

# Oil Mobility in Transition Zones

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## 1. Abstract

Oil-water transition zones may contain a sizable part of a field's STOIP, specifically in low permeable sandstone and carbonate reservoirs. The transition zone is the part of the reservoir where the water saturation decreases from 100% in the water zone to an irreducible water saturation some vertical distance above the free water level. The amount of recoverable oil in a transition zone depends -among other things- on the distribution of initial oil saturation ( $S_{oi}$ ) as a function of depth and the dependency of the oil's mobility, i.e., the residual oil saturation ( $S_{or}$ ) and relative permeability, on initial oil saturation.

The measurements of the residual oil saturation and the associated water-oil relative permeabilities as a function of initial oil saturation have rarely been performed. The most frequently used correlation to predict residual oil saturation as a function of initial oil saturation is the semi-empirical relation presented by Land based on matching of experimental data for gas/water system. Extending Land's correlation to water/oil systems is not straightforward as wettability of brine/crude/rock system is an additional parameter which needs to be taken into account.

In this study, oil mobility in the transition zone has been determined by actually measuring residual oil saturation, relative permeabilities and capillary pressures at various initial oil saturations.

The measurements show that the mobility of the oil increases for decreasing distance to the free water level (FWL) although the residual oil saturation after the water flooding showed, for the example studied here, no dependence on the initial oil saturation after restoring wettability. In other words the residual oil saturation will be reached faster when the oil is located closer to the FWL.

## 2. Introduction

Oil has (in water-wet rocks) the tendency to fill the larger pores preferentially. Transition zone phenomenon is best understood when compared with capillary tube experiments in the lab. When two immiscible fluids of different densities are poured in a tank, a sharp

interface will be established between them where the lighter fluid will float on top due to gravity effect. If a capillary tube is inserted in a tank containing oil and water, the oil-water contact will establish itself inside the tube at a different level than that outside the tube due to the capillary effect. The size of the tube will determine the height of the oil-water contact. As the radius decreases the contact level becomes higher inside the tube. This is known as the capillary effect. This capillary effect determines the distribution of the fluids inside the reservoir, where the glass tubes in the lab are replaced by a large number of pores and pore throats of different sizes.

In general reservoirs have first been filled with water and as a consequence the reservoir rocks are water-wet. Any change in wettability takes place after oil has migrated to the reservoir. As oil tries to enter the pores (originally water-wet) a certain threshold pressure has to be built up before the capillary pressure in the pore can be overcome. The capillary effect in the smaller pores is stronger and therefore higher pressure differential must be applied for oil to enter these pores. On the other hand the capillary pressure is smaller in the larger pores, therefore larger pores are filled most easily. Close to the Oil Water Contact (OWC) the oil/water pressure differential is small, therefore only the big pores can be filled with oil. The largest pore throat will determine the minimum capillary rise above the free water level. In between the free water level and the point at which connate water saturation is reached, the water saturation will decrease progressively and the transition from water to oil occurs. This interval is known as the capillary transition zone, see figure 1. The height of the transition zone and its saturation distribution versus height is determined by the range and distribution of pore sizes within the rock. In this interval both oil and water are mobile. Transition zone may vary in thickness from a few meters to over hundred meters and therefore it may contain a sizable part of the reservoir STOIP. Usually the transition zone is not perforated for oil production because it is considered not economic. However, in the transition zone where only the largest pores are oil filled, the relative oil mobility at a specific saturation is larger than at a similar saturation higher up in the reservoir where also small and poor conducting pores are oil filled.

### **3. Existing Models and Laboratory Measurements**

Measurements of residual oil saturations and associated water-oil relative permeabilities as a function of initial oil saturation have rarely been performed in the past. As discussed in [1] there are a number of reports on trapped gas relationships but hardly any reports on trapped oil especially for oil-water systems. The most frequently used correlation to predict the residual saturation is the semi-empirical relation presented by Land[2] based on matching of experimental data for gas/water system. After analysing the data in a number of papers Land found that the difference in the reciprocals of the initial and residual gas saturation is approximately constant. Residual saturation increases with an increase in the initial saturation, see Fig. 2.

$$S_{gr} = \frac{S_{gi}}{1 + CS_{gi}} \quad \text{where} \quad C = \frac{1}{S_{gr}^{\max}} - 1 \quad (1)$$

where  $S_{gr}$  is the residual gas saturation,  $S_{gi}$  is the initial gas saturation and  $S_{gr}^{\max}$  is the maximum residual gas saturation after a complete imbibition process which starts at the maximum possible initial gas saturation.

More recently J. Kleppe et. al.[3] recommended, in case there is no measurement available, to use a linear relationship to predict the residual saturation based on the maximum residual saturation at the end of the bounding imbibition, see Fig. 2.

$$S_{gr} = \frac{S_{gi}}{S_{gi}^{\max}} * S_{gr}^{\max} \quad (2)$$

where  $S_{gi}^{\max}$  is the maximum initial gas saturation. The measurements have been done for gas/oil system. The data shown in figure 2 are calculated using eqs. (1 and 2) for the same  $S_{gr}^{\max}$  and  $S_{gi}^{\max}$ . This shows that the two models give quite different results. Christiansen et. al. [1] presented new data on trapped oil relationship, however the technique used can never get to residual oil saturation as not enough pressure is applied in their set-up during the water displacing oil experiment. Moreover, the measurements have been done on water-wet samples. As clear from the discussion none of the existing models describes a water/oil/rock system at representing wettability. Therefore, using Land correlation (as often done) to predict the dependence of  $S_{or}$  on  $S_{oi}$  is not justified.

In addition to  $S_{oi}/S_{or}$  relationship, relative permeability of oil and water starting at different initial oil saturation are also needed for reservoir simulation. However, as far as we know, there is no data on the dependence of relative permeability on initial oil saturation. Due to the lack of proper data on both residual oil and relative permeability dependence on initial oil saturation in reservoir simulations only estimates of the oil mobility as a function of depth have been used. In fact generally two approaches are used: The first and most common one, uses residual oil saturations and imbibition relative permeability curves that are measured by starting at the maximum initial oil saturation. In this case a possible dependency of residual oil or relative permeability on  $S_{oi}$  is completely ignored and the recovery factor is highly under estimated. The second one is more sophisticated and does use a dependency of residual oil (i.e. Land model [2]) and relative permeability (i.e. Killough hysteresis model [4]) on initial oil saturation. However, these models have serious shortcomings: 1) initial/residual saturation correlation lack proper experimental data as only gas/water or gas/oil data are available, 2) all models for relative permeability dependency on initial oil saturations are either conceptual or based on very little data, 3) the models do not distinguish between rock types and 4) wettability characteristics of the rock are ignored as they assume water wetting.

In this study, oil mobility in the transition zone has been determined by actually measuring residual oil saturation ( $S_{or}$ ), relative permeabilities and capillary pressures at various initial oil saturations (capillary pressure curves will not be presented in this paper).

#### 4. Preparation of Core Samples

To properly assess oil mobility in the transition zone, a special measurement program was needed which addressed two important questions. Should the measurements be performed on the same sample or use a new sample for each  $S_{oi}$ ? In case the same samples are used should they be cleaned before going to the next  $S_{oi}$ ? Here we have three options.

Firstly, use different samples for each  $S_{oi}$ . This option ensures clean and fresh sample for each experiment; however, using different samples may affect the validity of the correlation. By using twin plugs and testing it by first establishing the correlation using the same sample the viability of this option can be proven.

Secondly, use the same sample but clean it following each drainage/imbibition cycle. This option ensures clean sample saturated with 100% brine before each measurement; however, this is risky as cleaning may damage the sample. Moreover, cleaning is time consuming, it may take more than two weeks before the sample is ready for the next experiment.

Thirdly, use the same sample without cleaning. Each time the sample will be prepared at different initial oil saturation (see the procedure below). In this case the  $S_{oi}/S_{or}$  correlation is more reliable as they are established on the same sample. Moreover, the experiment will be faster as we save the cleaning time and we will not run the risk of damaging the samples during repeated cleaning. This option implies that multi drainage and imbibition experiments are performed on one plug.

However, in applying the third option there are two important concerns:

- 1) In the second (or multi) drainage, we may fill different pores than the ones filled in the first drainage and that not all the residual oil will re-connect. This means more oil will be trapped in the imbibition part of the experimental cycle, consequently the measured  $S_{or}$  may be higher than the actual one.
- 2) Part of the experiment, for example in the second cycle, will be secondary drainage that is the part which was accessed in the first drainage, while the part of the plug that was previously not accessed will undergo primary drainage, see Fig. 3. In addition when aging the core one part will be aged longer than the previously not accessed part. This may create wettability heterogeneity within a homogeneous plug, as shown in Fig. 3.

These concerns should be taken into account during the interpretation of the raw data.

In this work we used a combination of the first and third option. This way we still use the same plug at different  $S_{oi}$  ( $S_{oi}$  increases for each cycle), and at the same time we use more plugs to cover a wide range of  $S_{oi}$ 's.

## 5. Experimental Procedure

All the measurements discussed in this paper have been performed using the Ultra-centrifuge technique. We used a combination of multi-speed and single speed experiments for the determination of residual oil, oil relative permeability, and capillary pressure which will be used in the numerical interpretation of the relative permeability data.

The experiments have been performed at 60 °C and atmospheric pressure using crude oil and synthetic brine. After each drainage experiment the plugs have been aged again in crude oil at 70 °C and 100 bar for four weeks. The experiments have been performed on several low permeable carbonate plugs (1 to 6 md). In designing the experiments we have always checked that the bond number [5] is below  $10^{-5}$ . The oil relative permeability ( $k_{ro}$ ), capillary pressure ( $P_c$ ) and residual oil saturation ( $S_{or}$ ) have been obtained by numerical interpretation of the raw experimental data using Shell numerical reservoir simulator (MoReS). This had important impact on getting the proper relative permeability curves as analytical interpretation does not take into account the capillary end effect and therefore give erroneous results.

We first have used three plugs to perform four different drainage/imbibition multi-speed cycles; each cycle targets different initial oil saturation. The experimental procedure applied consisted out of the following steps:

- 1) the core plug is cleaned to water-wet and fully saturated with brine, subsequently a drainage experiment is performed targeting initial oil saturation  $S_{oi}$ ,
- 2) after aging oil is displaced by water to residual oil saturation  $S_{or}$ . Subsequently oil is re-injected targeting higher initial oil saturation.
- 3) This procedure is repeated four times, each time targeting higher initial oil saturation.

Later we have done more work on several more plugs where each plug was prepared at different initial oil saturation and a combination of multi-speed and single speed experiments have been performed. The experimental procedure is as follows:

- 1) The core plugs are cleaned to water-wet and fully saturated with brine, subsequently a drainage multi-speed experiment is performed targeting initial oil saturation  $S_{oi}$ .
- 2) After aging in crude oil the oil relative permeability at  $S_{oi}$  is measured.
- 3) Oil is then displaced by water, in an imbibition multi-speed experiment, to residual oil saturation  $S_{or}$ .
- 4) The water permeability at residual oil is measured.
- 5) A secondary drainage multi-speed experiment is performed to restore the  $S_{oi}$  and determine the secondary drainage  $P_c$ .

- 6) A single speed imbibition experiment has then been performed to determine the imbibition oil relative permeability  $k_{ro}$ .
- 7) A drainage single speed experiment was performed to determine a drainage water relative permeability  $k_{rw}$ .

In some cases another drainage/imbibition cycle (third drainage/third imbibition experiments) has been performed to check the reproducibility of the data. The drainage data are not discussed in this paper.

Using the centrifuge to prepare the plugs at initial oil saturation results in inhomogeneous saturation profile, i.e., high oil saturation at the inlet face and low oil saturation at the outlet face. However, during aging saturation redistribution takes place and the profile becomes reasonably homogeneous, see [6].

## 6. Experimental Results and Discussion

As clear from the experimental procedure the measurements have been done at representative wettability by aging the plugs at the proper initial oil saturation. After aging, the plugs tend to become mixed-wet. The wetting status of the plugs and the effect of increasing initial oil saturation on wettability will be discussed in [6].

### 6.1 Initial oil/residual oil ( $S_{oi}/S_{or}$ ) Correlation

The  $S_{oi}/S_{or}$  measured using both experimental procedure discussed above are shown in tables 1 and 2. The average oil saturation at the end of the five drainage experiments and the residual oil saturation after the imbibition experiments are shown in table 1, the table also shows the permeability, porosity, length and diameter of the plugs used in the experiment. Table 2 shows the permeability, porosity, length and diameter of six more samples where each of them was prepared at different initial oil saturation. Also shown in the tables is the capillary pressure used to prepare the samples at each initial oil saturation. The data of the two tables are also plotted in figure 4. Two important observations can be made from table 1:

- 1- The residual oil saturation  $S_{or}$  for the four cycles is the same (within 2 saturation units) regardless of the initial oil saturation  $S_{oi}$ . This means doing cyclic measurements without cleaning the sample is not going to affect the amount of trapped oil. It also means that after oil re-injection previously trapped oil will reconnect otherwise we will not get the same  $S_{or}$ . This conclusion was supported by performing similar measurements where the first cycle was done on non-aged plugs and second cycle on the same plugs after aging (same  $S_{oi}$ ). We found that the residual oil decreased after the second cycle. This means that if oil invades a zone which was already flooded with water, the trapped oil will reconnect and will be remobilized.
- 2- The residual oil saturation  $S_{or}$  is also the same (within 2 saturation units) for the three plugs. This is supported by the data of the six other samples shown in table 2. From

figure 4 we find that, within the experimental accuracy,  $S_{or}$  is constant for  $S_{oi}$  ranging between 20-80%. The figure indicates that  $S_{or}$  starts to decrease for  $S_{oi} < 20\%$ , it will eventually go to zero when  $S_{oi}$  is zero.

The fact that after restoring wettability the residual oil is independent of initial oil saturation, for such a wide range of  $S_{oi}$ , stands as a surprising result. This is not expected to be a general case, more work needs to be done on  $S_{oi}/S_{or}$  relationship for different wetting status. The data shown in figure four shows that for this particular example  $S_{or}/S_{oi}$  relationship for the whole saturation range looks like:

$$S_{or}(S_{oi}) = S_{or}^{\max} \quad S_{oi} \geq 0.20 \quad (3a)$$

$$S_{or}(S_{oi}) = \frac{S_{oi} * S_{or}^{\max}}{S_{oi}^{\max}} \quad S_{oi} < 0.20 \quad (3b)$$

where  $S_{oi}^{\max}$  is the maximum initial oil saturation and  $S_{or}^{\max}$  is the maximum residual oil saturation. For the example studied in this work  $S_{oi}^{\max} = 0.8$  and  $S_{or}^{\max} = 0.05$ .

## 6.2 Relative Permeability

The fact that the residual oil saturation is independent of initial oil saturation does not mean one will reach the same oil saturation in the transition zone after water flooding. Residual oil saturation is obtained only, during field development, after an infinite number of pore volumes being injected, i.e., if the water flooding is sustained for a very long time. In many cases this is not economic. Therefore, it is for field development purposes more important to know the way the oil mobility is behaving close to the residual oil saturation rather than to know the actual residual oil saturation. This needs relative permeability measurement. Figure 5 shows relative permeability curves measured at 4 different initial oil saturations. The data measured using both procedures discussed earlier (i.e., either using the same plug at different initial oil saturation or using different plugs each of them at different  $S_{oi}$ ) agree quite well, they both show the same trend (figure 5). As clear from the figure for a given oil saturation, oil is more mobile as initial oil saturation decreases. It is also clear from the figure that while the residual oil saturation is independent of initial oil saturation the remaining oil saturation (ROS) at certain kro cut-off value increases with increasing  $S_{oi}$ . As initial oil saturation decreases then ROS approaches  $S_{or}$ . On the other hand ROS can be more than 10% higher than  $S_{or}$  for high initial oil saturation. In other words the data shows while residual oil is the same it is approached faster when oil is located closer to the oil water contact. The recoverable oil will be determined by ROS at certain kro cut-off value rather than the residual oil saturation which in many cases may be lower but un-attainable during the field life. Figure 6 shows the remaining oil saturation at kro=0.001 and kro=0.01 as a function of  $S_{oi}$ . The figure also shows  $S_{or}$  calculated using eq. 3. As shown in the figure ROS

increases as  $S_{oi}$  increases, i.e., at the end of the field life ROS will decrease as we approach FWL.

To explain the relative permeability behavior we have to understand the filling sequence of oil and water in the rock during drainage or imbibition experiments. All the experiments started with cleaned water-wet plugs saturated with 100% brine. In the drainage experiment oil starts to displace water from the big pores first as they have the smallest entry pressure (see the discussion in the introduction). While aging, some of the oil contacted parts of the rock become oil-wet. The higher the initial oil saturation the higher the fraction of pores that are rendered oil-wet. For simplicity suppose that all the pores filled with oil in the primary drainage are rendered oil-wet. Then in imbibition water will start displacing oil from the biggest pores first regardless of the initial oil saturation. Therefore, for a given oil saturation during imbibition oil will occupy more big pores when  $S_{oi}$  is low than when  $S_{oi}$  is high. This simple picture is still valid for the case when some oil-filled pores are still water-wet. As then water will displace oil from the small water-wet pores first and then the biggest oil-wet pores. In all cases at a given oil saturation oil will occupy more big pores as initial oil saturation decreases, thus oil is more mobile (i.e., has higher relative permeability).

## 7. Conclusions

In this paper we presented laboratory measurements of residual oil saturation and oil relative permeability as a function of initial oil saturation to properly characterize oil mobility in transition zone. We found that:

- 1- After restoring wettability by aging  $S_{or}$  is independent of  $S_{oi}$  for  $S_{oi} > 20\%$  for the particular example studied in this work. This is not expected to be a general case. More work is needed on  $S_{oi}/S_{or}$  relationship for different wetting status.
- 2- Land correlation is not suitable for oil/water systems as it was derived based on water/gas data where wettability alteration was not taken into account.
- 3- Upon oil re-injection previously trapped oil may reconnect. This means doing cyclic measurements without cleaning the sample is not going to affect the amount of trapped oil. In addition, it means that if oil invades a zone which was already flooded with water, the trapped oil will reconnect and will be remobilized.
- 4- There is a clear trend in the imbibition oil relative permeability for decreasing  $S_{oi}$ , i.e., for a given oil saturation oil becomes more mobile as initial oil saturation decreases.
- 5- More work is needed to accurately measure oil and water relative permeabilities. Work is already ongoing which uses steady state together with the centrifuge to measure both oil and water relative permeability curves at different initial oil saturation.

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Table 1: Soi/Sor for the six drainage/imbibition cycles in the centrifuge (Soi is oil saturation at the beginning of imbibition)

Sample	K (md)	Phi (%)	Length (cm)	Diam. (cm)	1 <sup>st</sup> imbibition			2 <sup>nd</sup> imbibition			3 <sup>th</sup> imbibition			4 <sup>th</sup> imbibition		
					Pc (bar)	Soi	Sor	Pc (bar)	Soi	Sor	Pc * (bar)	Soi	Sor	Pc (bar)	Soi	Sor
1	3.06	25.9	3.49	3.2	1.6	0.39	0.04	5.1	0.65	0.05	8.1	0.64	0.05	23.7	0.81	0.05
2	1.63	29.3	3.62	3.2	1.7	0.30	0.04	5.3	0.63	0.04	8.8	0.64	0.05	24.4	0.79	0.05
3	1.81	28.8	3.61	3.2	1.7	0.20	0.03	5.3	0.55	0.05	8.8	0.61	0.04	24.4	0.79	0.04

\* Higher pressure was applied in the third drainage than in the second drainage, however that did not result in higher Soi especially for samples 1 and 2, the reason is discussed in details in [6].

Table 2: Soi/Sor for 6 plugs used in the centrifuge.

sample	K (md)	Phi (%)	Length (cm)	Diameter (cm)	Pc (bar)	Soi	Sor
4	4.26	29.2	3.78	3.78	0.95	0.11	0.02
5	5.94	31.3	3.89	3.77	0.95	0.15	0.04
6	1.03	24.1	3.79	3.79	2.0	0.19	0.04
7	5.39	30.5	3.73	3.78	0.95	0.27	0.05
8	3.17	29.0	3.67	3.78	2.0	0.45	0.04
9	5.08	27.3	3.70	3.78	2.0	0.73	0.05

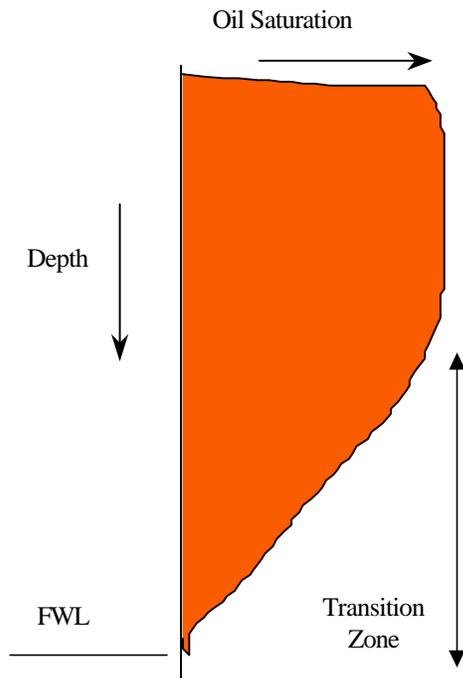


Figure 1: Oil reservoir, transition zone shown where oil saturation decreases with depth.

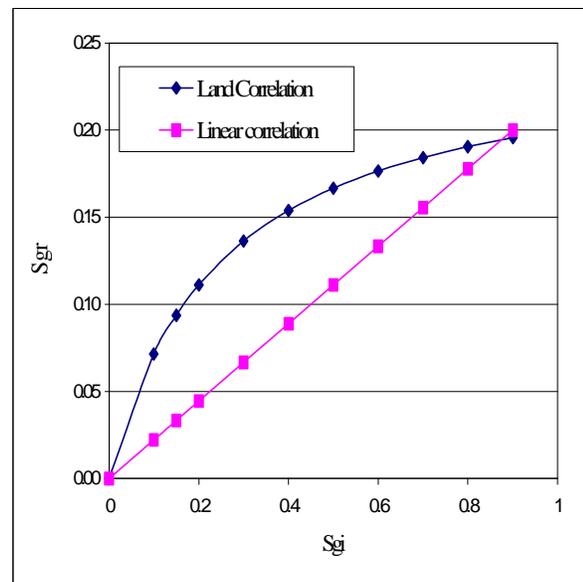


Figure 2:  $S_{gr}/S_{gi}$  correlations calculated using eqs. 1 (Land) and 2 (linear) correlations

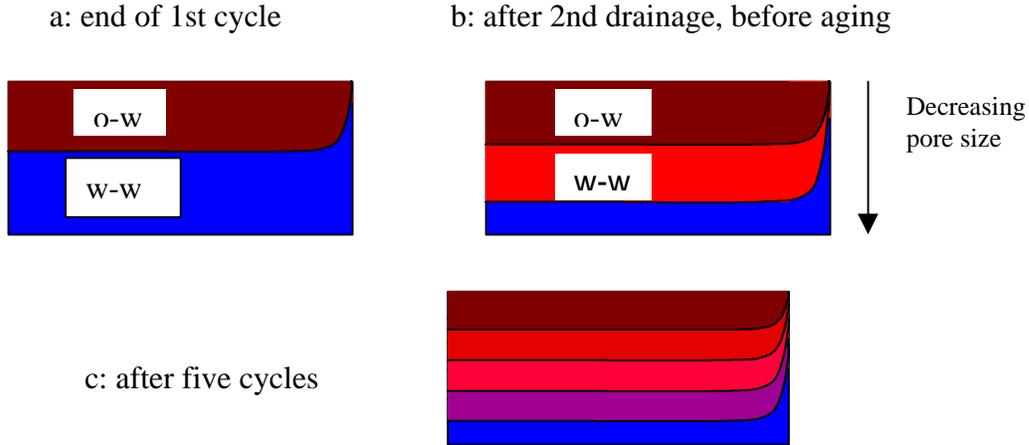


Figure 3: Cyclic aging may lead to wettability heterogeneity in a homogeneous plug: a) after the first drainage/imbibition cycle the accessed part may become oil-wet while the non accessed part stays as water-wet, b) during secondary drainage, oil will first flow in the oil-wet part and then it will access the water-wet part of the core, after aging those two parts may still have different wettability as one of them was aged twice as the other, c) a core after five different cycles, however if aging for one month at the highest oil saturation is enough to restore wettability then we may end up with a core of homogeneous wettability.

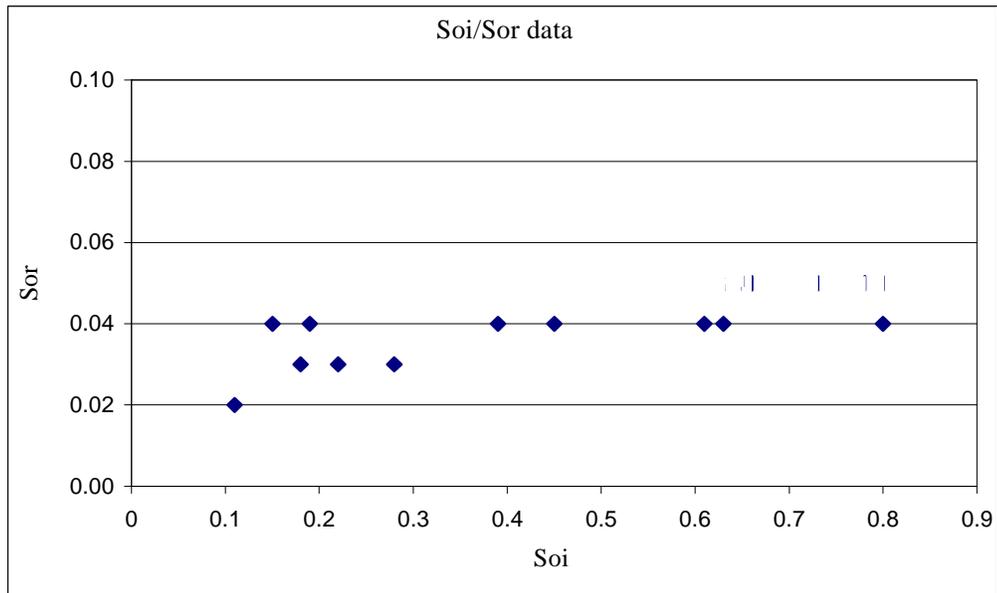


Figure 4:  $S_{oi}/S_{or}$  data measured using both experimental procedures (see text).

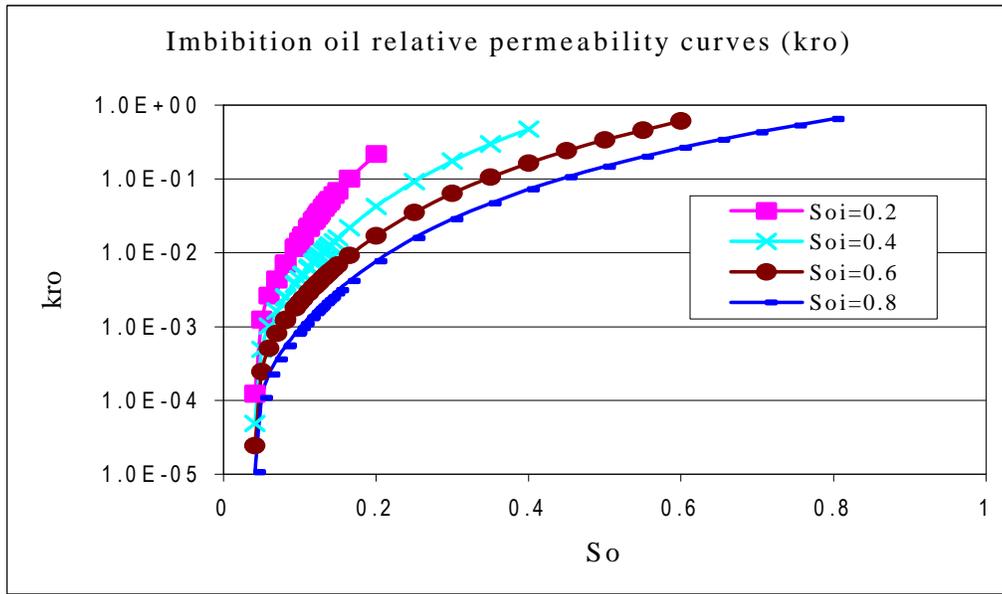


Figure 5: Oil relative permeability measured at four different initial oil saturation ( $S_{oi}$ ).

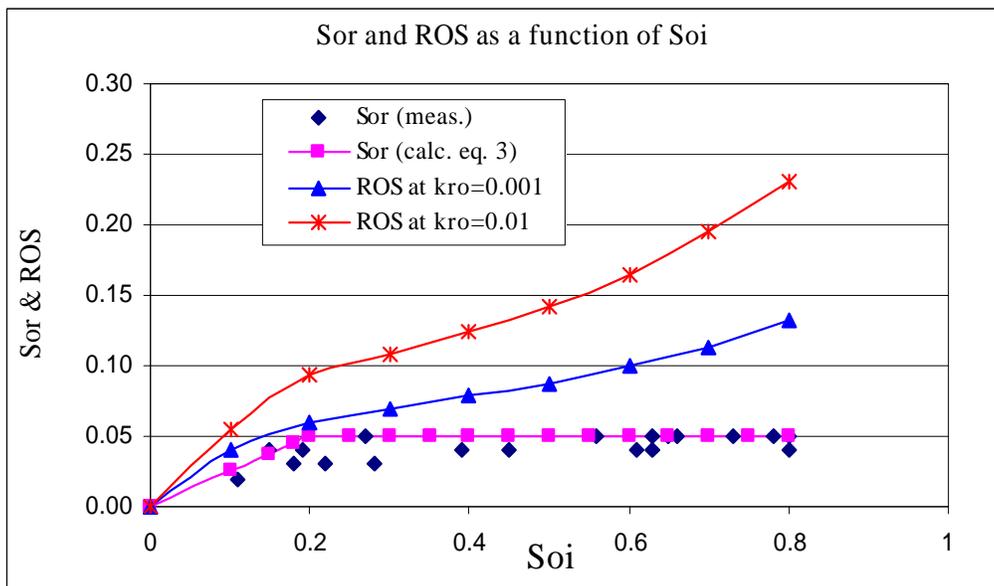


Figure 6: Residual oil saturation ( $S_{or}$ ) and remaining oil saturation (ROS) as a function of initial oil saturation ( $S_{oi}$ ).