of PC clusters, the IRSP is initially developed under Redhat Linux.

We have currently included the following softwares in IRSP.

- UTCHEM to perform chemical flooding simulations
- MDM (Yang, 1990) to generate stochastic distributions of reservoir properties
- GSLIB (Clayton and Journel, 1992)) to generate stochastic distributions of reservoir properties
- TECPlot (Tecplot Inc.) to generate 2D and 3D distributions of simulation output results
- MS Excel to summarize the oil recovery results of the simulations
- MATLAB (The mathWorks) for artificial neural network
- Design Expert (Stat-Ease) for experimental design and response surface

EXPERIMENTAL

This project does not include an experimental component.

RESULTS AND DISCUSSION

A user-friendly framework is designed and in the process of development to perform and optimize chemical flooding simulations in a reasonable time frame by automating the simulation input data generation. Several key simulation output results are generated automatically and plotted using Excel. These results will be fed to the economic package. The initial progress on Tasks 1 and 2 are reported as discussed below.

Task 1: Development of Uncertainty Modules and Experimental Design Model

There are a large number of uncertain parameters to design an optimized chemical flooding project. These parameters include those that characterize the reservoir such as permeability and its distribution, initial oil saturation and its distribution, the significance of crossflow (k_v/k_h). The second set of variables that affect the oil recovery are those related to the chemical data such as the surfactant structure and formulation, mass and concentration of injected surfactant, the need for mobility control such as foam or agent. The success of any oil recovery project involves the optimization of the production strategies. These include variables such as well type *i.e*. horizontal vs. vertical wellbores, well pattern, well locations, and injection/production rates.

A platform called Integrated Reservoir Simulation System (IRSS) is designed and developed that is a combination of softwares and hardwares to solve various oil reservoir engineering problems. Several window based commercial packages are used to analyze the results by IRSS.

In order to use the distributive and parallel features of PC clusters, IRSS is initially developed under Redhat Linux operating system.

We have currently included the following softwares in IRSS as shown in Fig. 1.

- UTCHEM to perform chemical flooding simulations
- MDM (Yang, 1990) to generate stochastic distributions of reservoir properties
- GSLIB (Clayton and Journel, 1992) to generate stochastic distributions of reservoir properties
- Tecplot RS (Tecplot Inc.) aids in a rapid exploration comparison of reservoir field measurements and simulation data. It integrates XY graphs with 2 and 3D grid visualizations. Effortlessly produce standard and customized reservoir plots, create animations, and output high-quality images. Create all the views the user needs to analyze the reservoir data and performance.
- MS Excel to summarize the oil recovery results of the simulations
- MATLAB (The Mathworks) for artificial neural network
- Design Expert (Stat-Ease) for experimental design and response surface

Task 2.0 Reservoir Simulation and Response Surface Model

Simulations to identify the key variables

We have made numerous surfactant/polymer flooding simulations in a typical onshore, light oil sandstone reservoir. We have performed sensitivity studies to key variables such as permeability and degree of heterogeneity, permeability realization, surfactant concentration and slug size, and initial oil saturation to test the framework. The reservoir is initially waterflooded for a different period of time. The reservoir is 3500 ft deep and 140 feet thick. The reservoir is 660 ft x 660 ft. The oil viscosity is 7.8 cp. The initial salinity was the same as that in the injected water with 0.611 meq/ml of total anions and 0.1275 meq/ml of total divalent cations that is equivalent to about 22,000 mg/l. The permeability distribution was generated with an arithmetic mean of 500 md and a Dykstra parsons' coefficient of 0.8 in the Base Case simulation. A spherical variogram and a log normal permeability distribution were used. Correlation lengths of 660 feet in the x and y directions and 28 feet in the z direction were used. Several cross sections of the Base Case permeability distribution are shown in Fig. 2. The vertical-to-horizontal permeability ratio was 0.1. A uniform porosity of 0.136 was used. The water preflush was about 2.81 PV in the Base Case to reach a water cut of about 98%. The surfactant concentration of 2.5 vol% was injected for a period of 0.25 PV. There was 1000 ppm polymer included in the surfactant slug. The same concentration of polymer was injected for another 0.5 PV for mobility control and better sweep efficiency. The polymer drive was followed by 2.25 PV of water injection. The injection was at a constant pressure of 1250 psi and the production well at a bottomhole pressure of 250 psi. The simulation results of the Base Case are shown in Figs. 3 through 5. It takes about 11 years to inject 2.81 PV of water prior to the chemical injection and the total project life is about 34 years as shown in Fig. 3. The produced total oil and surfactant concentrations are shown in Fig. 4. There is a spike in the oil production as the surfactant breaks through. The cumulative oil recovered as a fraction of remaining oil in place at the time of surfactant flooding is given in Fig. 5. There is about 20% incremental oil recovery at the end of 24-year flood.

We performed numerous simulations to identify the most important variables that affect the performance of surfactant flood in this reservoir. These include:

- Reservoir permeability

- Permeability realization
- Surfactant concentration
- Length of water injection prior to chemical flood

Several simulations were performed to investigate the importance of length of waterflooding prior to the chemical flood. Water was injected for a period of 1, 1.5, and 2 pore volumes as compared to that of 2.81 PV for the base case. Figure 6 shows the cumulative oil recovery for the waterflood. About 58% of original oil in place was recovered by 2.81 PV of water flooding compared to the oil recovery of 46% for 1 PV of waterflood. Surfactant/polymer flooding simulations were performed starting at the end of each preflush. The cumulative oil recovery due to chemical flooding as a function of time is given in Fig. 7. The incremental oil recovery of chemical flood decreases as the remaining oil in place reduces due to a longer waterflood (Fig. 8).

Simulations were performed with different surfactant concentrations in the chemical slug to explore the sensitivity of oil recovery to this design variable. Figure 9 shows the produced oil and surfactant concentrations for the case with 0.5 vol% surfactant concentration. There was no significant surfactant concentration produced at the well for this case.

To investigate the effect of initial saturations, the initial water saturation was changed from the Base Case value of 0.2 to 0.3 and 0.4. The reservoir was then waterflooded for 2.81 PV in each case followed by chemical injection. Cumulative oil recoveries are given in Fig. 10. The cumulative oil recovery as a fraction of original oil in place at the start of water flood (OOIP) and remaining oil in place at the time of chemical flooding (ROIP) is shown in Fig. 11. The incremental recovery due to chemical injection is fairly insensitive to the initial water saturation.

We generated several realizations of the same permeability field and performed simulations of surfactant/polymer flooding. Similar to the Base Case simulation, the simulations initiated with water saturation of 0.2 and waterflooded for 2.81 PV in each case. The same strategy of chemical injection was followed. Cumulative oil recovery as a function of ROIP is shown in Fig. 12. The ultimate recovery is the highest for the case with the lowest permeability, however it takes nearly 6000 years. The shortest project life of about 20 years for the case with average permeability of 1000 md. Figure 13 shows the cumulative oil recovery at 20 years for each simulation. The recovery increases from nearly zero for the 10 md permeability case to about 20% for the highest permeability of 1000 md. We also generated several realizations of the permeability fields and performed the chemical flooding simulations. The recoveries were not very sensitive to the realization we studied.

Simulations using the Experimental Design

A second series of simulations was performed using the Design of Experiment (DOE) package. The variables identified and the range for each as input to the DOE is listed below.

- Surfactant/polymer slug size 0.05 to 0.25 PV
- Surfactant concentration 0.005 to 0.03 volume fraction
- Polymer concentration 0 to 0.05 wt%
- Polymer drive slug size 0 to 0.25 PV
- Polymer concentration in the drive 0 to 0.025 wt%

Table 2 gives the list of simulations and the values for each key variable generated by the DOE. A base case simulation input file was generated and then the values of the design variables were input in the instruction files for the framework. By running the framework, 31 UTCHEM input files were generated automatically incorporating the corresponding input values for the specific design and distributed to multiple processors. Once these simulations are completed, the framework will process the output files of all these simulations and creates a summary of the oil recovery for all the cases.

Three-dimensional simulations with 8 x 96 x 5 gridblocks were set up. Two horizontal wells were placed along the edges of the model parallel to the y axis and in the second layer. Table 3 gives the reservoir and fluid properties. The model was first flooded with water to reach a watercut of about 98% prior to the surfactant injection. This will reduce the initial high oil saturations to nearly waterflood residual oil values. The injection rate was constant at 4000 ft^3/d and the production well was placed at a constant pressure of 4000 psi during the entire flood. Surfactant and polymer were then injected at the designed concentrations and slug size. The flood was then followed by water at a salinity in the under optimum Type II(-) environment. The flood was performed at the near the optimum salinity.

The sensitivity of oil recovery to the designed variables is shown in Figs. 14 and 15. The oil recovery ranged between 36 to 74 % of OOIP that translates to 8.3 to 63.3% ROIP once subtracting the oil production from the initial waterflood. The maximum oil recovered was about 110,000 bbls (Fig. 16). Cumulative oil recovery as a function of amount of polymer and surfactant injected are shown in Fig. 17 and 18 respectively. The highest oil recovery is for the simulation with the most amount of surfactant injected. Figure 19 gives the cumulative oil recovery at the end of one year of chemical flooding as a function of both surfactant and polymer utilized. The figure indicates that the recovery is low when a small amount of chemical is used. The highest oil recovery of about 58% is for the case with 1000 lbs of polymer and 9000 ft^3 (561,600 lbs) of surfactant. The cumulative oil recovery as a function of time for the simulations are shown in Fig. 20.

CONCLUSIONS

An integrated platform to perform various reservoir simulation studies is designed and is under development. The platform can be used to perform stochastic simulations, sensitivity studies, reservoir parameter optimization, and research on developing and evaluating new methods. The platform can use different simulators and methodologies for reservoir simulation studies. The framework includes the input file for the reservoir simulator, UTCHEM and an instruction file for the automated sensitivity and optimization studies. The current instruction file includes three sets of parameters. These include the reservoir characterization, chemical data, and well placement and production strategy. Several other softwares have been included in the framework to facilitate the use of the model. Geostatistical packages such as MDM and GSLIB are added to the framework to generate distributions of reservoir properties such as permeability, and permeability heterogeneities, and initial oil saturation. The visualization software package Tecplot has been added to the framework to automatically generate 2D and 3D maps of the simulation results.

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The Mathworks, http://www.mathworks.com/

Yang, A.P., " Stochastic Heterogeneity and Dispersion," Ph.D. dissertation, The University of Texas, Austin (1990).

Table 1. Input parameters for the Base Case simulation

Property	Value
Reservoir size	660ft x 660ft x 140ft
Reservoir gridblock size	66ft x 66ft x 28ft
No. of gridblocks	11 x 11 x 5
Permeability	Stochastic, MDM method using V_{DP}=0.8, K_{avg}= 500 md (arithmetic)
Porosity	0.136
Initial water saturation	0.2
Water viscosity	0.7 cp
Oil viscosity	7.78 cp
Initial reservoir pressure	900 psi
Injection pressure	1250 psi
Production constraint	250 psi
Chemical slug composition	0.611 meq/ml salt, 2.5 vol % surfactant, 0.1 wt % polymer, water
Polymer drive composition	0.611 meq/ml salt, 0.1 wt % polymer, water
Post Flush	0.611 meq/ml brine

Table 2. The list of surfactant flood simulations designed by DOE

Run	Surf./Polymer slug size (PV)	Surf. conc (vol fraction)	Polymer conc (wt%)	Polymer drive (PV)	Polymer conc. in drive (wt%)	Cum oil (fraction of OOIP)
1	0.05	0.03	0	0	0	37.57
2	0.05	0.03	0	0.25	0	39.288
3	0.25	0.005	0.05	0	0.025	53.771
4	0.05	0.005	0.05	0	0	40.585
5	0.25	0.005	0.025	0	0	50.948
6	0.05	0.005	0	0.25	0	36.29
7	0.05	0.03	0	0.25	0.025	53.034
8	0.25	0.0175	0	0	0.025	47.152
9	0.25	0.005	0	0.25	0.025	51.372
10	0.25	0.005	0.05	0.25	0	56.733
11	0.25	0.03	0.025	0.25	0.025	73.492
12	0.05	0.005	0.025	0.25	0.025	43.591
13	0.05	0.03	0.025	0	0.025	46.621
14	0.15	0.005	0.025	0.125	0.0125	47.932
15	0.05	0.03	0.05	0	0	49.952
16	0.25	0.03	0.05	0.25	0	73.643
17	0.15	0.005	0.025	0.125	0.0125	47.932
18	0.25	0.03	0	0	0.0125	53.162
19	0.15	0.0175	0.025	0.25	0.0125	60.587
20	0.25	0.03	0	0.25	0	52.529
21	0.25	0.03	0.05	0	0	74.501
22	0.15	0.0175	0.025	0.25	0.0125	60.587
23	0.25	0.005	0.05	0	0.025	53.771
24	0.05	0.005	0.05	0.25	0	41.487
25	0.05	0.0175	0.025	0.125	0.0125	46.37
26	0.25	0.0175	0	0	0.025	47.152
27	0.05	0.0175	0.025	0.125	0.0125	46.37
28	0.25	0.005	0	0.25	0	39.5
29	0.05	0.03	0.05	0.25	0	50.337
30	0.05	0.03	0.05	0.25	0.025	55.897
31	0.05	0.005	0	0	0.0125	36.074

Table 3. Input parameters for the base case simulations in DOE

Property	Value
Reservoir size	160 ft x 4800 ft x 8.8 ft
Reservoir gridblock size	20 ft x 50 ft x (1.6-1.8 ft)
No. of gridblocks	8 x 96 x 5
Permeability in each layer	X direction: 3.269, 4.453, 1.489, 1.188, 0.71 Y direction: 9.8, 13.358, 4.466, 3.564, 2.136 Z direction: 1.634, 0.89, 0.744, 0.594, 0.356
Porosity in each layer	0.174, 0.169, 0.257, 0.173, 0.118
Initial water saturation in each layer	0.172, 0.162, 0.393, 0.381, 0.424
Water viscosity	0.3 cp
Oil viscosity	2 cp
Initial reservoir pressure	4000 psi
Reservoir Temperature	100 F
Injection rate	4000 ft3/d
Production constraint	4000 psi
Chemical slug composition	0.611 meq/ml salt, 2.5 vol % surfactant, 0.025 wt % polymer, water
Polymer drive composition	0.4 meq/ml salt, 0.025 wt % polymer, water
Post Flush	0.4 meq/ml brine

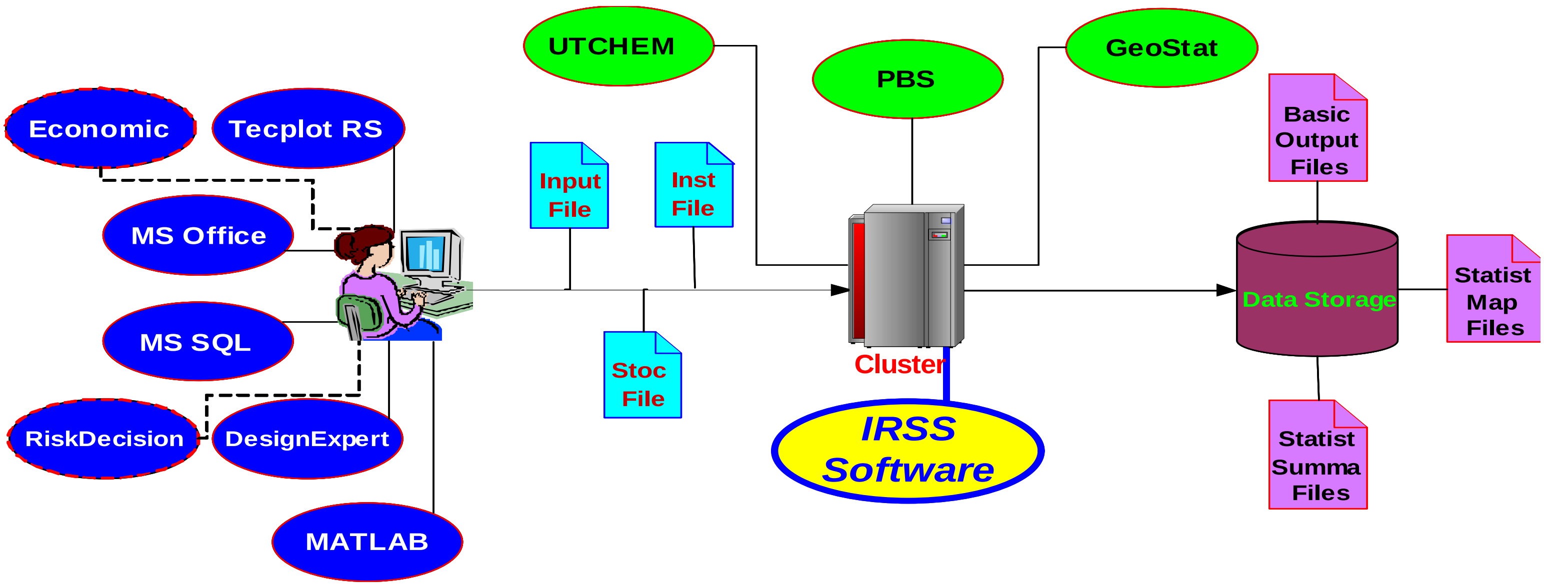

Fig. 1. Integrated Reservoir Simulation Platform

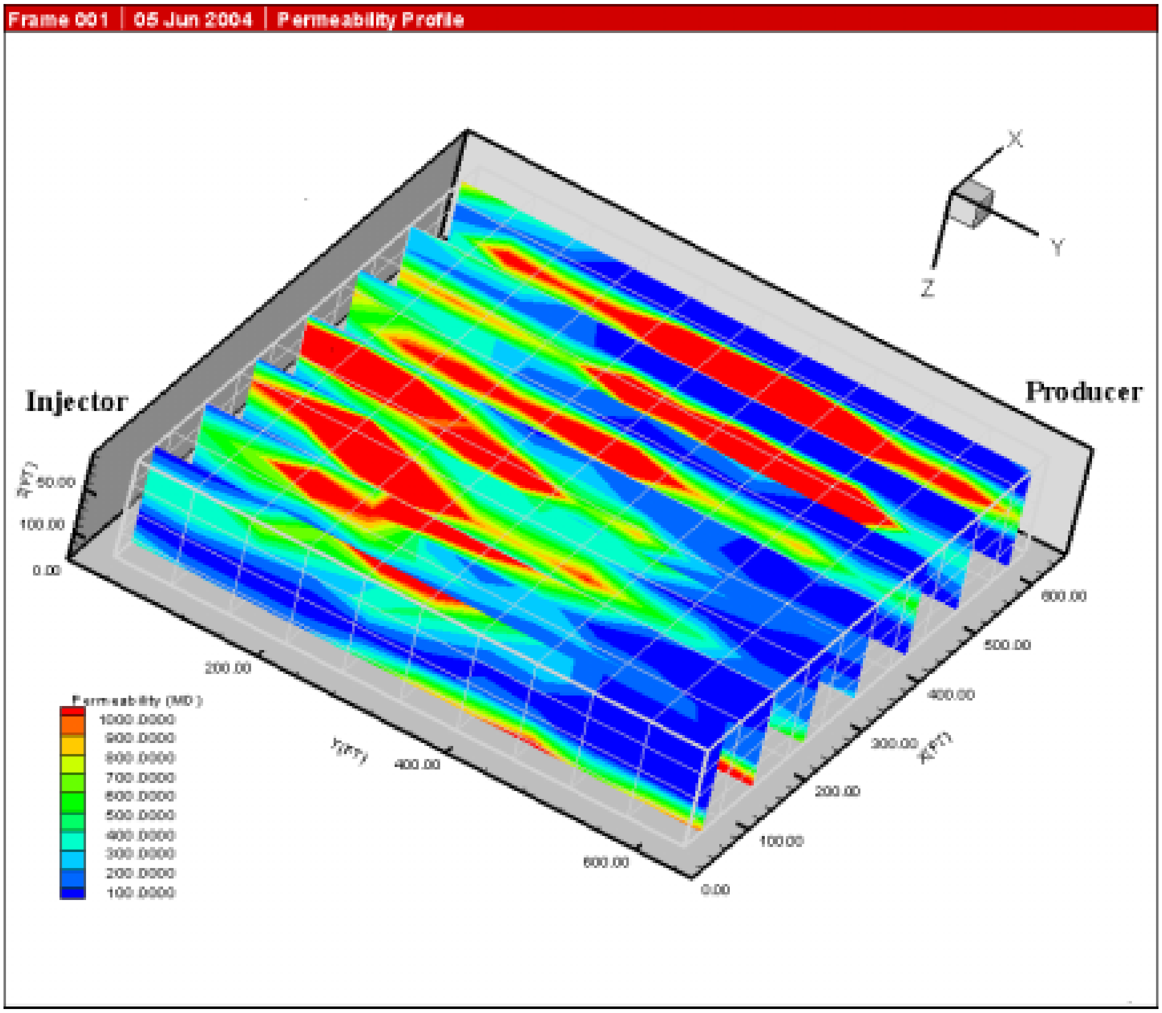

Fig. 2. Permeability distribution for the Base Case simulation

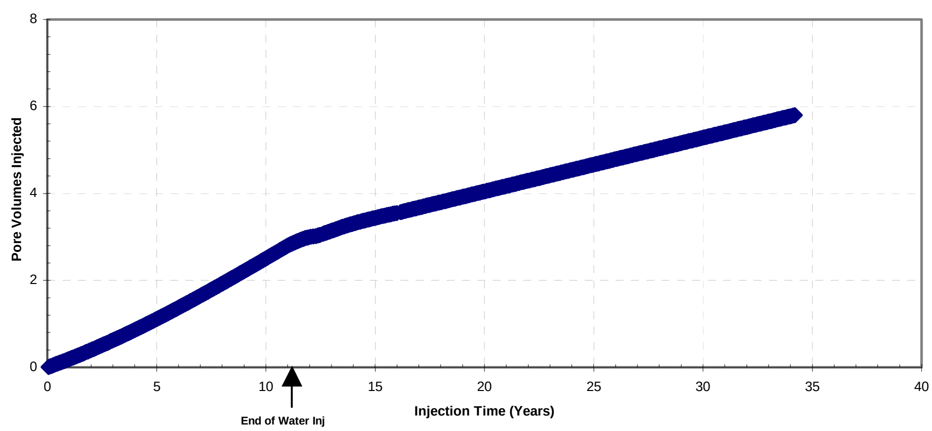

Fig. 3. Time vs. pore volume injected for the Base Case simulation (K = 500 md)

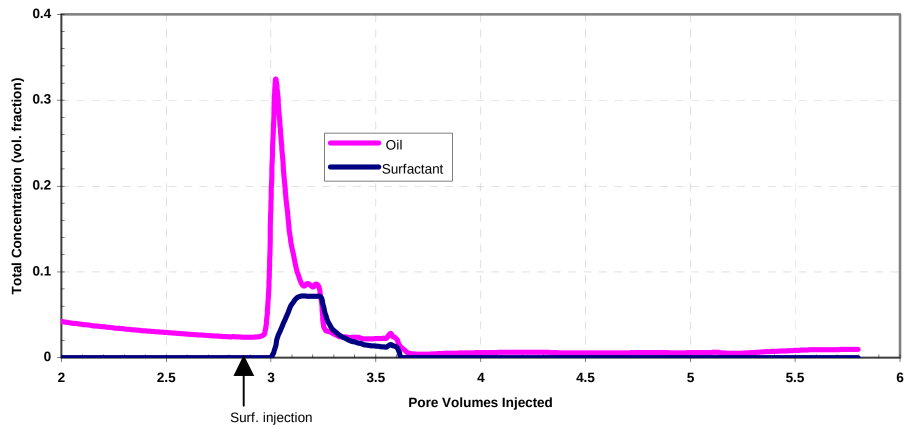

Fig. 4. Produced oil and surfactant concentration for the Base Case simulation (K = 500 md)

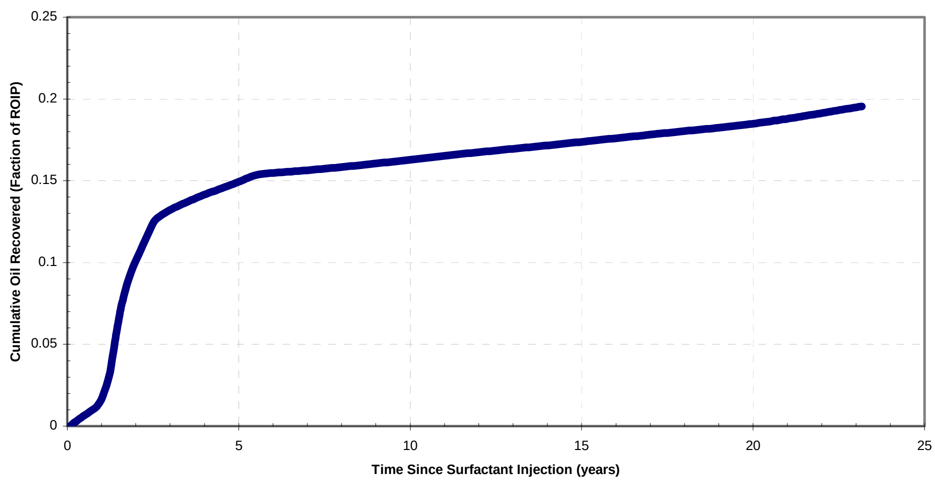

Fig. 5. Cumulative oil recovery for the Base Case simulation (K = 500 md)

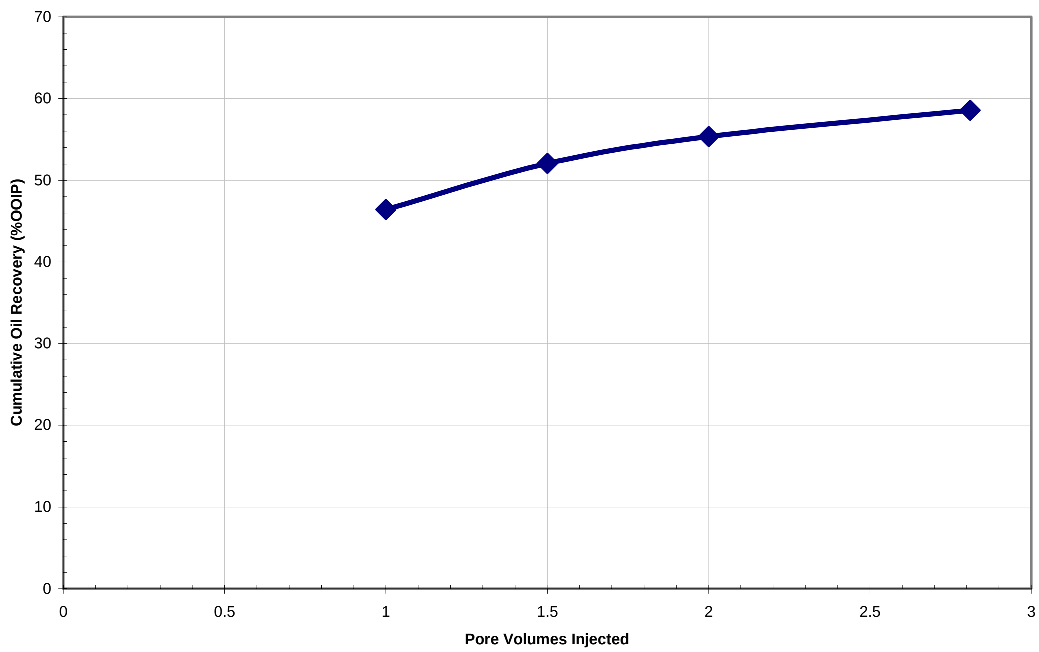

Fig. 6. Oil recovery as a function of different waterflooding period

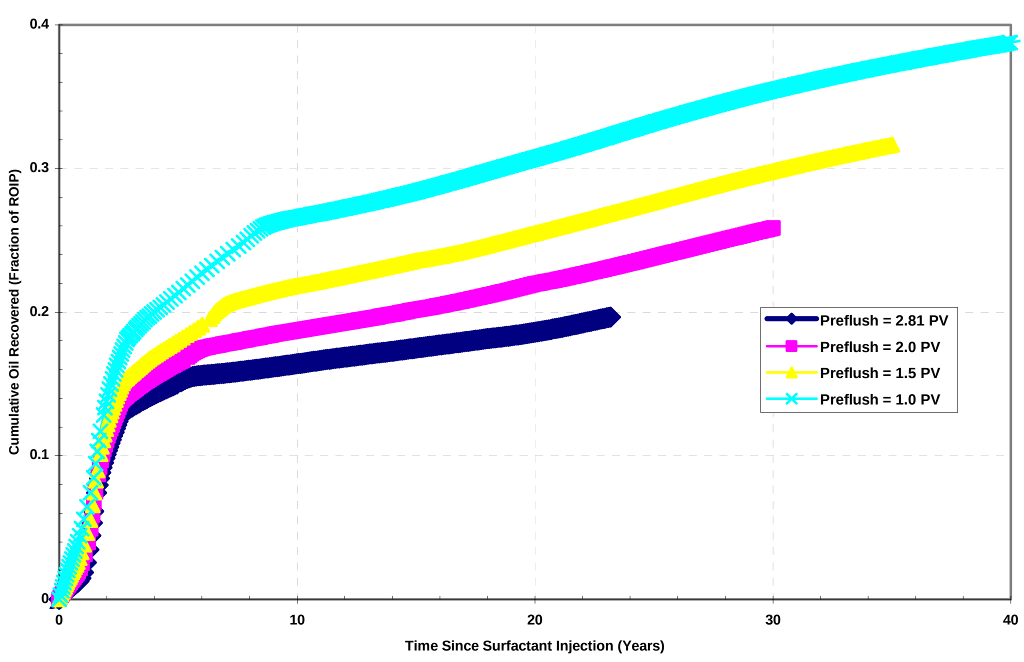

Fig. 7. Cumulative oil recovered for different water preflush time

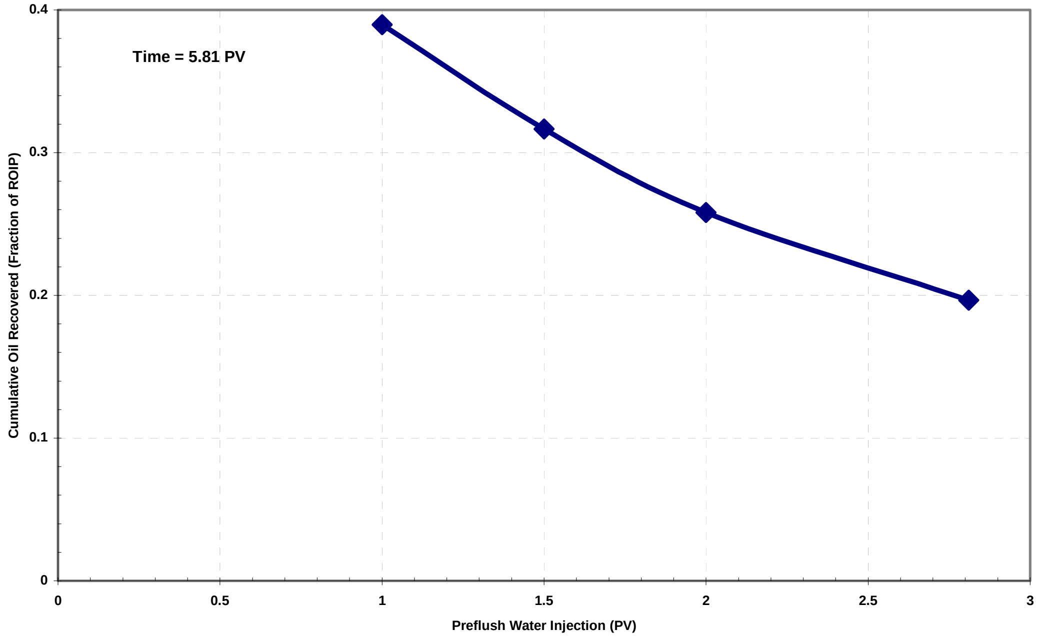

Fig. 8. Effect of water preflush on chemical flooding oil recovery (K = 500 md)

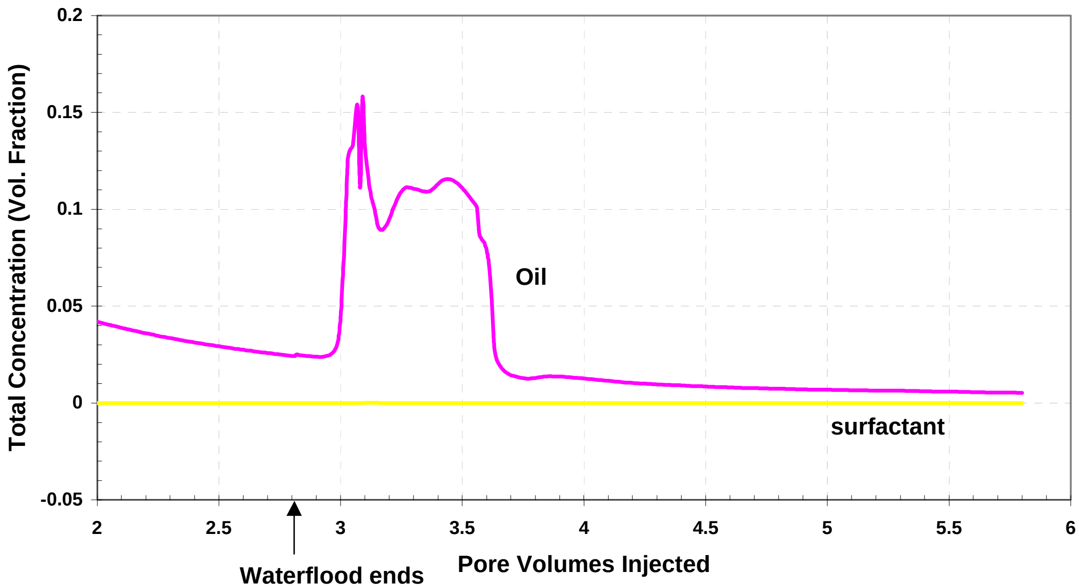

Fig. 9. Produced oil and surfactant concentrations for the case of 0.5 vol% surfactant concentration

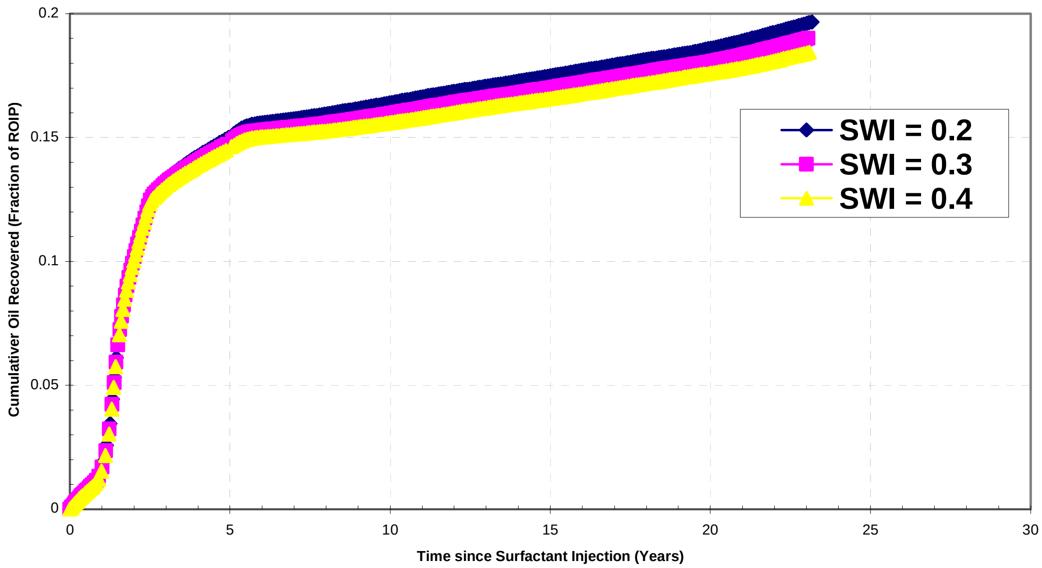

Fig. 10. Chemical flooding oil recovery for different initial water saturation

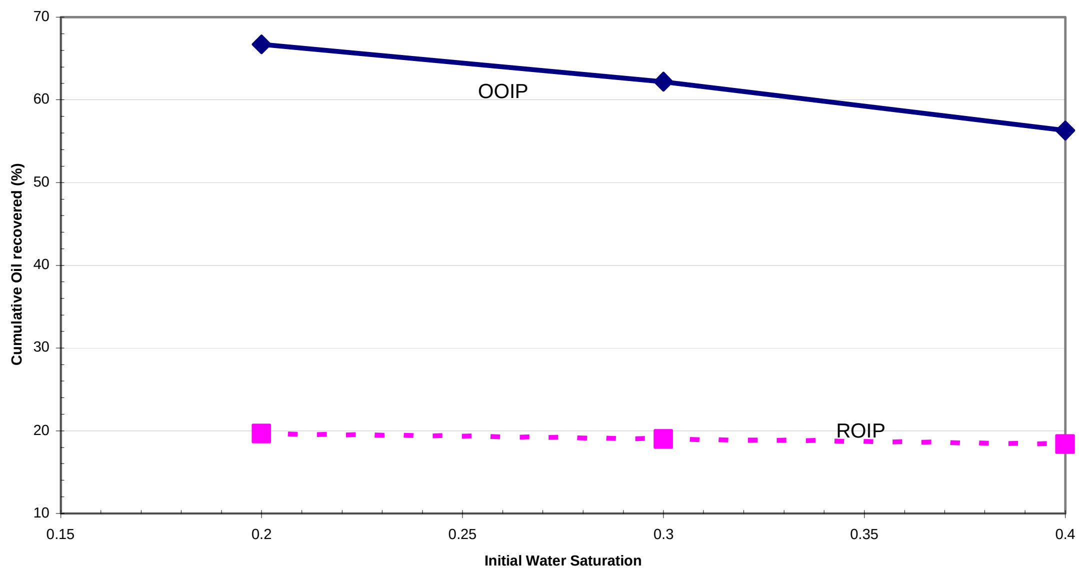

Fig. 11. Effect of initial water saturation on oil recovery during the chemical flooding (K = 500 md)

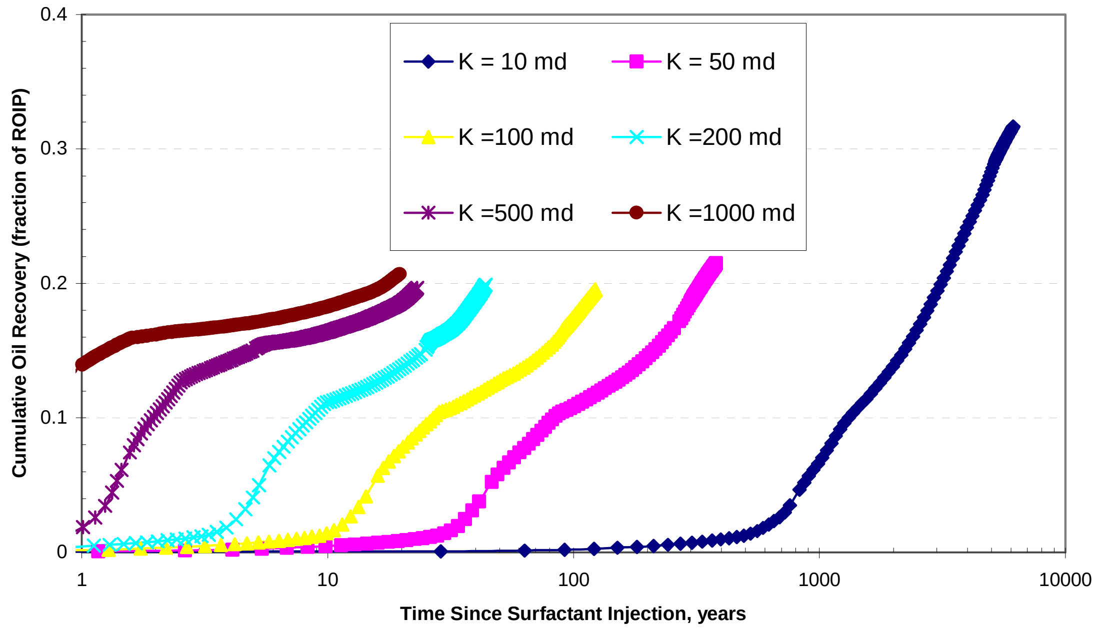

Fig. 12. Comparison of oil recovery for different reservoir permeability

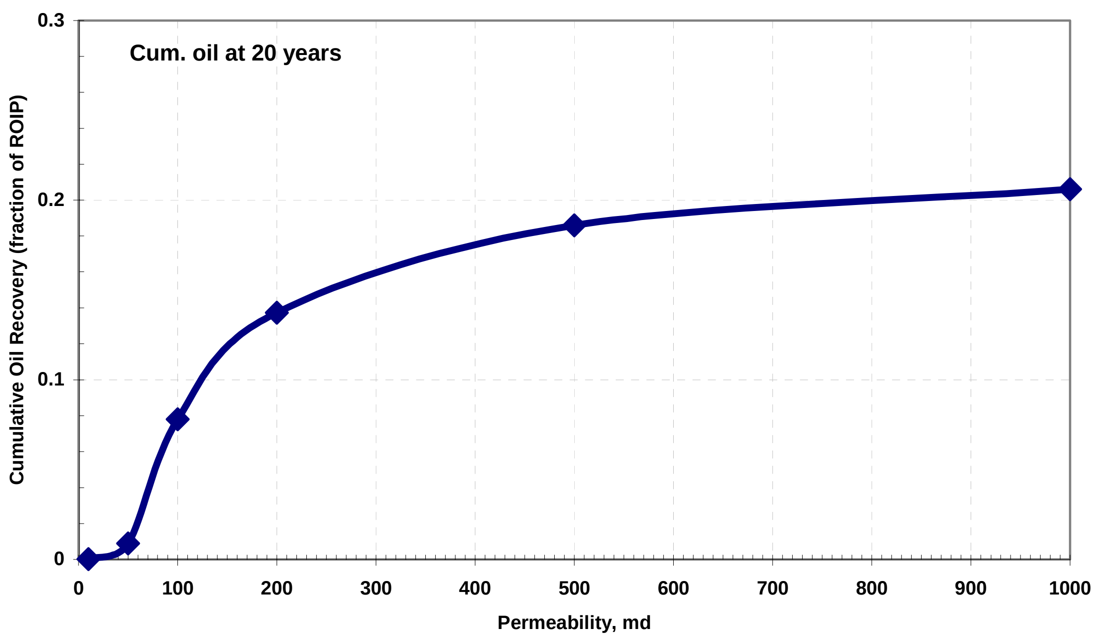

Fig. 13. Oil recovery as a function of permeability

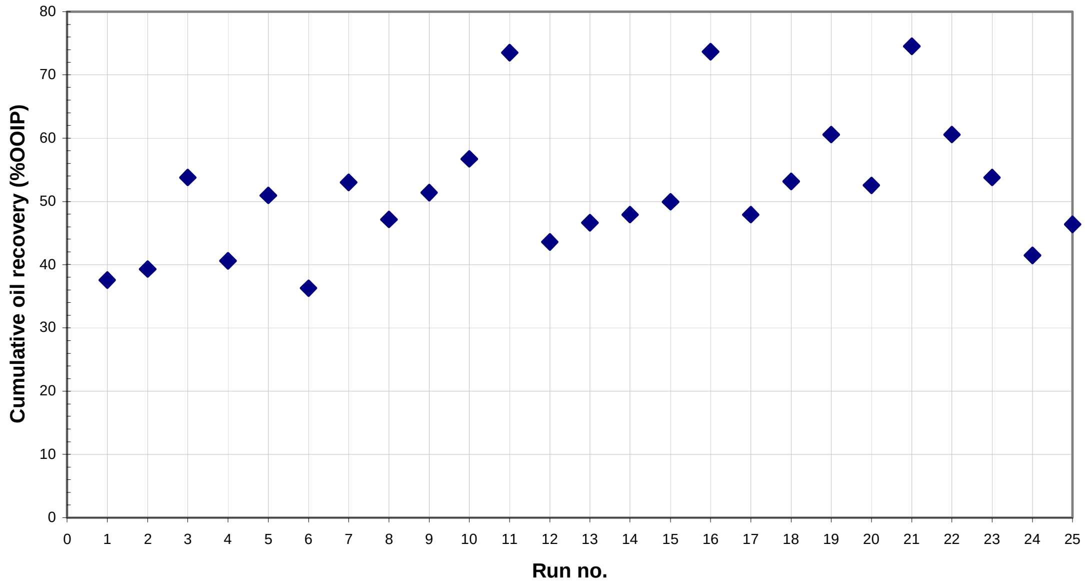

Fig. 14. Cumulative oil recovery as a fraction of OOIP for different chemical flooding simulations

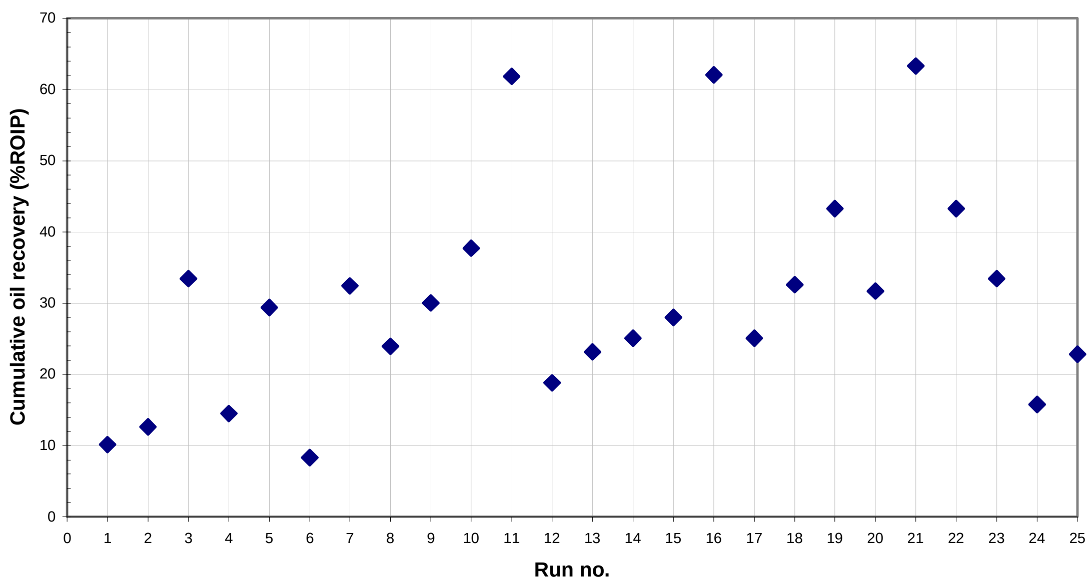

Fig. 15. Cumulative oil recovery as a fraction of ROIP for chemical flooding simulations

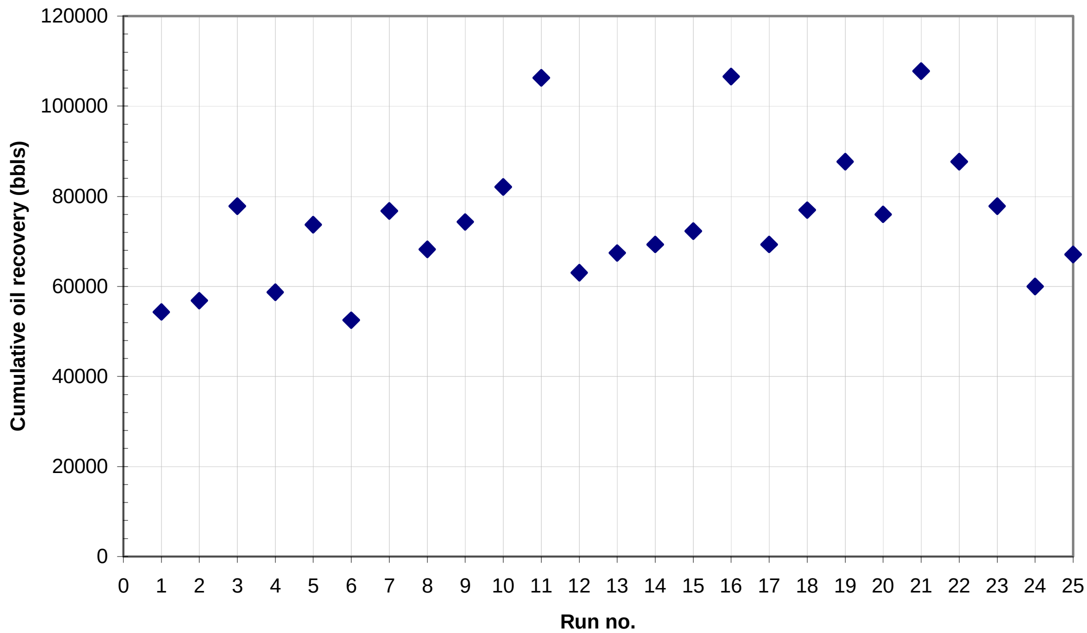

Fig. 16. Oil recovery for different chemical flooding simulations

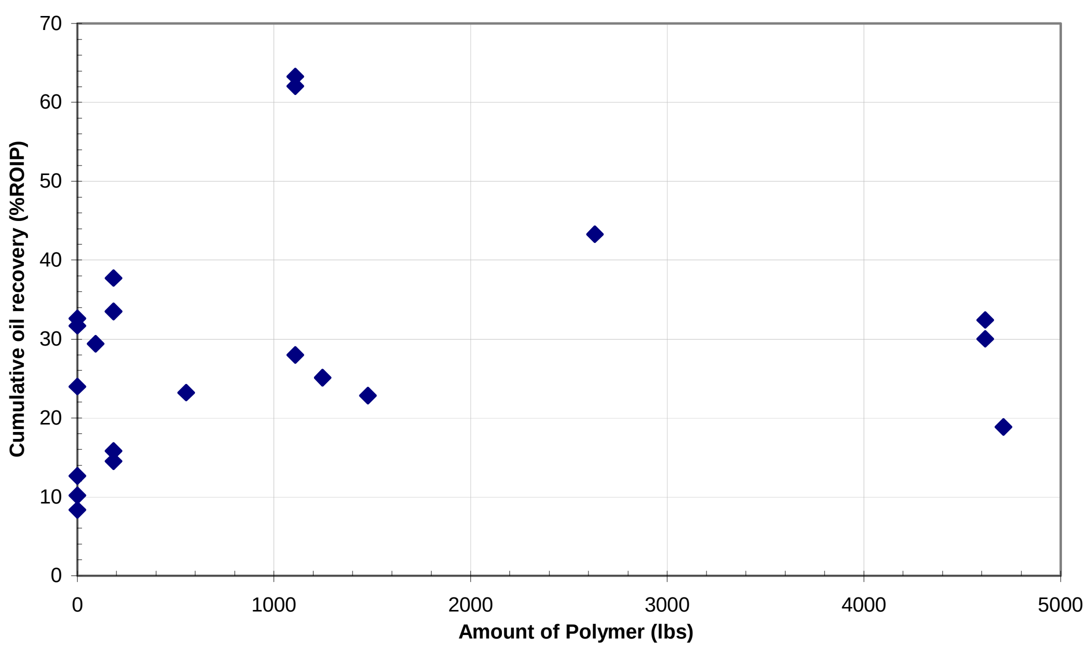

Fig. 17. Chemical flood oil recovery as a function of polymer injected

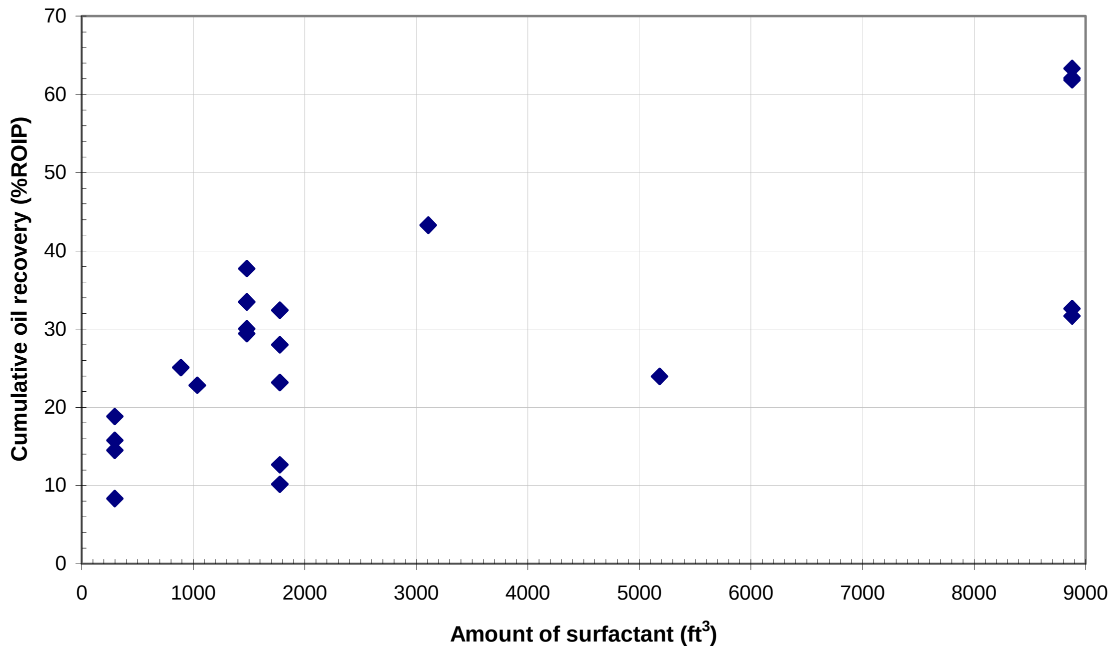

Fig. 18. Chemical flood oil recovery as a function of surfactant injected

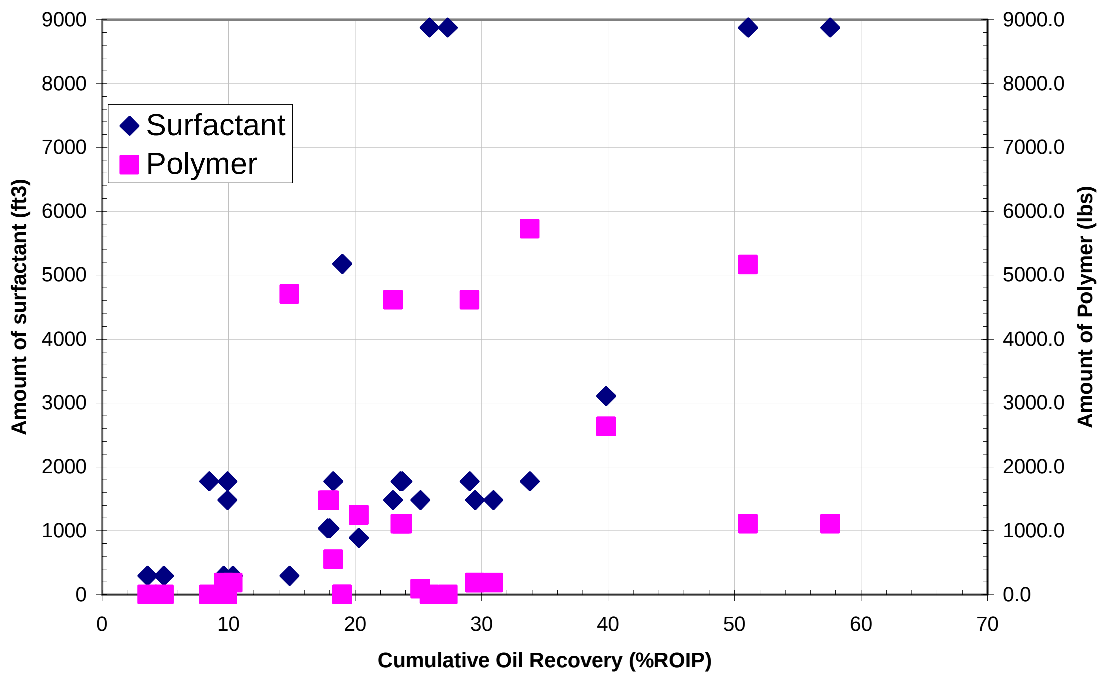

Fig. 19. Chemical flood oil recovery at the end of one year as a function of polymer and surfactant used

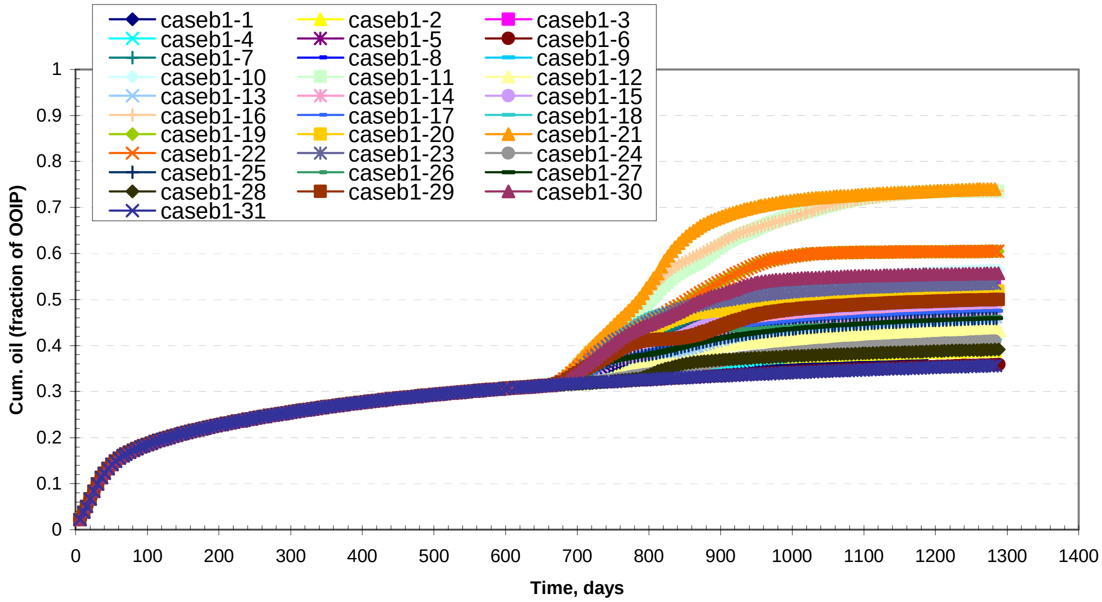

Fig. 20. Cumulative oil recovery as a function of time