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High Oil Recoveries from Transition Zones

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Abstract
Oil-water transition zones may contain a sizable part of a field's STOIIP, specifically in low permeable sandstone and carbonate reservoirs. 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.

In this paper we present 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 the residual oil saturation after water flooding showed, for the example studied here, no dependence on initial oil saturation. On the other hand we found that there is a clear trend in the imbibition oil relative permeability for decreasing S_{oi}, i.e., for a given oil saturation oil mobility increases as initial oil saturation decreases. In other words, laboratory measurements show that the mobility of oil in the transition zone is much higher than conventional analysis would suggest. Consequently, in a given time span more oil can be produced from the transition zone than generally assumed and potentially large volumes of reserves can be added to reservoirs with large transition zones.

The impact of the measured relative permeabilities and residual oil saturations on oil recovery has been quantified for a generic field example by numerical modeling using MoReS, the Shell group reservoir simulator. The recovery factor was found to increase from 32% using a single set of relative permeability curves for the whole field independent of initial oil saturation to 56% using the measured S_{oi} dependent relative permeability curves. The water cut at abandonment was for both cases taken at 95%.

Transition Zone
Oil in transition zones has, in water-wet rocks, the tendency to fill the larger pores preferentially. As oil tries to enter a pore (originally water-wet) a certain threshold pressure has to be built up before the capillary pressure in the pore can be overcome and the oil can actually enter the pore. In the smaller pores the capillary effect is stronger and therefore higher pressure differentials are needed for oil to enter these pores, as a result larger pores are filled most easily. The largest pore throat will determine the minimum capillary rise above the free water level. The transition zone is the part of the reservoir where the saturations grade from 100% water in the water zone to an irreducible water saturation some vertical distance in the reservoir above the free water level, (Figure 1). 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 STOIIP. 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. It has indeed been shown in this study that large volumes of oil can be produced from transition zones.

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 because they are difficult and time consuming. Therefore, 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 (S_{oi}). 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 [1]) and relative permeability (i.e. Killough hysteresis model [2]) 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 [3].

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.
The measurements have been performed by preparing several core samples at different initial oil saturations. After aging the plugs to restore wettability a water displacing oil experiment was performed targeting S_{or}. Details of the experimental program can be found in [3]. All the experiments have been carried out using the Ultra centrifuge equipment.

Experimental Results

The measurements have been performed on 9 low permeable carbonate plugs (1 to 6 mD) from a lower Shuaiba formation in Oman. We have a combination of single speed and multi-speed experiments. Some of the plugs have gone through several drainage/imbibition cycles, each cycle targeted different S_{oi}. The experimental raw data have been interpreted using numerical simulation.
Figure 2 shows the residual oil saturation as a function of initial oil saturation. As shown in the figure S_{or} is constant for a wide range of S_{oi}, the residual oil starts to decrease for S_{oi} < 20%. This S_{oi}/S_{or} relationship is not expected to be a general case, more work needs to be done on S_{oi}/S_{or} relationship for different wetting status and using different rock types.
Figure 3 shows the imbibition oil relative permeability (kro) starting at 4 different initial oil saturations. The figure shows a clear trend in kro for decreasing S_{oi}, for a given oil saturation kro increases as initial oil saturation decreases. The data shows that for a given oil saturation oil becomes more mobile as initial oil saturation decreases. In other words, while the residual oil is the same it is reached faster when oil is located close to the free water level.
These results emphasize the importance of the relative permeability curves in field development over the residual oil saturation. Residual oil saturations are 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. The recoverable oil will be determined by remaining oil saturation (ROS) at certain kro cut-off value (i.e. value of fractional flow) rather than the residual oil which in many cases may be lower but un-attainable during the field life. Figure 3 shows that ROS at certain kro cut-off value increases as initial oil saturation increases.

Oil Relative Permeability Model

For accurate prediction of oil mobility in transition zone a proper model to describe the dependence of S_{or} and kro on S_{oi}. As discussed in [3] we found that S_{oi}/S_{or} relationship for the whole saturation range can be presented by the following eq.:

$$S_{or}(S_{oi}) = S_{or}^{\max} \qquad S_{oi} \geq 0.20 \qquad (1a)$$

$$S_{or}(S_{oi}) = \frac{S_{oi} * S_{or}^{\max}}{S_{oi}^{\max}} \qquad S_{oi} < 0.20 \qquad (1b)$$

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 [4].
For relative permeability curves we have used a modified Corey presentation to generate the relative permeability curves used to fit the raw experimental data:

$$kro = Kro(S_{oi})*\left(\frac{So - S_{or}(S_{oi})}{S_{oi} - S_{or}(S_{oi})}\right)^{no(S_{oi})} + \frac{c(S_{oi})}{1 + c(S_{oi})}\left(\frac{So - S_{or}(S_{oi})}{S_{oi} - S_{or}(S_{oi})}\right) \qquad (2)$$

where $S_{or}(S_{oi})$, $Kro(S_{oi})$ and $no(S_{oi})$ are the residual oil saturation, the oil end point and the Corey exponent respectively, $c(S_{oi})$ is a constant to make the oil relative permeability more linear close to residual oil saturation. Those four parameters need to be defined for each S_{oi} value. The residual oil saturation is measured and it is defined using eq. 1. The oil relative permeability at initial oil saturation $Kro(S_{oi})$ was measured for several plugs which have been prepared at different S_{oi}. We found that $Kro(S_{oi})$ can be presented by the following equation:

$$Kro(Soi) = Kro(Soi_{\max}) - a_1 * \left(Soi_{\max} - Soi\right)^{a_2} \qquad (3)$$

where $Kro(S_{oi}^{max})$ is the oil relative permeability at the highest initial oil saturation, S_{oi}^{max} is the highest initial oil saturation, a_1, a_2 are fitting parameters to fit the measured data. For this example the following parameters have been used: $Kro(S_{oi}^{max})$=0.65, S_{oi}^{max}=0.8, a_1=1.1 and a_2=2.5.

The Corey exponent $no(S_{oi})$ and the factor $c(S_{oi})$ are variables used to generate the relative permeability curves which fitted the raw experimental data. We found that those two parameters can be defined as follows:

$$no(S_{oi}) = no(S_{oi}^{\max}) + b_1 * \left(S_{oi}^{\max} - S_{oi}\right)^{b_2} \qquad (4)$$

$$c(S_{oi}) = c_{\max} - c_1 * (S_{oi})^{c_2} \qquad (5)$$

where $no(S_{oi}^{max})$ and c_{max} are the oil Corey exponent and the constant $c(S_{oi})$ at the highest initial oil saturation respectively, b_1, b_2, c_1 and c_2 are fitting parameters. To fit the experimental data we used the following parameters: $no(S_{oi}^{max})$ =3, S_{oi}^{max} =0.8, b_1= 1, b_2=2.5, c_{max}=0.021, c_1 = 0.02 and c_2 = 2.0.
Figure 4 shows the relative permeability end points $Kro(S_{oi})$, the oil Corey exponents $no(S_{oi})$, the residual oil saturation $S_{or}(S_{oi})$ and the constant $c(S_{oi})$ calculated using the above equations. Also shown in the figure is ROS at kro=0.001 and 0.01 as a function of S_{oi}. Oil relative permeability curves for each S_{oi} can now be generated by substituting the four different parameters defined in eqs. (1, 3-5) in eq. 2.

Field Example

Oil relative permeability curves at 10 different initial oil saturations have been calculated using the above model. We first tested the obtained relative permeability curves and the corresponding residual oil saturation against well-test production data (one month) of a well in the carbonate reservoir from which the plugs used in this study have been obtained. The well was situated in the transition zone. The relative permeability curves have been inserted in a MoReS (Shell group simulator) well model. The simulated oil production rate and the water cut show a very good agreement with the field data (Fig. 5). Note, however that at this early stage of the displacement the production performance is only moderately sensitive to the relative permeability curves. Later in the field life the relative permeabilities become much more important. The impact of the measured relative permeability curves and corresponding residual oil saturation on recovery efficiency has therefore been quantified by constructing a generic field example for which the single well model was used as basis. The model consists of five different layers in the z-direction 35 m thick, 400 m wide and 1200 m long. Two injectors and one producer are positioned in the model. The data presented in figure 6 is a result of two different simulation runs. The first run has been performed using a single set of relative permeability curves to characterize the whole field independent of initial oil saturation. The relative permeability curve is the one measured at the highest initial oil saturation as one would conventionally measure. The second run has been performed using the measured S_{oi} dependent relative permeabilities. Figure 6 shows that the recovery factor has increased from 32% to 56% when using S_{oi} dependent relative permeability curves. The water cut at abandonment was taken at 95%.

The flow performance as for example the producing water cut is for the oil in the transition zone also dependent on the imbibition water relative permeability *krw*. Our experiments were not designed to measure the water relative permeability at different initial oil saturation, the centrifuge technique used in this work can only measure the relative permeability of the displaced phase. Therefore, one water relative permeability curve was used in both the history match and the forecasting runs. To explore the effect of the water relative permeability on recovery efficiency the water relative permeability curve was increased by a factor of 2, no major difference in recovery or water cut was found. More work is needed to properly model the water relative permeability as a function of initial oil saturation.

Conclusion

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 S_{or} is independent of S_{oi} for the particular example studied in this work. On the other hand we found that there is a clear trend in the imbibition oil relative permeability for decreasing S_{oi}, i.e., oil becomes more mobile near S_{or} as initial oil saturation decreases. When using S_{oi} dependent relative permeability curves the recovery factor of a generic field example has increased by 75%.

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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References

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2) J. E. Killough: “Reservoir Simulation With History-Dependent Saturation Functions”, SPEJ pp 37-48, Feb. (1976).
3) S.K. Masalmeh and S. Oedai: “Oil Mobility in Transition Zone”, paper SCA0002 to be presented at the International Symposium of the Society of Special Core Analysts, Abu Dhabi, October 18-22 (2000).
4) The residual oil saturation may seem to be low. However, with current technology where the measurements are done at representative wettability and the raw data is interpreted using numerical simulation to count for the capillary end effect low residual oil values are not uncommon, see e.g., Kokkedee J.A., Boom W., Frens A.M and Maas J.G.: "Improved Special Core Analysis: Scope for a Reduced Residual Oil Saturation", Paper 9601 presented at the 1996 International Symposium of the Society of Special Core Analysts, Montpellier, September 8-10.

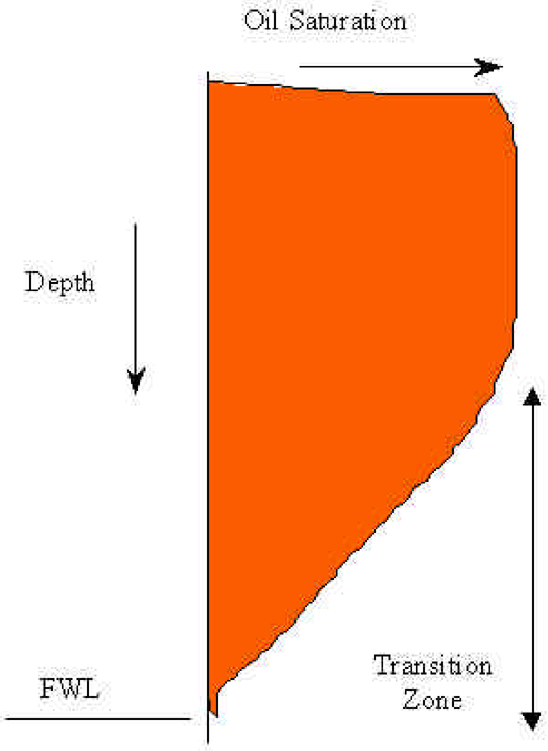

Figure 1: **Oil reservoir, transition zone shown where oil saturation decreases with depth.**

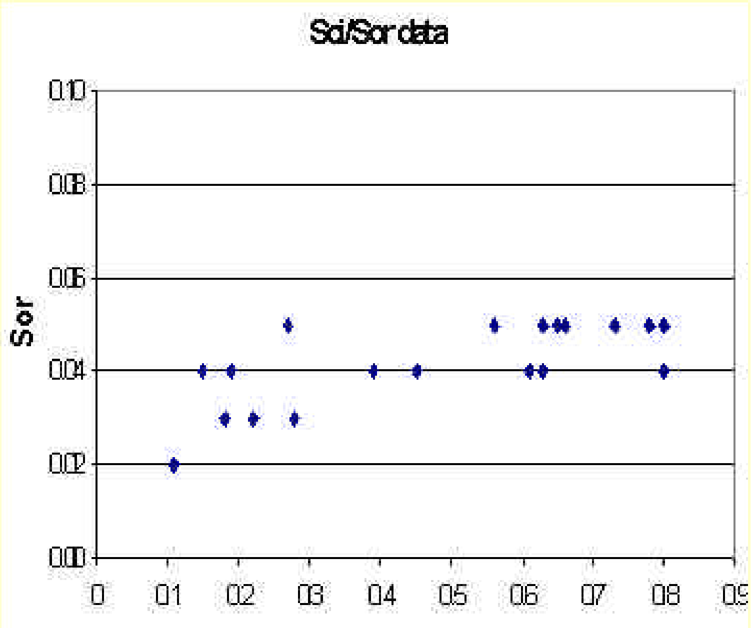

Figure 2: **Soi/Sor data measured using both experimental procedures (see text).**

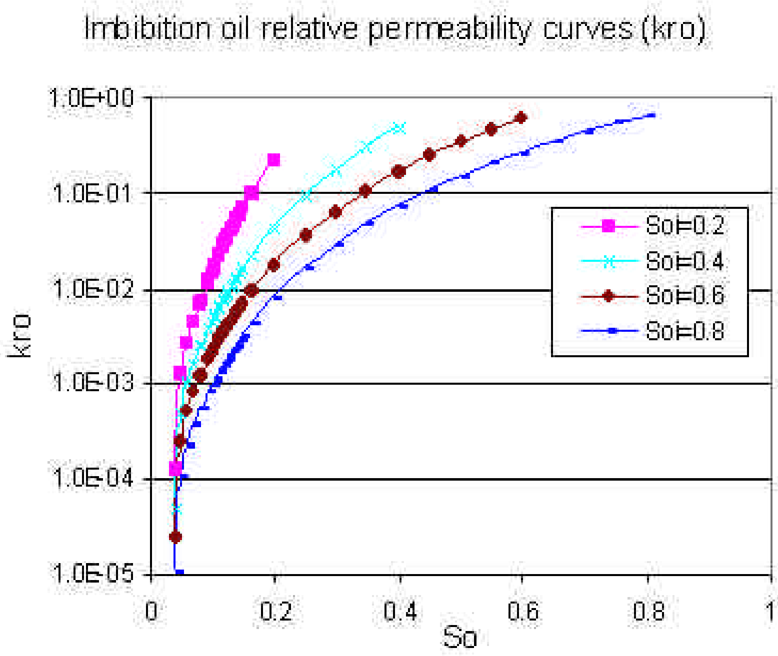

Figure 3: **Oil relative permeability measured at four different initial oil saturations (Soi).**

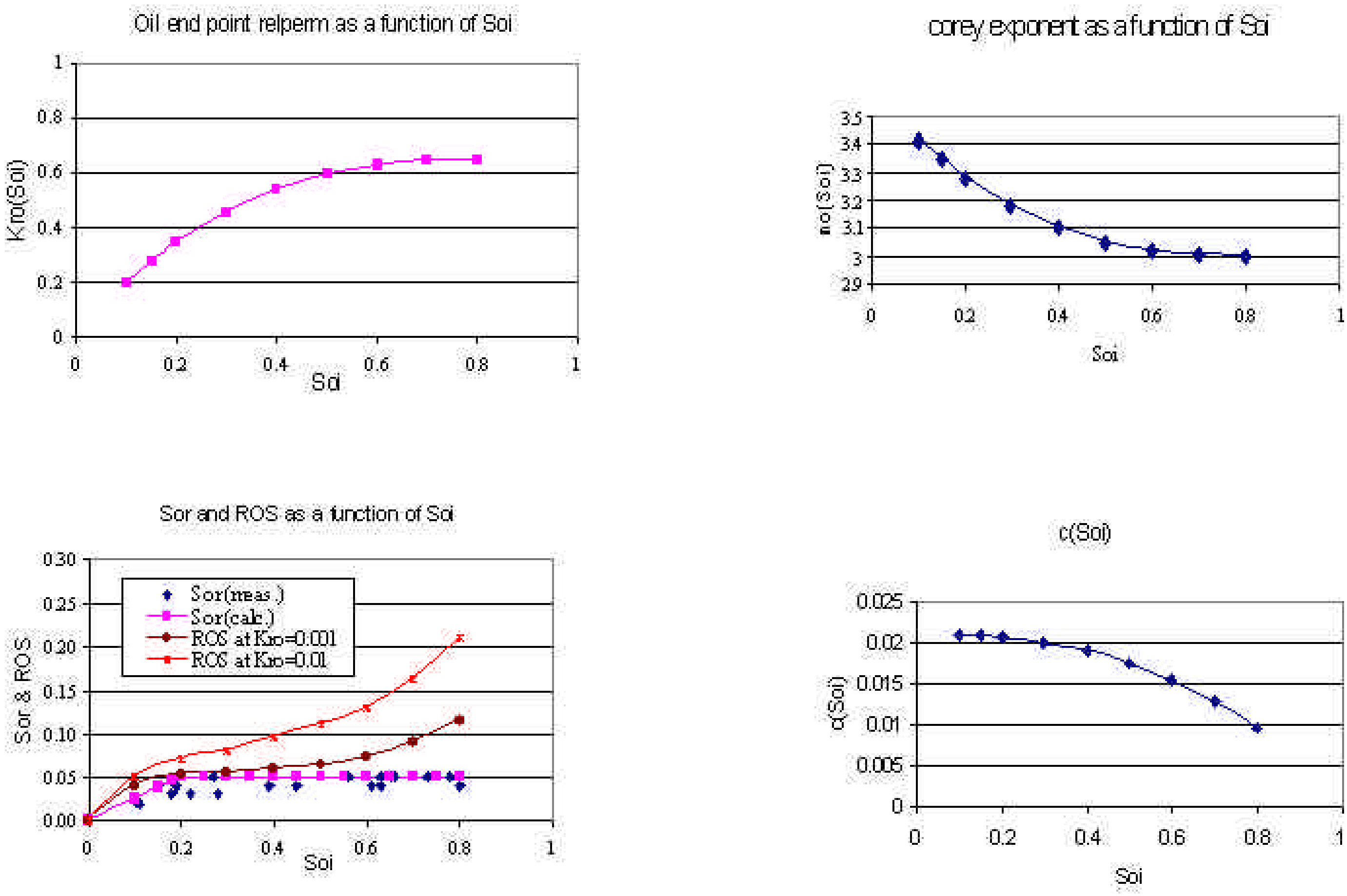

Figure 4: **Oil relative permeability end points Kro(S_{oi}), the oil Corey exponents no(S_{oi}), the residual oil saturation S_{or}(S_{oi}), remaining oil saturation (ROS) at kro=0.001 and 0.01 and the constant c(S_{oi}) as a function of S_{oi}.**

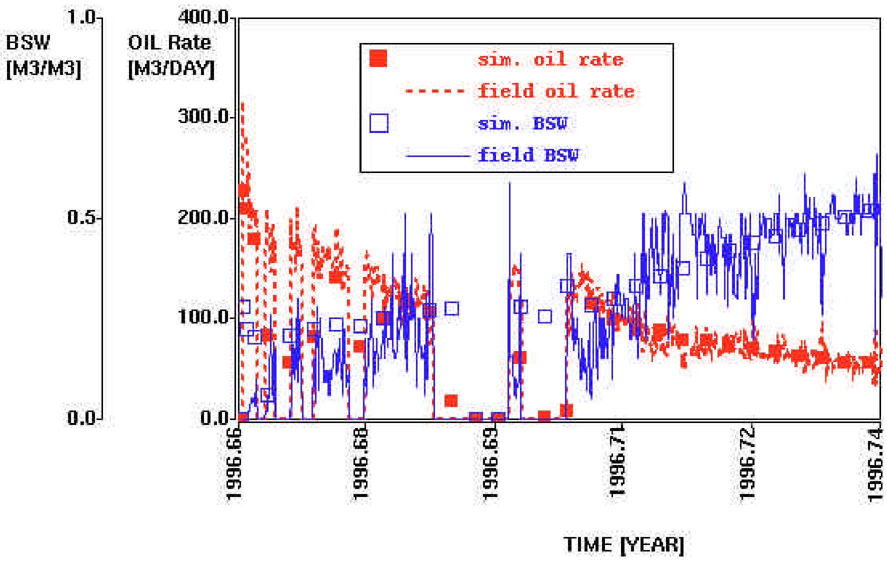

Figure 5: **A comparison between simulated and field oil rate and water cut data.**

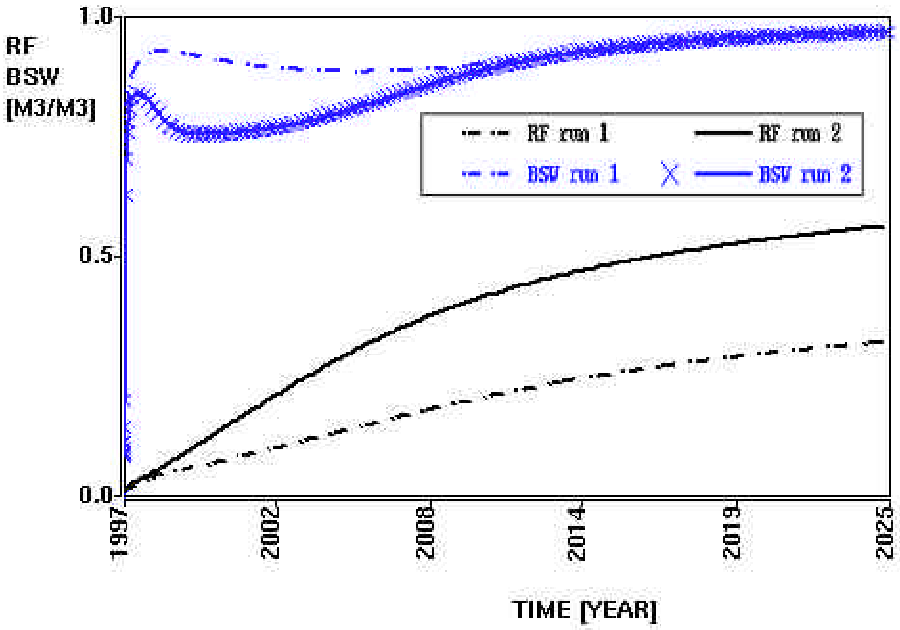

Figure 6: **Recovery factor (RF) and water cut (BSW) using Soi independent (run 1) and Soi dependent (run 2) kro curves.**