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Modeling Imbibition Capillary Pressure Curves

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Abstract

Although spontaneous imbibition capillary pressures are relevant in all reservoirs having undergone or undergoing gravity stable water displacement, they are not commonly measured nor considered for reservoir modelling. Imbibition is particularly important when establishing initial hydrocarbons in place for reservoirs already having residual hydrocarbon columns prior to production commencement.

As part of a saturation-height study, an empirical model relating imbibition capillary pressure curves to their drainage precursors was created. Drainage saturation-height functions could then be used to create imbibition equivalents based upon the saturation history of the reservoir rock. Calibration was carried out using laboratory measurements of both drainage and imbibition capillary pressure curves.

This "imbibition from drainage" (IFD) model was verified against log derived water saturations from wells in the initial study area. The match was excellent in those wells considered to have reliable petrophysical evaluations. The IFD model was even able to describe imbibition capillary pressure curves for sections of reservoir in drainage transition zones prior to the commencement of water imbibition. The model has since been further verified in other hydrocarbon accumulations found in different basins.

The IFD model developed represents the first publication of a technique for creating meaningful spontaneous imbibition capillary pressure curves and imbibition saturation-height functions through reservoirs with significant capillary transition zones. The technique should be widely used to describe water saturations in reservoirs with residual hydrocarbon columns, providing better estimates of initial hydrocarbons in place than with more commonly used drainage data. Iteration of the model also allows determination of both original and current day Free Water Level locations in systems having residual hydrocarbon columns from either leakage prior to production or from gravity controlled water sweep during production.

Introduction

There are a number of oil and gas accumulations worldwide that cannot be adequately described using conventional drainage capillary pressure curves. In many of these cases, the transition zone described by the capillary pressure curves is much longer than that suggested by the wireline log evaluation. In these situations, and if there are residual hydrocarbons evident below the pressure-derived Free Water Level (FWL), the hydrocarbon saturations are better modelled using imbibition capillary pressure curves.

This paper backgrounds the type of imbibition capillary pressure curves available and how they are measured. It then details how to create mathematical expressions to efficiently describe these curves for use in reservoir modelling and reserves determinations. Unlike techniques previously used to describe reservoirs in imbibition mode[1], the model presented here will also describe short hydrocarbon columns i.e. those columns which never reached irreducible water saturation, so imbibition has occurred into the drainage capillary pressure transition zone. Investigations have found no references to any techniques to model such situations in the literature.

Note that although the technique presented herein has not previously been described in the literature, results of the first model developed using the technique have been presented [2] .

Drainage and Imbibition

Figure 1 illustrates the difference between drainage and imbibition capillary pressure curves. It shows how saturations in a reservoir can alter such that imbibition rather than drainage curves provide a better description.

Initially the reservoir is charged with hydrocarbons down to a point A (typically a spill point, unless hydrocarbon charge is limited). The hydrocarbon saturation profile at this stage is best represented by *drainage* capillary pressure curves. These curves are measured by gradual displacement of the wetting fluid in rock samples with a non-wetting fluid i.e. a process mirroring the displacement of water with hydrocarbons in the reservoir.

Should there be a breach of the reservoir at point B, the hydrocarbons from below this point will leak away allowing water to imbibe back into the previously hydrocarbon-bearing rock below B. The hydrocarbon saturation profile above point B is now best represented by *imbibition* capillary pressure curves. These curves are measured in a process mirroring the displacement of hydrocarbon-filled rock by water in the reservoir.

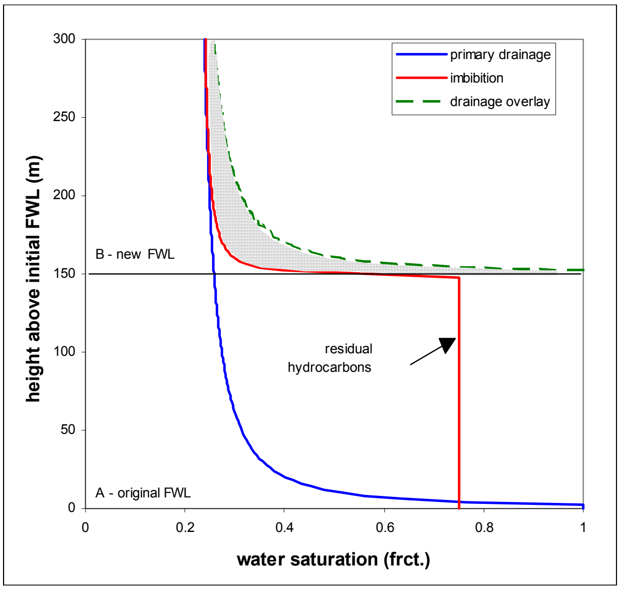

Figure 1 - Saturation history model illustrating the difference between drainage and imbibition capillary pressures.

The (shaded) difference between the imbibition and drainage capillary pressure curves based upon the same Free Water Level (at point B) represents the increased hydrocarbons-in-place addressed by modelling this behaviour correctly.

Measurement Techniques

Techniques to determine drainage capillary pressure curves are well known and include Mercury-Air, Centrifuge and Porous Plate experiments[3,4,5].

To readily measure spontaneous imbibition capillary pressure curves is most easily done using either the Mercury-Air or Porous Plate techniques, although some specialised centrifuge equipment is now available for the acquisition of such data.

In general, Mercury-Air experiments are preferred to model completely water-wet and gas-bearing systems owing to the greater number of data points, fully automated acquisition and relatively low cost.

If the system is mixed or oil-wet however, the Mercury-air experiments may be unsuitable, depending on the water saturations at which wettability alteration occurs. It is normally better to use samples aged at low water saturations in reservoir crude with either the Porous Plate technique or in the centrifuge using the secondary drainage curve to approximate spontaneous imbibition.

Imbibition Modelling in the Literature

Adams et. al.[1] could successfully model imbibition in the Maui Gas Field owing to the original column length being sufficient such that all reservoir above the current FWL had reached irreducible water saturation prior to water imbibition back into the structure. As a consequence, there was no link required between the drainage and imbibition states of the reservoir when developing saturation-height functions for saturation description. The imbibition capillary pressure curves could be modelled independently from the drainage data, using similar relationships to those derived for the drainage measurements.

When presented with a reservoir having short initial oil columns that have undergone some imbibition[2], it is clear that the shape of the imbibition curve must depend on how far up the initial drainage capillary pressure curve the reservoir reached. *Figure 2* illustrates how a single drainage capillary pressure curve can have multiple imbibition curves, depending on the lowest water saturation that particular piece of rock ever reached.

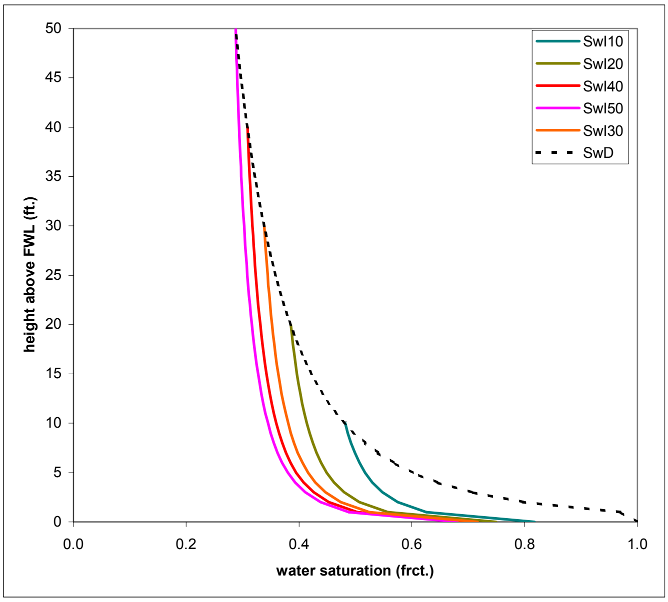

Figure 2 - A single drainage capillary pressure curve can engender a multiplicity of imbibition capillary pressures, depending on the maximum height above the Free Water Level reached.

Imbibition from Drainage

From *Figure 2*, it is clear that to adequately model imbibition behaviour, the drainage state must be a precursor i.e. it must be known how high up the drainage curve the reservoir being modelled reached.

Fortunately, when acquiring imbibition measurements in the laboratory, the drainage state prior to imbibition is measured. The realisation that, in a complete description, imbibition capillary pressure curves were inextricably linked to their drainage precursors allowed development of a suitable model to focus on the differences between the two curve types.

Using a laboratory dataset consisting of pairs of drainage and imbibition capillary pressure curves *Figure 3* was produced. This plot of drainage water saturation (SwD) against the change in saturation between the drainage and imbibition data (ΔSw) suggests that a series of parallel lines may be used to describe the measurements. Note that on *Figure 3* the very low water saturation data are from high pressure mercury-air capillary pressure curve measurements at pressures well beyond those found in the real reservoirs. These data have been excluded from the interpretation that follows.

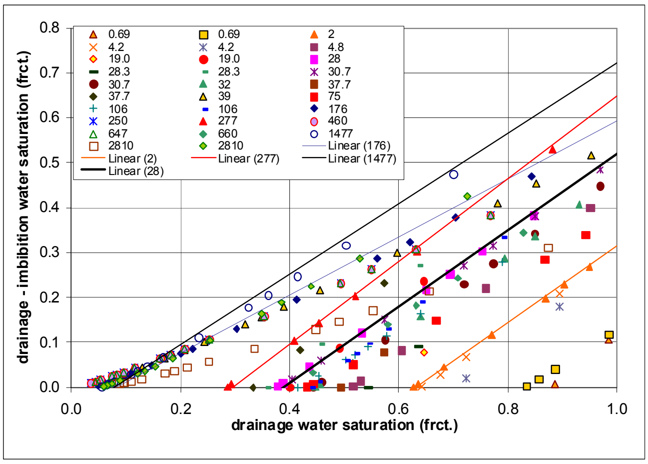

Figure 3 - The measured drainage water saturations are plotted against the change in saturation between the drainage and imbibition data for all the imbibition capillary pressure curve data. The legend denotes the sample permeabilities.

Also from *Figure 3,* it is apparent that permeability on its own is insufficient to describe the variation in location of the measured data within the plot. However, we do know that in addition to permeability, the minimum water saturation that the sample had experienced should have an influence.

Figure 4a plots the permeability against the slope of the data in *Figure 3*, while *Figure 4b* makes the same plot using minimum water saturation instead of permeability. As can be seen by the correlation coefficients for the trend lines shown, there is little or no correlation between either permeability or minimum water saturation and the slope of the data. In fact, an average slope is a reasonable assumption.

Figure 5a plots the permeability against the intercept of the data in the *Figure 3*, while *Figure 5b* makes the same plot using minimum water saturation instead of permeability. Both for permeability and minimum water saturation, a clear correlation with the intercept is discernible. The values of the correlation coefficients, too, are significant. It is clear that both permeability and minimum water saturation are controls on the location of the intercept.

From these observations, it was likely that a successful model of the imbibition capillary pressure curves could be built by making the slope (s) a constant and the intercept (int) a function of permeability and minimum water saturation. An

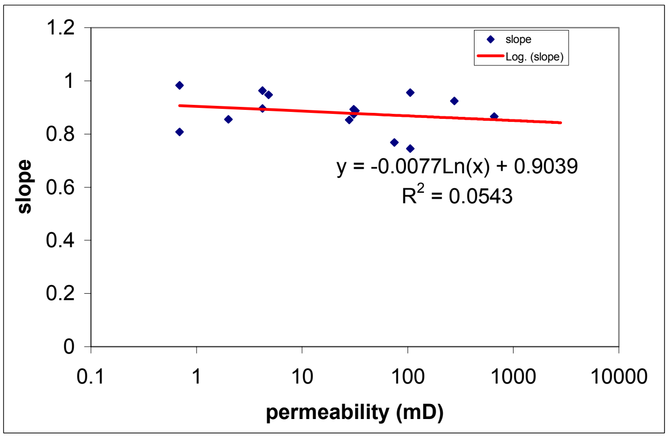

Figure 4a - Slope of each capillary pressure curve data set in ΔSw vs. SwD diagram plotted against permeability.

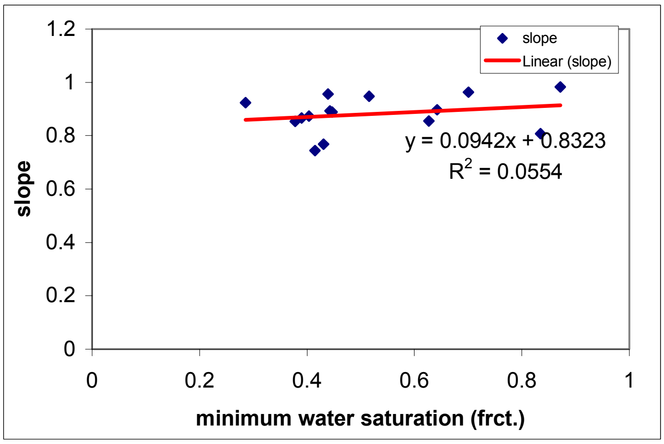

Figure 4b - Slope of each capillary pressure curve data set in ΔSw vs. SwD diagram plotted against minimum water saturation undergone by the sample.

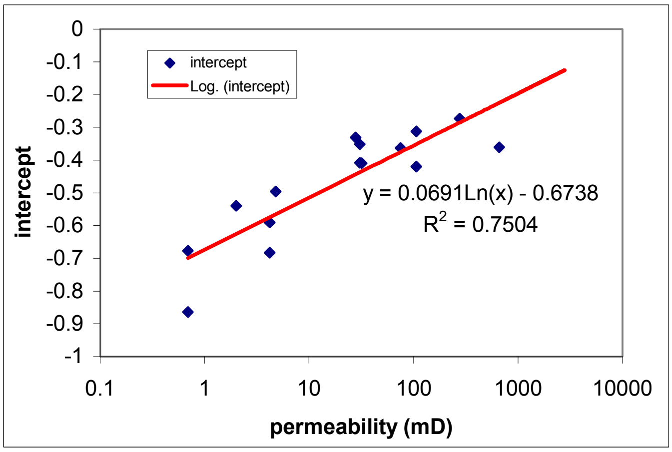

Figure 5a - Intercept of each capillary pressure curve data set in ΔSw vs. SwD diagram plotted against permeability.

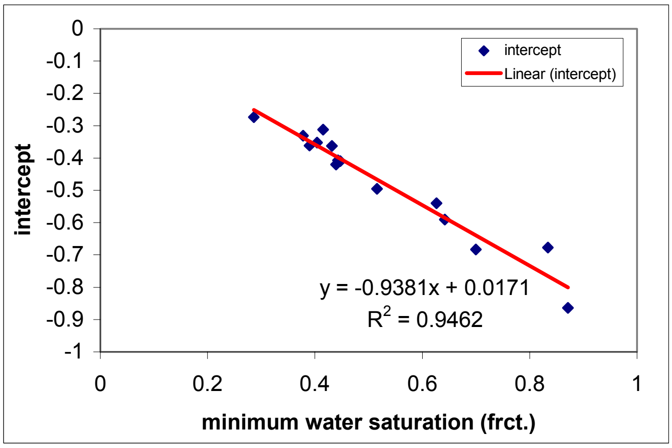

Figure 5b - Intercept of each capillary pressure curve data set in ΔSw vs. SwD diagram plotted against minimum water saturation undergone by the sample.

error minimisation exercise using all the imbibition data with the corresponding drainage measurements could then be used to determine the coefficients for the model below:

$$S_{wI} = S_{wD} - \Delta S_w \quad ..(1)$$

$$\Delta S_w = s \cdot S_{wD} + int \quad ..(2)$$

int $= a + b \cdot \log10(k) + c \cdot S_{wD,min}$ ..(3)

s = a fitting variable ,

where S_{wI} is the imbibition water saturation expressed as a fraction of pore volume, S_{wD} is the drainage based water saturation at the same height above the FWL, k is the permeability expressed in milliDarcies, $S_{wD,min}$ is the minimum water saturation reached at that point in the reservoir expressed as fraction of pore volume and s, a, b and c are variables used to tailor the model to the experimental data.

Note that detailed derivation of imbibition saturation-height functions according to this Adams-IFD (imbibition from drainage) model is described in the Appendix.

Modelling Laboratory Measurements

Some comparisons of the model against the laboratory data used to derive the model formulae are shown in *Figure 6a*. While *Figure 6b* more quantitatively illustrates the differences between the modelled and measured water saturations. As expected , owing to the error minimisation scheme used to create the expressions, the mean difference is zero, while the standard deviation is also small at 0.04. In other words, the model developed will give water saturations that are within 6% of pore volume of the real value at the P90 and P10 uncertainty levels, for this dataset.

With successful development of an imbibition model for the Eromanga Basin, it was decided to test the model in other Basins on different Fields:

Figure 7a compares modelled and laboratory data for a Field in the Browse Basin. While *Figure 7b* more quantitatively illustrates the differences between the modelled and measured water saturations for the capillary pressure data in the same Field. The description of the core measurements appears excellent.

Figure 8a compares modelled and laboratory data for a Field in the Taranaki Basin. While *Figure 8b* shows the differences between the modelled and measured imbibition water saturations for the capillary pressure data in the same Field.

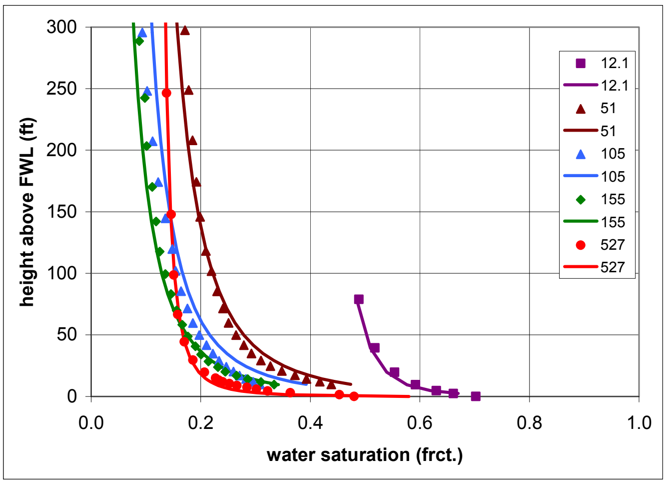

Figure 6a - Modelled imbibition capillary pressure curves are compared with the measured data points over a range of permeabilities for the Eromanga Basin[2].

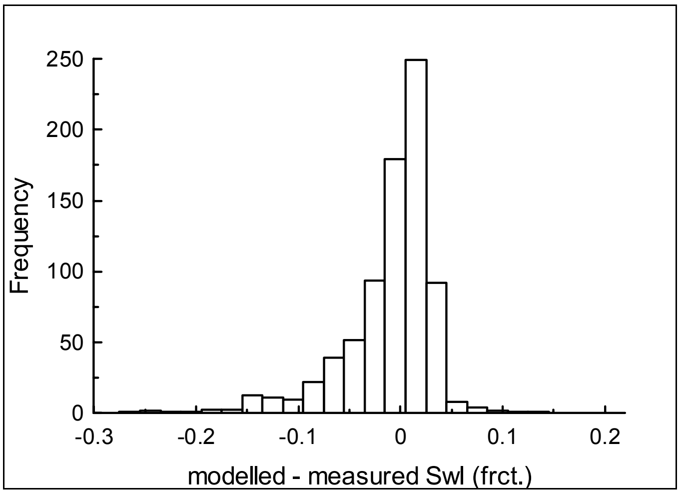

Figure 6b - Histogram of the differences between the modelled and measured imbibition water saturations for the Eromanga Basin[2]. Mean is zero with standard deviation of 0.04.

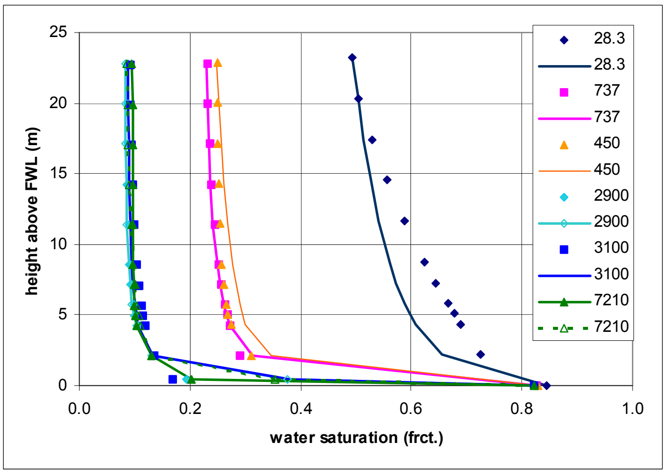

Figure 7a - Modelled imbibition capillary pressure curves are compared with the measured data points over a range of permeabilities for a Browse Basin oilfield.

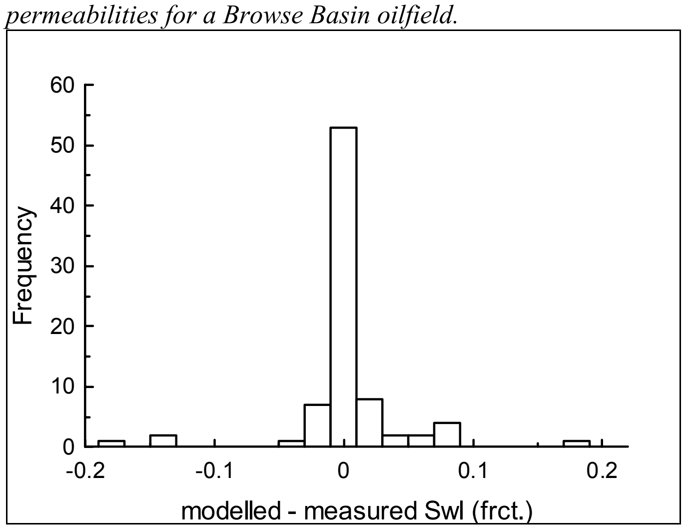

Figure 7b - Histogram of the differences between the modelled and measured imbibition water saturations for the Browse Basin oil field. Mean is zero with standard deviation of 0.04.

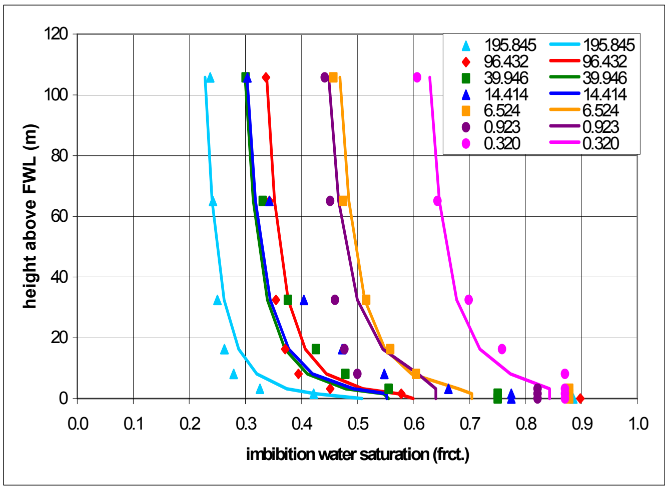

Figure 8a - Modelled imbibition capillary pressure curves are compared with the measured data points over a range of permeabilities for a Taranaki Basin oilfield.

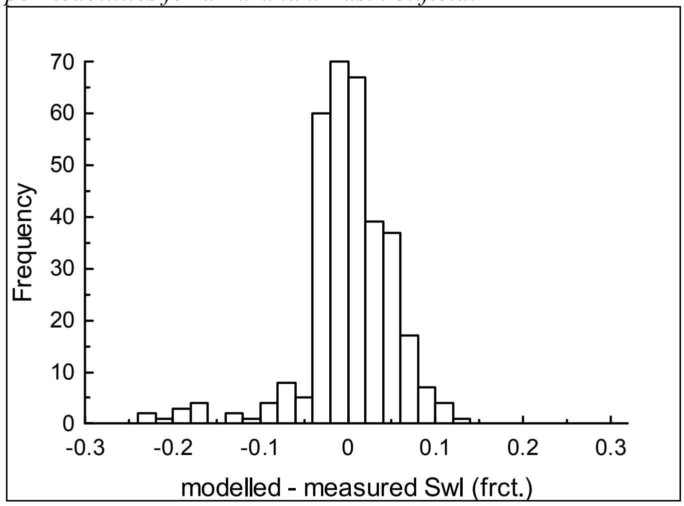

Figure 8b - Histogram of the differences between the modelled and measured imbibition water saturations for the Taranaki Basin oil field. Mean is zero with standard deviation of 0.??.

In the Reservoir

Successful modelling of laboratory measurements has been illustrated in the preceding section over three different Fields in three different sedimentary Basins. However successful modelling of laboratory data must be validated with Field measurements to be accepted for reservoir modelling purposes.

Figures 9a and *9b* show comparisons between the drainage, imbibition and wireline log derived water saturations for two Eromanga basin oil wells. *Figure 9a* also shows the imbibition saturation uncertainties at the 10% at 90% probability levels.

Figure 10 shows a similar comparison between the drainage, imbibition and wireline log derived water saturations for a Browse basin oil well. The match between the log derived oil saturations and the imbibition capillary pressure curve is very good, with the original drainage (2647.5 m RT) and present day (2645.3 m RT) Free Water Levels matching those observed on the wireline logs and formation pressure data.

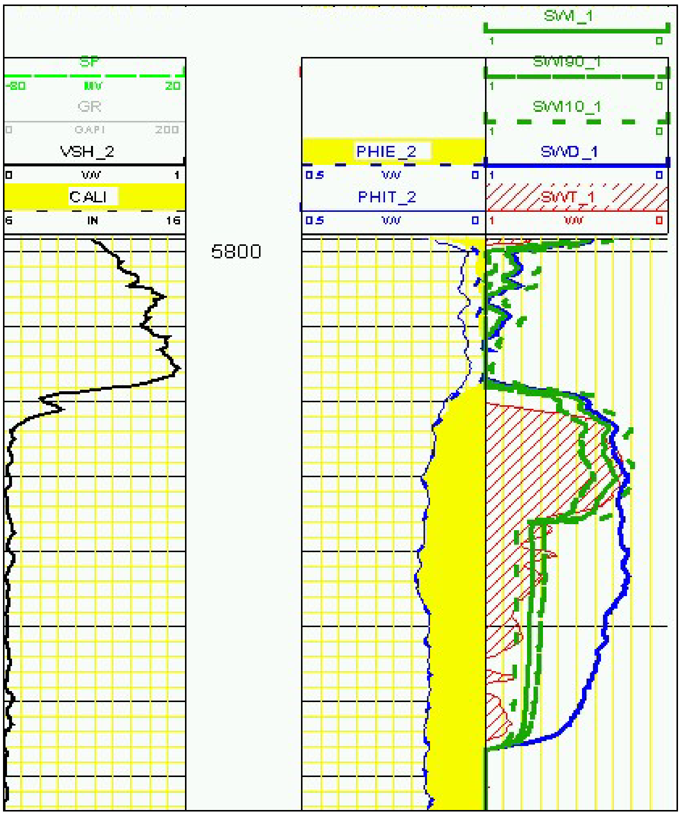

Figure 9a - Drainage (SWD) and imbibition (SWI) saturation-height functions are compared with the log evaluation(SWT) for the main reservoir in this Eromanga basin well. Here the dashed lines illustrate the uncertainty in SWI at P10 and P90 levels.

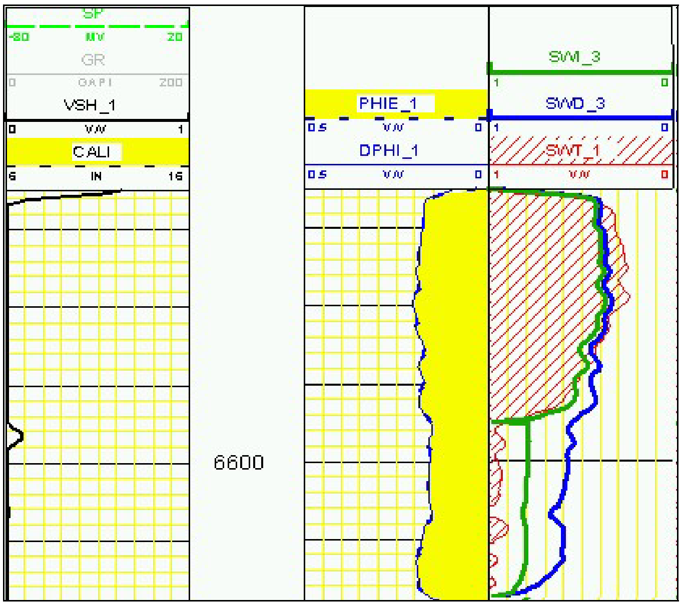

Figure 9b - The permeability based drainage (SWD) and imbibition (SWI) saturation-height functions are compared with the log evaluation(SWT) for the main reservoir in another Eromanga basin well.

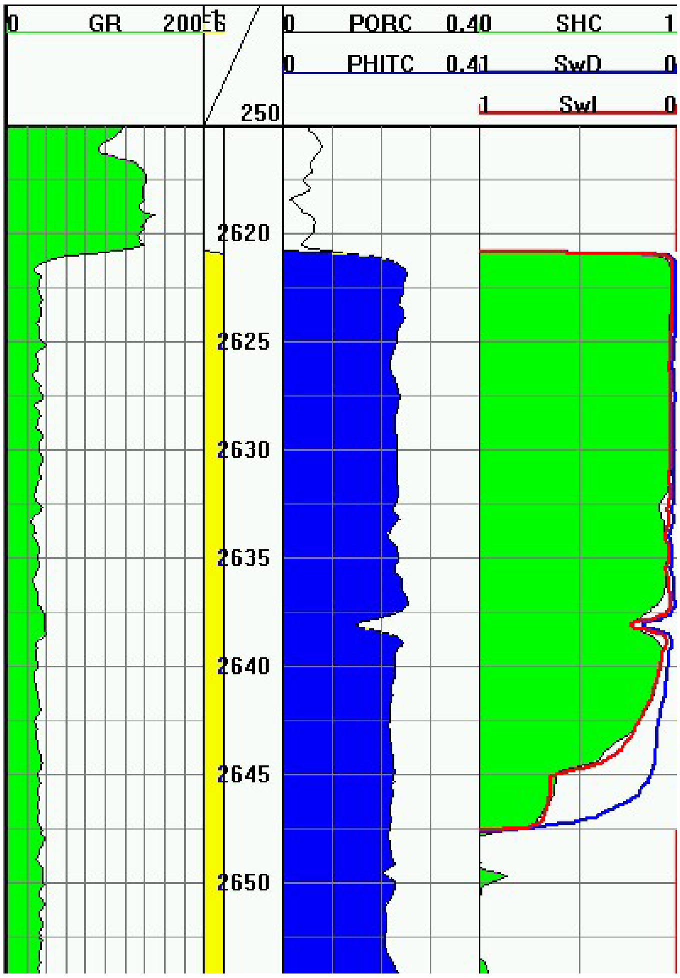

Figure 10 - Drainage (SWD) and imbibition (SWI) saturation-height functions are compared with the log evaluation(SHC) for the main reservoir in this Browse Basin well.

Figures 11a and *11b* show comparisons between the drainage, imbibition and wireline log derived water saturations for two Taranaki basin oil wells also. Here too the matches between the wireline log derived oil saturations and the imbibition saturation height functions are very good.

Locating Free Water Levels

Once the imbibition saturation-height model has been constructed, it can also be used to locate the ranges where the original and current day Free Water Levels are located. Although inversion of the imbibition saturation-height algorithms is possible to achieve this objective, experience shows it's more expedient to iterate the model with different water levels until the best match is obtained.

Model Limitations

The Adams-IFD imbibition saturation-height model is currently in the first incarnation. As such, there remains scope to further reduce uncertainty and deviations between modelled and measured data by refinement.

In particular, the current IFD Model assumes linearity in porosity (or permeability) and minimum water saturation reached. Real relationships are likely to be more complicated, although the differences may not be significant enough to warrant changes. Additional research is required in this area.

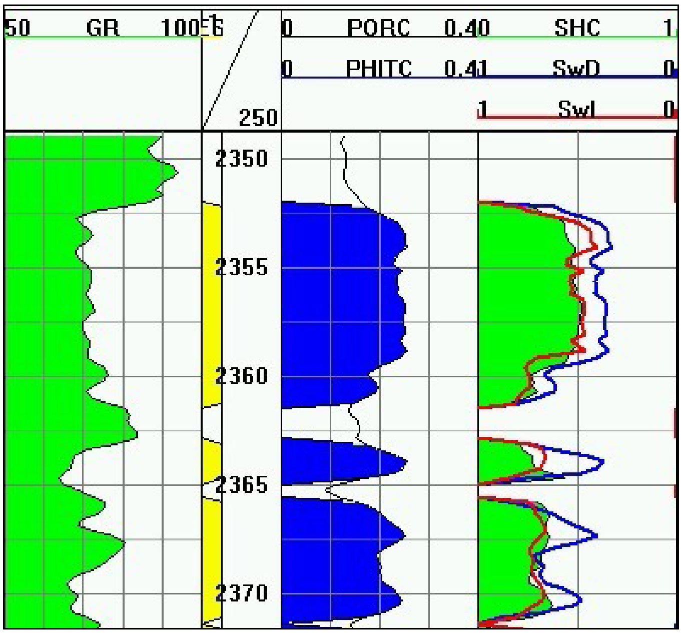

Figure 11a - Drainage (SWD) and imbibition (SWI) saturation-height functions are compared with the log evaluation(SHC) for the main reservoir in this Taranaki Basin well.

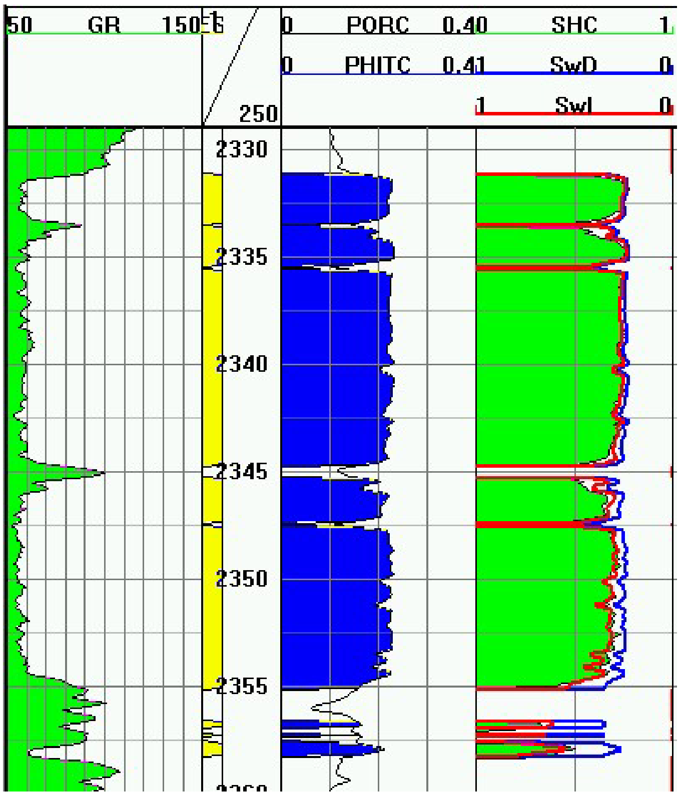

Figure 11b - Drainage (SWD) and imbibition (SWI) saturation-height functions are compared with the log evaluation(SHC) for the main reservoir in another Taranaki Basin well in the same Field as the previous Figure.

Conclusions and Recommendations

A saturation-height model has been described that enables spontaneous imbibition capillary pressure curves to be described as a function of their drainage capillary pressure curve precursors. As a consequence it is now possible to create meaningful imbibition saturation height functions to independently check wireline log evaluations in systems having undergone imbibition. These functions are also eminently suitable for implementation in reservoir modelling.

The model described has been tested to date in three different fields in three different sedimentary basins, proving able to independently match wireline log evaluated water saturations, confirming the validity of the petrophysical descriptions in these fields.

The technique is recommended to describe water saturations in reservoirs with residual hydrocarbon columns, providing better estimates of initial hydrocarbons in place than the more commonly used drainage data.

The Adams-IFD model as described is in its first version. Further improvements can be expected as usage increases.

Acknowledgements
The author would like to thank SANTOS Limited for the opportunity to carry out an interesting and challenging study during which the techniques described herein were first utilised.

Nomenclature
FWL = free water level
IFD = imbibition from drainage
int = intercept
P10 = value which has only a 10% chance of being exceeded
P90 = value which has a 90% chance of being exceeded
s = slope
Sor = residual oil saturation (frct.)
SwD = primary drainage water saturation (frct.)
SwI = spontaneous imbibition water saturation (frct.)
ΔSw = difference in Sw between drainage and imbibition capillary pressure curves at same pressure (height)

References

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Appendix - The Adams IFD Model
For clarity, this appendix details the steps required to successful build imbibition saturation-height functions using the model described in this paper. Note that the key step is obtaining a good description of the drainage data first, since the imbibition model is based on the drainage representation.

1. Collate all relevant data i.e. core depth, log depth, facies descriptor, in-situ porosity, in-situ permeability, drainage and imbibition capillary pressure data, technique and pressure capillary pressure experiments carried out at, in-situ hydrocarbon and water densities, in-situ contact angles.
2. Correct mercury-air data (if any) for closure and clay-bound water. Stress and fluid correct all capillary pressure data to in-situ fluids and heights or pressures.
3. Quality control data at in-situ conditions.
4. Determine drainage saturation-height functions and uncertainties, using Facies if required i.e.

   $$SwD = f(\phi \text{ or } k, haOFWL) \qquad ..(A\text{-}1)$$

   where SwD is the drainage based water saturation of a point with in-situ porosity ϕ or in-situ permeability k at a height above the original FWL haOFWL.
5. Calculate intermediate curve:

   $$Sw2 = f(\phi \text{ or } k, haCFWL) \qquad ..(A\text{-}2)$$

   where Sw2 is the drainage based water saturation (use SwD function) of a point with in-situ porosity ϕ or in-situ permeability k at a height above the current FWL haCFWL.
6. Calculate the difference between the drainage and imbibition saturations:

   $$\Delta SwI = a \cdot Sw2 + b + c \cdot (\phi \text{ or } \log(k)) + d \cdot Sw1 \qquad ..(A\text{-}3)$$

   where Sw1 is the point on the drainage saturation-height function SwD that the same point reached i.e. the minimum water saturation that point in the reservoir has been subjected to. The symbols a, b, c and d are values derived by fitting to the laboratory measurements.
7. The imbibition saturation SwI is then:

   $$SwI = Sw2 - \Delta SwI \qquad ..(A\text{-}4)$$

8. Plot and reconcile with log-derived water saturations.
9. Document relationships derived and when to use them.