EXPERIMENTAL INVESTIGATION OF THE GAS-OIL DRAINAGE PERFORMANCE OF WATER FLOODED ROCK

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ABSTRACT

The feasibility of flooding a sandstone reservoir with lean (immiscible) gas has been investigated. The gas-oil recovery process that is the subject of this study is Gas Oil Gravity Drainage (GOGD), viscous oil displacement by gas is not considered. The centrifuge technique is chosen for this study because it closely resembles the physical processes that occur during GOGD.

Partly oil and water filled plugs are spun in air, that like lean gas, is immiscible with oil and water. The standard automated centrifuge set-up has been adjusted to allow for automatic detection of both produced oil and water volumes. From the measured oil and water production as function of time, relative permeability relations for oil and water have been deduced.

A consistent interpretation of the experimental results could be obtained by using oil, water and gas phase relative permeabilities that depend only on their phase saturations. A three-phase relative permeability approach did not show consistent results and suffered from lack of sufficiently flexible theoretical three phase relative permeability models.

The results show that residual oil saturation for GOGD are lower than for water flooding. They also show that water flooding before GOGD slightly increases the residual oil saturation. However, if after a water flood an oil flood is performed, the low GOGD residual oil saturation is largely restored. Oil re-saturation before GOGD is expected to occur in many field applications of GOGD.

INTRODUCTION

The field under consideration has undergone a water flood; the estimated remaining oil saturations are in the 20 and 40% range. Several enhanced oil recovery projects are being considered to recover part of this remaining oil. One of them is the injection of an immiscible gas, e.g. lean hydrocarbon gas or possibly air or nitrogen, at the crest of the field. Estimating the drainage potential of the remaining oil in a gas environment is the subject of this paper. For a field application example of this recovery process, see [1, 2].

When looking in detail to the saturation history of a piece of rock during a water flood and the subsequent GOGD process, a rather complicated picture of oil de- and re-saturation is observed. During the water flood, the oil saturation decreased. However, by injecting gas at the crest and simultaneous liquid production down dip, an oil rim of drained oil forms in between the crestal gas and the mobile water deeper in the reservoir.

This oil rim slowly moves downwards through the reservoir with time when the gas cap expands. Therefore the oil saturation will first increase (passing by of the rim) before the actual GOGD starts. Special attention has been paid to mimic this saturation history closely in the experiments.

Gravity drainage has already been the subject of study by a number of authors, the studies were performed experimentally [3, 4, 5, 6, 7] as well as theoretically [8, 9, 10] of which the latter were mainly in the context of a three phase relative permeability description. Generally one has observed that gas can mobilize oil that was "immobile" after water flooding, i.e. residual saturations for gravity drainage in gas are lower than residual saturations for water flooding [3, 5, 9]. One also observed that the oil mobility is high for oil saturations close to residual ($k_{ro} \sim S_{oil}^2$). Also some sparse data on dependency of residual saturations on saturation history were measured [4, 5] indicating lower GOGD residual oil saturations after oil re-saturation of water flooded plugs. This data was considered sufficiently encouraging to commence a programme to measure the drainage potential for the reservoir under consideration. The particular issues and questions that have been addressed by the experimental program are:

- How mobile is the oil in the considered reservoir under a GOGD process?
- The water flood will have the tendency to disconnect the oil. In how far will this disconnection impair the gas oil drainage performance?
- Before actual drainage starts an oil rim will pass by and will re-saturate the rock. How effective is re-saturation in re-connecting oil and improving drainage performance, especially at low oil saturations?
- What is the variation of oil relative permeability and capillary pressure within different geological facies types and reservoir units?

EXPERIMENTAL PROCEDURE

In preparation of the actual GOGD experiments, the reservoir's de- and re- saturation history has been mimicked in the plugs. This means that after aging, the plugs were water flooded followed by an oil flood and finally drained in gas (air). The experiments were performed at atmospheric pressure and 60^0C with dead crude oil. The following experiments have been performed: Gas (air) drainage of aged plugs at connate water saturation (OG experiments), gas drainage of water flooded plugs (OWG experiments) and gas drainage of oil re-saturated water flooded plugs (OWOG experiments). Three plugs (2a2, 2b2 and 3c2) were subject to the full sequence OG, OWG and OWOG, the others were only subjected to elements of the sequence. The plugs were selected from the following geological facies: channel, shoreface and mouthbar. Most of the plugs have been analysed with SEM and XRD.

The selected plugs were Soxhlet cleaned in Toluene and thereafter flooded with a mixture of Chloroform/methanol/water to remove hydrocarbons and saltwater. Next, the plugs were CT-scanned to identify possible heterogeneity. After visual inspection and statistical analysis of the CT-data, 18 plugs were considered to be acceptable for SCAL measurements. Because of the poorly consolidated nature of the plugs, they were wrapped in shrinkage sleeve to avoid fracturing and grain loss during handling. Next the air and brine (23 g/l NaCl) permeability of the plugs was determined. The data from the selected samples are listed in Table 1 and 2.

XRD analysis (whole rock and clay fraction), SEM analysis and a thin section description (including grain size analysis) were undertaken for samples that were taken from the plug trim ends. The samples ranged from very fine- to fine-grained (only sample 11a was medium grained) comprising arkosic to quartz arenites. No overall differences were evident in the grain size and petrography of the samples by facies type or Cycle. Next the 100% brine saturated core samples were placed in the centrifuge surrounded by crude oil and centrifuged to connate water saturation. Hereafter they were aged in dead crude at 100 bars and 90°C for four weeks to restore wettability.

The centrifuge used in the experiments is a fully automated Beckman L8-60MP rock centrifuge. The production of the produced fluids was monitored using an automated CCD camera system. The change of the fluid interface water/oil and oil/gas is automatically detected, gathered by a computer system and converted after the experiments to a produced water and oil volume.

Gas-Oil Drainage (OG) Measurements

Four core plugs (2-a1, 2-b1, 3-c1, 14-a1) were selected. Prior to the gas-oil drainage centrifuge experiment, the “end point” oil permeability was determined by measuring the differential pressure over the core plugs at three oil flow rates, Table 1. Next, batches of three plugs with similar permeability were placed in the centrifuge holder, this time the surrounding fluid is air. A multi-speed centrifuge experiment was carried out at a series of fixed centrifugal accelerations to determine the capillary pressure. Final water and oil saturations are summarized in Table 2.

For the relative oil permeability four core plugs (2-a2, 2-b2, 3-c2 and 14-a2) were selected. Again, prior to the centrifuge experiments, the end point oil permeability was measured by applying three different oil flow rates, Table 1. Three core plugs of similar permeability were placed in centrifuge holder surrounded by air. A single-speed centrifuge experiment was performed at a single, fixed centrifugal acceleration.

Relative Gas-Oil and Gas-Water Permeability (OWG) Measurements on Water Flooded Plugs

Although the four core plugs (2-a2, 2-b2, 3-c2 and 14-a2) selected for these experiments were used in the previous centrifuge runs it was decided to re-use these plugs. The reason for this was twofold; firstly the limited number of acceptable core plugs, and secondly preparing of new plugs would be very time consuming in view of the four-week aging sequence. The core plugs almost completely filled with air were, prior to the measurements, miscible flooded with crude at a backpressure of 2 bars to replace the air with crude oil. At the end of this displacement, the “end-point” oil permeability was measured, Table 1. The oil saturation was calculated by the difference between the air weight and oil-saturated weight. Next, the core plugs were mounted in a Hassler core holder, a sleeve pressure of 30 bars was applied to avoid bypassing of the injected fluid. The plugs were then brine flooded vertically until a water saturation of approx. 50% was established. Water saturation was calculated from the produces volumes. Next, three core plugs of similar permeability were placed in centrifuge holder surrounded by air. A single-speed centrifuge experiment was performed at a single, fixed centrifugal acceleration to determine the relative permeability of the expelled phases.

Relative Gas-Oil and Gas-Water Permeability (OWOG) Measurements on Oil Re-Saturated Plugs

For this experiment 6 plugs (2-a2, 2-b2, 3-c2, 8-a, 9-d and 12-d) were selected. Some of the plugs had been used in the previous centrifuge experiment. Again, prior to the centrifuge experiments plugs 2-a2, 2-b2, 3-c2 were miscible flooded at 2 bar back-pressure with crude oil to replace air with crude. At end the of the oil flood, end-point oil permeability was determined. The end point oil permeability of the remaining plugs 8-a, 9-d and 12-d was also measured. Core plugs were mounted in Hassler core holders and were brine flooded vertically until a water saturation of 50% was attained. The flow was reversed, still keeping the core holder vertically, to oil flooding. Oil flooding was continued until water production ceased (see Table 2 for the saturations). Next, three core plugs of similar permeability were placed in centrifuge holder surrounded by air. A single-speed centrifuge experiment was performed at a single, fixed centrifugal acceleration to determine the relative permeability of the expelled phases.

Dean & Stark

Finally, the total water content of each plug was determined by Dean & Stark extraction. In this way the final water saturation can be obtained, Table 2. The mass balance and Dean & Stark saturation data agree within 3 to 4%. In view of the repeated saturation and de-saturation runs that were performed before the Dean & Stark could be performed, the correspondence between mass balance and Dean & Stark is considered as acceptable.

NUMERICAL ANALYSIS OF THE EXPERIMENTS

The experiments were analyzed using Shell's numerical reservoir simulator MoReS. GOGD is essentially a three-phase displacement process and in a scouting study it was attempted to characterize the displacement in terms of three phase relative permeabilities. The water-oil and the gas-oil relative permeabilities were measured first. The oil, water and gas relative permeabilities at a specific oil, water and gas saturation were then constructed by using different theoretical three phase relative permeability models: Stone, Hirasaki or Linear Isoperms. However, this approach failed, none of the above mentioned 3 phase models was sufficiently accurate and “flexible” to properly describe the measured production profile using the measured water-oil and gas-oil relative permeabilities. This confirms the findings as reported by various authors [6, 7, 10].

A more pragmatic approach that is very similar to proposals reported by others [3, 6, 8, 9] appeared to work well. The basic idea is that, in the experiments, a similar saturation path through the "three phase saturation diagram" should be followed as in the field. For gravity drainage the centrifuge technique provides this analog. Having properly described the experimental production curve by using a (simple) set of relative permeabilities that are in fact only applicable along the specific path in the three-phase diagram, this set is then directly applicable for field modeling purposes. Note that the objective of the general three phase relative permeability models is to describe the relative permeabilities over the whole of the three phase saturation ranges. The proposed method claims only to be valid along the measured saturation path and the results are therefore only applicable for GOGD processes.

As a first try, single phase relative permeability curves k_r were used, meaning that the drainage performance of oil, water and gas is only dependent on the value of its own saturation:

$$k_{r(i)} = k'_{r(i)} \left(\frac{S_{(i)} - S_{res(i)}}{1 - S_{ini(i)}} \right)^{n_{(i)}}$$

where k_r' refers to the end point relative permeability, S_{res} to the residual saturation, S_{ini} to the initial saturation, n to the Corey exponent and i to respectively oil, water or gas.
In film flow type of conditions this is a reasonable assumption. Due to the non-wetting nature of the gas with respect to oil and water establishment of a continuous liquid film (oil plus water) is likely. Whether within this liquid film the oil and water form individually a continuous film does not necessarily need to be the case. It is expected that at low oil and water saturations this is likely to happen as one phase impairing the flow of the other will drain more rapidly, thus providing opportunity for the other phase to smear and connect. The single-phase relative permeability approach appeared to work well and reproducible and consistent results were obtained. This approach was therefore chosen as the method to use for the analysis of the experimental data.

RESULTS AND DISCUSSION

Capillary Pressure Measurements

Analysis of the relative permeability by the single speed centrifuge technique requires knowledge of the capillary pressures. Therefore for a number of twin plugs, the capillary pressures of oil with respect to gas (air) in the presence of connate water have been measured by the multi-speed centrifuge technique. A typical oil production curve (plug 2a2) and its numerical fit are shown in Fig. 1. The capillary pressure curves are shown in Fig. 2. The figure shows that typical capillary entry pressures (defined here as the pressure at 0.5 oil saturation) are in the 0.05 Bar pressure range. Centrifuge rotation speed was chosen such that the critical Bond number ($5\ 10^{-5}$) was not exceeded.
Fig. 1 also shows the water production curve, this production curve is typical for the other plugs as well. The quality of the data is poor compared to the oil production data and it was not possible to match the curve as close as was achieved in the oil production

match. The reason is not well understood although due to the small volumes of the produced water the measuring accuracy might play a role.

The wettability of the plugs used in this study was not determined separately, however, previous measurements on similarly prepared plugs of the same formations showed intermediate to oil wet behavior with USBM numbers in the –1 range.

Oil Relative Permeability

OG, OWG and OWOG Experiments

The oil relative permeability curves for OG, OWG and OWOG (see also section 2) are displayed for the plugs 2a2, 2b2 and 3c2 in the Figs. 3, 4 and 5 respectively. The marker in the figures indicates the initial saturation in the plug. For OG, OWG and OWOG, this is approx. 0.8, 0.5 and 0.7 respectively. The sections of the curves at higher saturations are mainly based on extrapolation and are therefore less accurate. The error band of the numerically matched relative permeabilities is assessed to be 1% wide (+/- 0.5%) for oil saturations less than 40%.

A consistent, although relatively small, trend can be observed in Figures 3, 4 and 5. For oil saturation close to residual saturation, the oil (versus gas) relative permeabilities after the water flood (OWG) are smaller than the oil relative permeabilities when starting from initial oil saturation (OG). Also the oil relative permeabilities after the water flood are smaller than the oil relative permeabilities after the water flooded plugs have been re-saturation with oil (OWOG). Apparently oil re-saturation (OWOG) partly restores the oil relative permeabilities. A possible model for explaining this phenomenon is disconnection of oil by the water flood resulting in a poorer performance of the drainage. By re-invading the water flooded rock by oil, the remaining oil reconnects and is (partly) available for gas drainage.

Table 3 shows the “remaining” saturations at the various stages of the drainage process. Instead of showing residual oil saturations and Corey exponents, the saturation at a relative permeability of 10^{-5} is shown. This value of 10^{-5} is chosen as a value that can be obtained in practice (but not necessary will). The saturation values in Table 2 show that due to the water flood, the remaining oil saturations for the gas drainage can deteriorate by as much as 2 to 9%. An oil flood after the water flood can (partly) restore the oil’s drainage capacity, the remaining oil saturation with respect to the water flood data can be reduced by as much as 2 to 4%. The Corey exponent for the curves are 4.5 ± 0.2, the Corey exponent of 2 as reported in [3, 9] has not been observed.

The Corey exponent of the previously measured water-oil curve, 4.5, is equal to the averaged gas-oil drainage Corey exponents. For a relative permeability of 10^{-5}, saturation values for gas oil drainage are 0.09 while a water-oil value of 0.15 was measured. This shows that with gas flooding, lower remaining oil saturations can be obtained than with water flooding.

Correlation of the Relative Permeability with Reservoir and Geological Units

Fig. 6 shows gas-oil relative permeability data for OWOG experiments only. In the legend next to the plug identification is the geological unit name from which the plug is taken. The data set per unit is rather sparse and conclusions are therefore speculative and of a qualitative nature. If one can speak of any trend, then the shoreface plugs appear to perform better than the mouthbar and channel plugs. The Upper Rannoch plug appears to show intermediate performance. However, if one looks as a confirmation of this trend to the OG data (Fig. 7), one observes that the data are close to each other and that the trend observed in the OWOG has disappeared. Apparently the relative permeability curves are not very sensitive to the originating geological (sub-)unit and consequently to variations in grain size, sorting, petrography or facies.

Water Relative Permeability

The quality of the water production data is poorer than that the quality of the oil production data. The interpreted water relative permeability data do show a large spread and do not show the consistent trends with flooding history (OG, OWG and OWOG) as observed in the oil relative permeability data (Fig. 8). It is interesting to note that during OG, as much as 0.05 to 0.10 saturation units of connate water can be produced, indicating that gas increases the water (as well as the oil) mobility at low saturations. Note that the residual saturations (Table 3) are larger for water than for oil. This is possible due to the mixed wet nature of the rock and to spreading of the oil. The initial oil spreading coefficient $S_{o,wg}=\sigma_{wg}-(\sigma_{ow}+\sigma_{og})$ is equal to 71-(30+20)=21, this positive value indicates that the oil is spreading in between gas and water and can form more easily a continuous film than the water, resulting in lower residual oil saturations (and higher relative permeability data) for the oil. The marker in the figures indicates the initial saturation; above this saturation the relative permeability data are less accurate.

CONCLUSIONS

1) Within the reservoir no correlation between the measured relative permeabilities and the different geological units could be identified. In fact, very little spread between the relative permeabilities of the different units was observed.
2) The drainage performance of the (remaining) oil is dependent on the saturation history:
    - Water flooding deteriorates the drainage performance of remaining oil. For example, for the plugs 3c2, 2a2 and 2b2, the increase of the remaining oil saturation at $kro = 10^{-5}$ (due to water flooding) is respectively 0.11, 0.02 and 0.03.
    - Oil flooding after a water flood partially to fully restores the drainage performance. For the plugs 3c2, 2a2 and 2b2 the restoration resulted in a decrease of the remaining oil saturation at $kro = 10^{-5}$ by respectively 0.02, 0.04 and 0.03.
3) A consistent interpretation of the experimental results could be obtained by using oil, water and gas phase relative permeabilities that depend only on their phase saturations. A three-phase relative permeability approach did not show consistent results and suffered from lack of sufficiently flexible theoretical three phase relative

permeability models. The single-phase relative permeability approach is only tested for GOGD processes and is expected to be only applicable for this type of processes.

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Table 1. Basic petrophysical properties, initial water saturation and end-point oil permeability of core plugs used in gas-oil gravity drainage experiments.

Sample id	**Depositional Environment**	**Rock type**	**Porosity (frac. PV)**	**K_air (mD)**	**K_brine (mD)**	**S_i drainage**	**K_oil (mD) OG**	**K_oil (mD) OWG**	**K_oil (mD) OWOG**
2-a1	Shoreface	Quartz Arenite	0.301	4545	3539	0.184	1227		
2-a2	Shoreface	Not available	0.296	4920	3897	0.134	1226	1322	1447
2-b1	Shoreface	Quartz Arenite	0.305	4622	3686	0.164	1056		
2-b2	Shoreface	Not available	0.301	4902	3811	0.137	1404	1319	1348
3-a1	Channel	Not available	0.261	9110	6166				
3-c1	Channel	Quartz Arenite	0.272	3369	2431	0.175	997		
3-c2	Channel	Not available	0.284	3776	2668	0.148	1154	1069	1156
8-a	Mouthbar	Arkosic Arenite	0.278	444	281	0.073			97
8-b	Mouthbar	Arkosic Arenite	0.276	394	279				
9-c	Channel	Quartz Arenite	0.248	5164	2941				
9-d	Channel	Quartz Arenite	0.248	4227	2759	0.047			1226
11-a	Channel	Quartz Arenite	0.237	1576	810				
11-b	Channel	Not available	0.239	1474	737				
11-c	Channel	Not available	0.234	1686	891				
12-d	Shoreface	Arkosic Arenite	0.219	314	206	0.192			86
14-a1	Shoreface	Arkosic Arenite	0.278	458	332	0.101	218		
14-a2	Shoreface	Not available	0.277	426	263	0.118	192	176	
14-b	Shoreface	Not available	0.291	616	421				

Note: S_i is initial water saturation at the end of water-oil drainage

Table 2. Gas-oil drainage final water and oil saturation at different stages and Dean & Stark final water saturation

Sample id	**S_f Oil OG**	**S_f Water OG**	**S_f Oil OWG**	**S_f Water OWG**	**S_f oil OWOG**	**S_f Water OWOG**	**Water content (ml)**	**S_f Water Dean-Stark**
2-a1	0.05	0.06					1.15	0.07
2-a2	0.09	0.07	0.12	0.08	0.09	0.03	1.1	0.07
2-b1	0.09	0.04					1.1	0.07
2-b2	0.07	0.09	0.11	0.09	0.06	0.11	1.4	0.09
3-c1	0.11	0.07					1.45	0.10
3-c2	0.12	0.13	0.16	0.11	0.09	0.12	2.5	0.16
8-a					0.09	0.05	1.3	0.09
9-d					0.07	0.05	1.25	0.09
12-d					0.06	0.18	2.85	0.24
14-a1	0.15	0.07					1.45	0.10
14-a2	0.08	0.10	0.13	0.12			1.9	0.13

Note: S_f is final oil and water saturation at the end of the gas-oil gravity drainage centrifuge run.

Table 3. Oil saturation at a kro=10 $^{-5}$ for: gas-oil drainage at connate water (OG), gas-oil drainage after a water flood (OWG) and gas-oil drainage after a water flood followed by oil re-saturation (OWOG).

Plugs	**OG**	**OWG**	**OWOG**
2a2	0.084	0.111	0.072
2b2	0.061	0.078	0.051
3c2	0.064	0.150	0.142

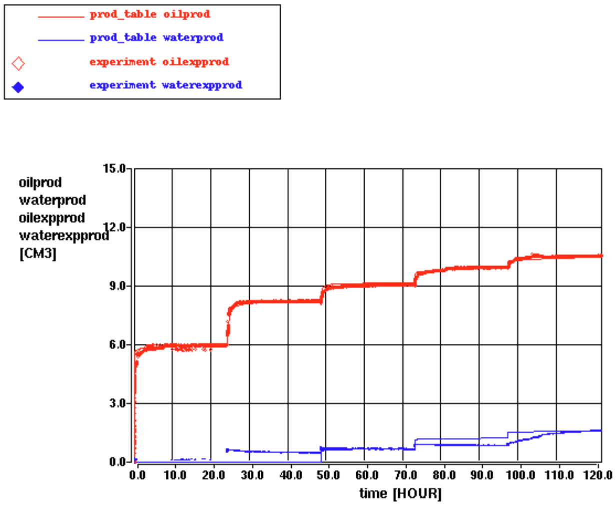

Figure 1. Multi-speed centrifuge production curve and numerical match. The upper curve and data points (symbols) correspond to produced oil (the curve is hidden behind the symbols), the lower curve and data points correspond to produced water.

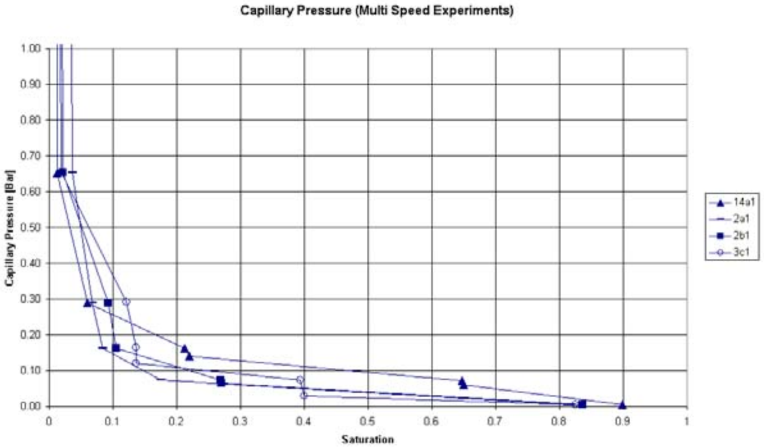

Figure 2. Oil gas Pc curves as obtained with the multi-speed centrifuge technique.

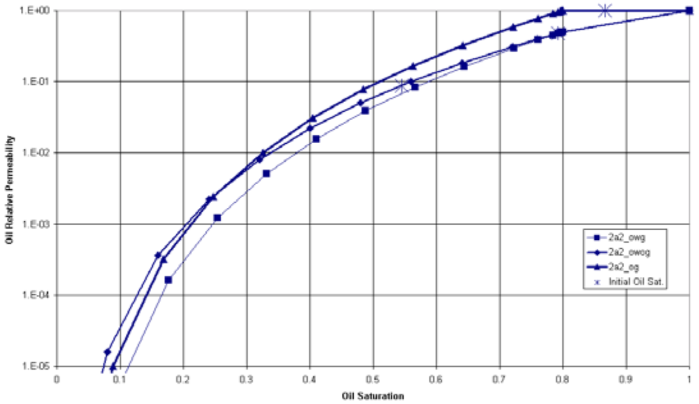

Figure 3. Oil relative permeability for the OG, OWG and OWOG process for plug 2a2.

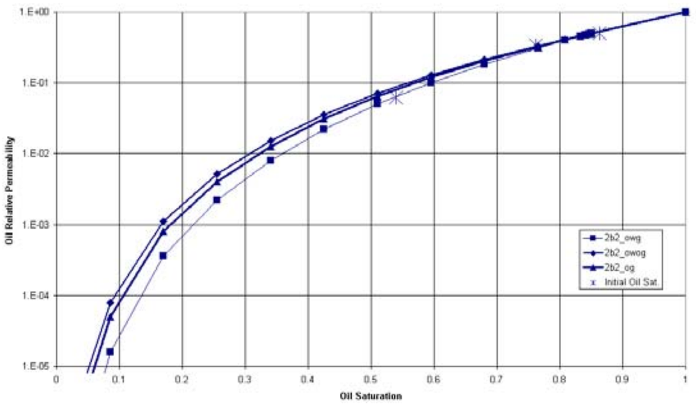

Figure 4. Oil relative permeability for the OG, OWG and OWOG process for the plug 2b2.

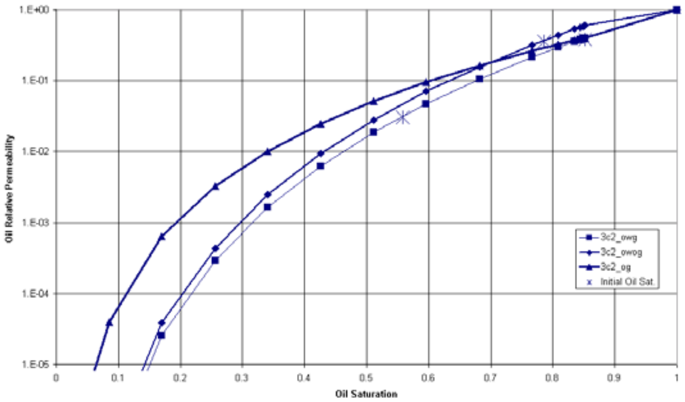

Figure 5. Oil relative permeability for the OG, OWG and OWOG process for the plug 3c2.

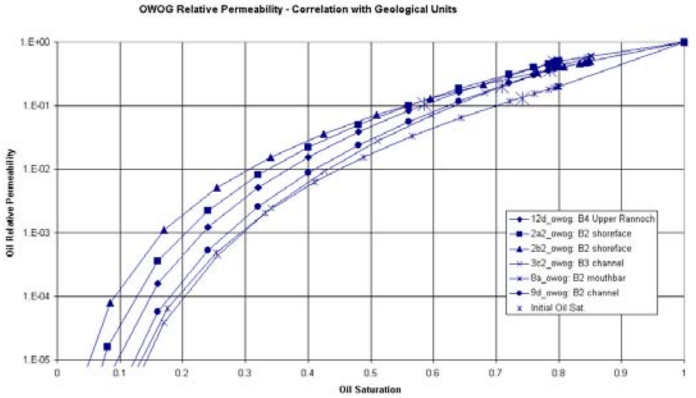

Figure 6. Correlation with geological units, OWOG experiments.

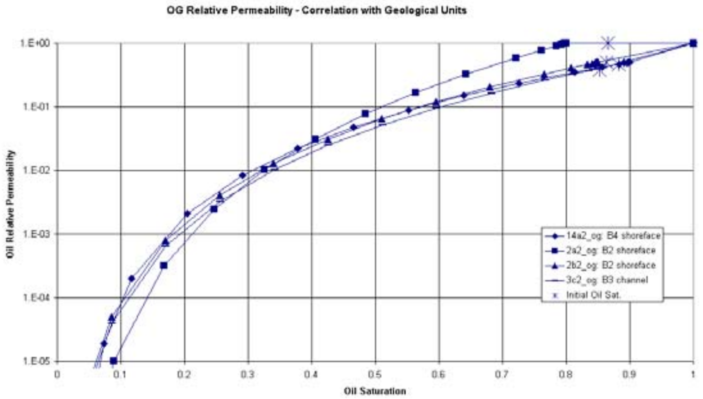

Figure 7. Correlation with geological units, OG experiments.

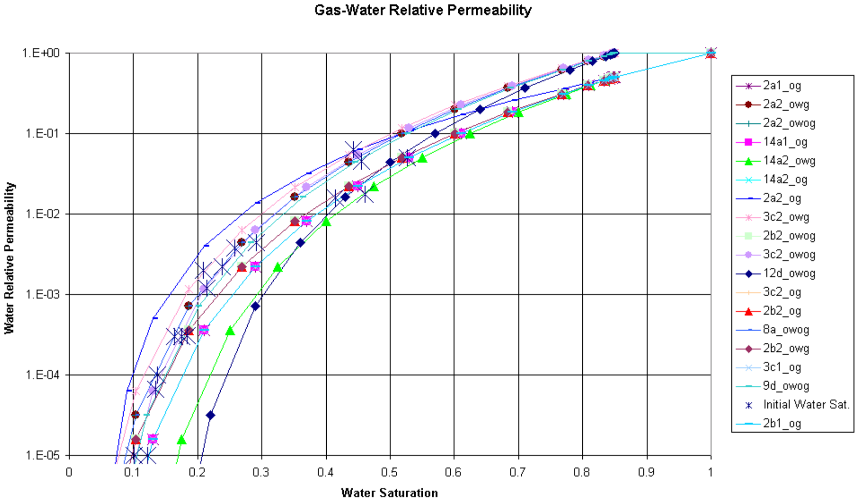

Figure 8. Water relative permeability data.