AN EMPIRICAL METHOD FOR EVALUATION OF CAPILLARY PRESSURE DATA

Erik Søndenå
Elf Petroleum Norge A/S

ABSTRACT An empirical method for the evaluation of capillary pressure data is presented. This method, an extension from Wright and Wooddy (1955), relate water saturation, permeability and capillary pressure in one equation. The method is well suited for computer processing.

Water saturations, as functions of permeability and capillary pressure, are compared with the corresponding predictions from a similar method by Johnson (1987), from the Leverett J-function and from the Caplog method (multilinear regression) used by Alger et al. (1989)

Capillary pressure data from 120 core samples from 6 different reservoirs were used in the comparison.

Based on each methods capability to predict the observed relationship between input parameters and the raw capillary pressure data it was found that the new method was superior to the Leverett J-function in all cases, in general superior to the Caplog method and equal to the Johnson method.

INTRODUCTION

In the evaluation of oil and gas fields the combination of well-log and core analysis data is usually used. One of the most important core analysis data is capillary pressure data. With these data and the hydrocarbon/water contact it is possible to describe the water saturation in the reservoir. However, the log data can be used independently to determine original water saturations. The two methods, water saturations from capillary pressure data and from

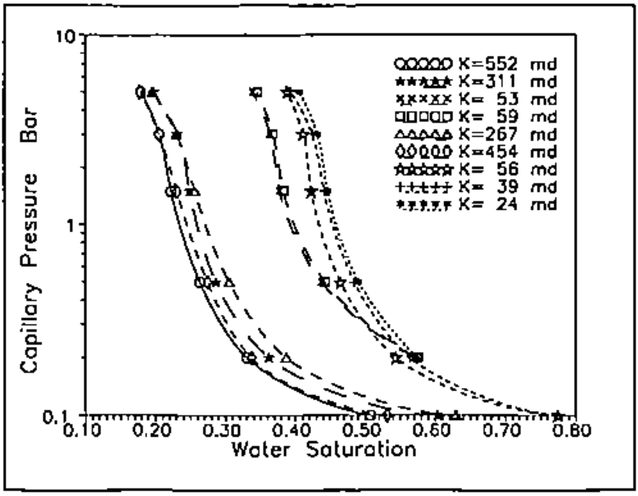

FIGURE 1 Capillary pressure curves determined on samples from well 9.

log data can be compared so as to ensure proper log evaluation.

In Figure 1 different capillary pressure curves determined on samples from the same well, (well 9), are presented. As capillary pressure data are obtained on small core samples that represent an extremely small part of the reservoir, it is necessary to combine all the capillary pressure data to classify a particular reservoir. Since capillary pressure is inversely proportional to the pore radius, it would be expected that the core plug with the highest mean pore radius also would have the highest permeability. It therefore becomes necessary to evaluate the various sets of capillary pressure data with respect to the permeability of the core sample from which they were obtained. From Figure 2 we find that the endpoint water saturation for the well 9 data decreases with increasing permeability.

Methods for correlation of capillary pressure data

Different methods of correlating capillary pressure data for a reservoir exist.

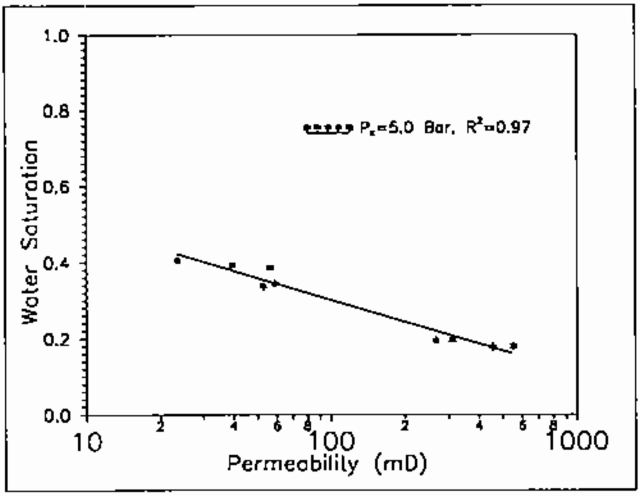

FIGURE 2 Endpoint water saturation versus permeability, well 9.

Leverett Method, J-function

The first method is that proposed by Leverett (1941) wherein a correlation function commonly referred to as the J-function is used.

The J-function correlation term uses the physical properties of the rock and the fluid and is expressed as,

$$J(S_w) = \frac{P_c}{\gamma} \cdot \sqrt{\frac{K}{\phi}} \tag{1}$$

where $J(S_w)$ is experimentally determined as a function of water saturation, S_w.

Alger et al. Method, Caplog

Another method is one proposed by Alger et al. (1989), the Caplog method, an extension of Heseldin (1974). Alger et al. (1989) and Heseldin (1974) chose to relate porosity to bulk volume of hydrocarbon instead of water saturation with a family of parametric

(V_{bh}) curves of constant capillary pressure:

$$V_{bh} = \phi\cdot(1-S_w) \qquad (2)$$

They relate the V_{bh} to capillary pressure and porosity by multilinear regression.

$$V_{bh} = a + b\cdot\ln(P_c) + c\cdot\phi \qquad (3)$$

Alger et al. (1989) have also included permeability in the equation.

$$V_{bh} = a + b\cdot\ln(P_c) + c\cdot\phi + d\cdot\ln(K) \qquad (4)$$

Johnson Method.

Johnson (1987) shows that the relationship between water saturation and permeability on a log/log plot is reasonably linear and could be described by an equation of the form:

$$\ln(S_w) = A\cdot\ln(K) + b \qquad (5)$$

or

$$S_w = B\cdot K^A \text{ where } B = \exp(b) \qquad (6)$$

He found that the lines defining the water saturation/permeability relationship at the various capillary pressure were approximately parallel with varying intercepts. The slopes of the line were averaged to give a constant value. The intercepts decrease monotonically with increasing capillary pressure. Lines of constant slope were then fitted through the centroid of each capillary pressure data set to generate a new set of intercept, B'. A relationship was found between the intercept, B', and the capillary pressure P_C by use of a bi-logarithmic plot of B' versus P_c. A straight line relationship was found of the form:

$$\ln(B') = C\cdot\ln(P_c) + d \qquad (7)$$

or

$$B' = D\cdot P_c^C \text{ where } D = \exp(d) \qquad (8)$$

The final equation using Equation 6 and 8 is

$$S_W = D\cdot P_c^C\cdot K^{A'} \qquad (9)$$

Before the relationship between Sw,K,ϕ and P_c defined in Equation 1,4, and 9 above can be applied in petrophysical analysis the capillary pressure has to be related to height above free water level,

$$h = \frac{P_c(S_w) \cdot \gamma_r}{\Delta\rho \cdot g \cdot \gamma_l} \quad (10)$$

Capillary pressure instead of height above free water level is used in this paper. Using Equation 10, P_c can easily be converted to height above free water level.

The main objective of this study was to evaluate the existing methods for evaluation of capillary pressure data and to develop a new and better method.

This paper first presents the basis of a new method. Results from this method are then validated by comparison with existing methods. Capillary pressure curves have been determined on core plugs in 11 wells, from 6 different North Sea reservoirs, (five sandstone reservoirs and one chalk reservoir), using the porous plate method. Single core holders were applied. 120 capillary pressure curves are used in the comparison of different methods for evaluation of the data. The permeability of the samples is between 0.05 md and 25000 md. The permeability of the core plugs from well 1 is between 0.05 md and 50 md. For the other wells the samples varied with a factor of 10 to 500 from the lowest to the highest permeability. The samples were drained for water using nitrogen and refined oil, increasing the capillary pressure in 4 to 8 steps, depending on the well.

PRESENTATION OF A NEW EVALUATION METHOD

The new method is an extension from Wright and Wooddy (1955). Wright and Wooddy plotted water saturation versus the logarithm of permeability for a constant value of capillary pressure. A straight line could be fitted to the data for each value of capillary pressure and an average capillary pressure curve computed from permeability distribution data for the field. The resulting straight line equation takes the general form of:

$$S_w = A \cdot \ln(K) + B \tag{11}$$

In the Wright and Wooddy method an equation for each capillary pressure is necessary.

In the method by Johnson (1987) a relationship was found between the intercept B and the capillary pressure. The slopes A were averaged. We propose to plot both the slope A and the intercept B against capillary pressure on a log/log plot. Both the slope and the intercept have a straight line relationship in a log/log plot.

$$\ln(A') = C \cdot \ln(P_c) + d \tag{12}$$

and

$$\ln(B') = E \cdot \ln(P_c) + f \tag{13}$$

or

$$A' = D \cdot P_c^C \quad \text{where} \quad D = \exp(d) \tag{14}$$

and

$$B' = F \cdot P_c^E \quad \text{where} \quad F = \exp(f) \tag{15}$$

The final equation has the following relationship:

$$S_w = D \cdot P_c^C \cdot \ln(K) + F \cdot P_c^E \tag{16}$$

COMPARISON OF THE DIFFERENT METHODS

To compare the different methods for evaluation of the capillary pressure data, evaluations of data from well 9 are presented in detail while for the other wells only the regression data for all methods are presented. In Table 1 the rock properties for the samples from well 9 are presented.

Leverett J-function

In Figure 3 the capillary pressure curves from Figure 1, converted to J-function versus water saturation using Equation 1, are plotted on a log/log plot. A relationship was found between the water saturation and the J-function by use of bi-logarithmic plot of S_W versus J. One straight

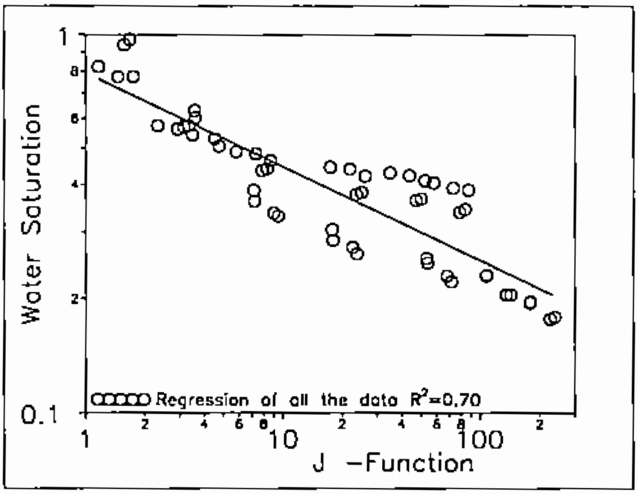

FIGURE 3 The capillary pressure curves from well 9 averaged to Leverett J-function vs. water saturation.

line relationship may be found of the form:

$$\ln(S_w) = A \cdot \ln(J) + b \tag{17}$$

or

$$S_w = J^A \cdot B \quad \text{where} \quad B = \exp(b) \tag{18}$$

TABLE 1-Rock properties for samples from well 9

Sample	*K* *[md]*	*φ* *[fraction]*
1	552	0.245
2	311	0.241
3	53	0.215
4	59	0.212
5	267	0.211
6	454	0.223
7	56	0.186
8	39	0.185
9	24	0.175

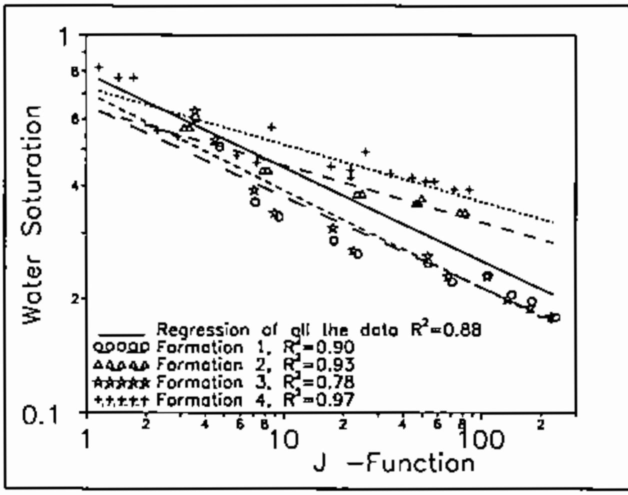

FIGURE 4 The capillary pressure curves from well 9 averaged to Leverett J-function vs. water saturation for each formation.

Using the capillary pressure data from Figure 1 the resulting equation that fits the data is

$$S_w = 0.751 \cdot J^{-0.234} \qquad (19)$$

This equation fits the capillary pressure curves from Figure 1 with a correlation coefficient (R^2) of 0.80 and the standard deviation, σ, of 0.070.

If a J-function is used for each of the 4 different formations in this Brent reservoir the standard deviation is 0.05 and the correlation coefficient (R^2) is 0.88 (Figure 4).

Cap log method

Using the capillary pressure data from Figure 1 evaluated by the Caplog method the resulting equation (Equation 4) that fits the data is,

$$V_{bh} = -0.091 + 0.017 \cdot \ln(P_c) + 0.706 + 0.015 \cdot \ln(K) \qquad (20)$$

having a correlation coefficient (R^2) of 0.92 on S_w.

TABLE 2. Correlation coefficient for different formation in well 9.

Formation	*R^2*
Fm 1	0.90
Fm 2	0.93
Fm 3	0.78
Fm 4	0.97
Total	0.88

Johnson Method

In Figure 5 the capillary pressure data from Figure 1 are evaluated according to the method by Johnson (1987). In Table 3 the slopes, A, the intercepts, B, and the regression coefficient (R^2) using Equation 5 for each P_c are listed. The slope A of the lines in Figure 5 were averaged to give a constant value A' of -0.234. Lines of constant slope were then fitted through the centroid of each capillary pressure data set to generate a new set of intercepts, B', Table 4. The new intercepts B' versus capillary pressure are presented in a log/log plot in Figure 6. A straight line relationship (Equation 8) is found:

$$B' = 1.109 \cdot P_C^{-0.185} \qquad (21)$$

The new intercepts B' and regression coefficients R^2 are presented in Table 5. The final results of the above averaging process is the following relationship (Equation 9):

$$S_W = 1.109 \cdot P_C^{-0.185} \cdot K^{-0.234} \qquad (22)$$

Equation 22 fits the data in Figure 1 with a correlation coefficient (R^2) of 0.92 and a standard deviation (σ) of 0.058 on S_w.

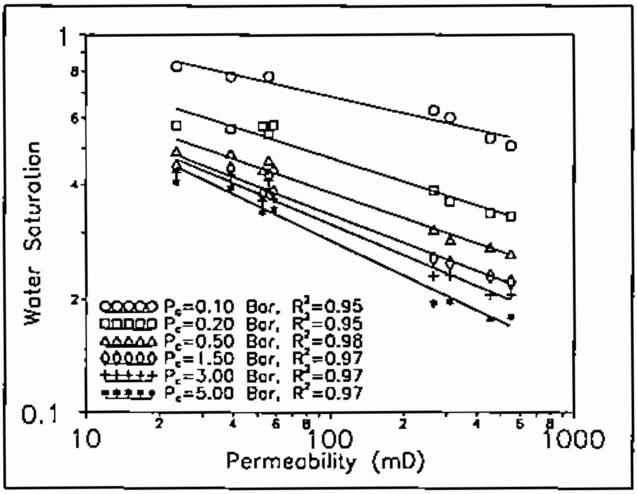

FIGURE 5 P_c derived Sw at different capillary pressure versus permeability, Johnson method.

TABLE 3. Parameters of $S_W = B \cdot K^A$ by the method of Johnson (1987).

P_c [bar]	*A*	*B*	*R^2*
0.1	-0.147	1.349	0.95
0.2	-0.207	1.220	0.95
0.5	-0.222	1.066	0.98
1.5	-0.247	1.044	0.97
3.0	-0.271	1.048	0.97
5.0	-0.307	1.119	0.97

TABLE 4. Averaged slope A' and corresponding intercept B' by the method of Johnson (1987).

P_c [bar]	*A'*	*B'*
0.1	-0.234	1.970
0.2	-0.234	1.370
0.5	-0.234	1.120
1.5	-0.234	0.990
3.0	-0.234	0.940
5.0	-0.234	0.870

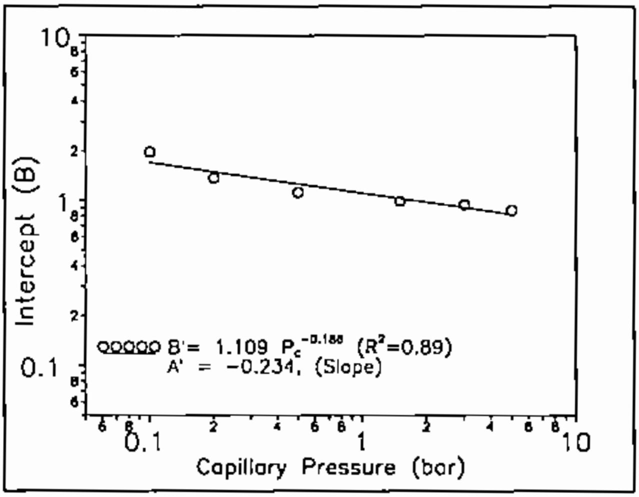

FIGURE 6 Intercept of forced ln(S_w)/ln(K) lines (B') versus Pc.

TABLE 5 A'=averaged slope and B'=1.109 $P_C^{-0.186}$ from the method by Johnson (1987).

P_C [bar]	*A'*	*B'*	*R^2*
0.1	-0.234	1.698	0.85
0.2	-0.234	1.494	0.93
0.5	-0.234	1.261	0.91
1.5	-0.234	1.029	0.98
3.0	-0.234	0.905	0.97
5.0	-0.234	0.823	0.95

The New Method

In Figure 7 the capillary pressure data from Figure 1 are plotted with a linear scale for water saturation and logarithmic scale for permeability. The slopes, the intercepts and the regression coefficients using Equation 11 are listed in Table 6. The absolute values of the slopes and the intercepts decrease with increasing capillary pressure. Both the slopes and the intercepts have a

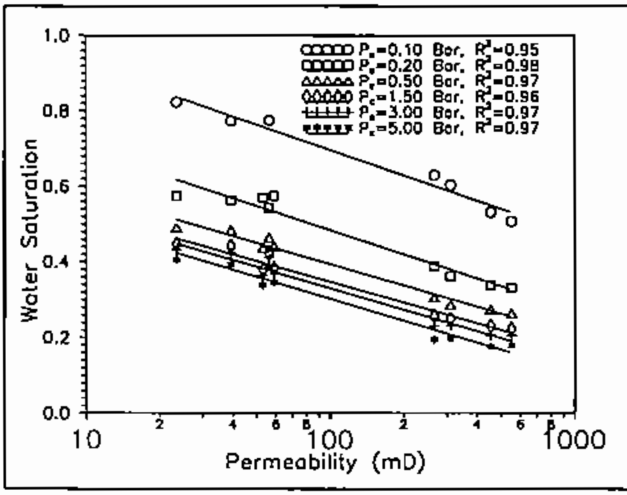

FIGURE 7 P_c derived S_W at different capillary pressures versus permeability, New method.

straight line relationship in a log/log plot, Figure 8. The newintercepts B', the new slopes A' and the regression coefficient R^2 are presented in Table 7. The straight line equation from the slope versus capillary pressure using Equation 14 takes the form

$$A' = 0.085 \cdot P_c^{-0.041} \tag{22}$$

and the straight line equation from the intercept versus capillary pressure (Equation 15), takes the form

$$B' = 0.784 \cdot P_c^{-0.117} \tag{23}$$

The final equation is the following relationship (Equation 16):

$$S_w = 0.085 \cdot P_c^{-0.041} \cdot \ln(K) + 0.784 \cdot P_c^{-0.117} \tag{24}$$

This equation fits the data in Figure 1 with a correlation coefficient, (R^2) of 0.94 and a standard deviation (σ) of 0.051 on S_W.

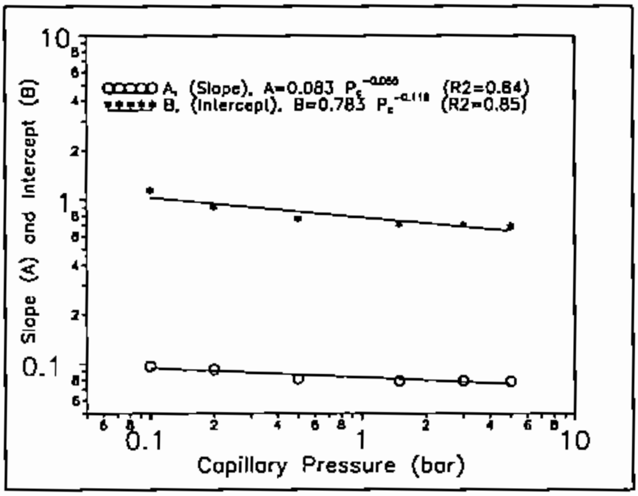

FIGURE 8 Intercept of forced $\ln(S_w)/\ln(K)$ lines (B') versus P_c

TABLE 6 Parameters of $S_w = A \ln(K) + B$

P_c[Bar]	A	B	R^2
0.1	-0.097	1.143	0.95
0.2	-0.093	0.910	0.98
0.5	-0.081	0.768	0.97
1.5	-0.079	0.711	0.97
3.0	-0.079	0.706	0.96
5.0	-0.078	0.687	0.97

TABLE 7 $A' = 0.085 \cdot P_c^{-0.041}$ and $B' = 0.784 \cdot P_c^{-0.117}$

P_c [bar]	A'	B'	R^2
0.1	-0.093	1.026	0.89
0.2	·0.091	0.946	0.94
0.5	-0.087	0.850	0.91
1.5	-0.084	0.748	0.98
3.0	-0.081	0.689	0.97
5.0	-0.080	0.649	0.96

RESULTS AND DISCUSSIONS OF THE DIFFERENT METHODS

11 wells have been evaluated. For each well the water saturations from the capillary pressure measurements were compared with the water saturation using the different evaluation methods (Equation 18;4;9;16). Standard deviation and correlation coefficient from the 4 different evaluation methods presented above are presented in Table 8.

The correlation coefficient from the J-function varied from 0.72 to 0.94, with an average R^2 of 0.84. The correlation coefficient from the method by Alger et al. (1989), the multilinear regression analysis, varied from 0.82 to 0.96 with an average R^2 of 0.89. The correlation coefficient from the method by Johnson (1987) varied from 0.89 to 0.96 with an average R^2 on 0.93. The correlation coefficient from the proposed New Method varied from 0.88 to 0.95 with an average R^2 of 0.93.

The evaluations of the capillary pressure data show that the empirical method described above, (the New Method) above gives better correlation coefficient and standard deviation than the Leverett J-function for all the reservoirs tested.

Except for one well also the method by Johnson (1987) gives better correlation coefficient and standard deviation than the J-function.

TABLE 8 Standard deviation and correlation coefficient from 4 different evaluation method of capillary pressure data from 11 different wells.

					J-function		*Cap log*	*Johnson Method*		*New Method*	
Well	*Number of core*	*Sw Data*	K_{min}; K_{max} (mD)		σ	R^2	R^2	σ	R^2	σ	R^2
1	25	100	0.05	51	0.089	0.72	0.85	0.069	0.91	0.062	0.93
2	10	60	58	8700	0.054	0.87	0.88	0.029	0.96	0.040	0.93
3	10	60	153	12900	0.044	0.91	0.91	0.032	0.95	0.040	0.92
4	10	79	79	12000	0.065	0.86	0.83	0.041	0.94	0.043	0.94
5	10	75	1	10057	0.104	0.84	0.86	0.068	0.89	0.070	0.88
6	10	38	11	586	0.039	0.94	0.96	0.051	0.90	0.037	0.94
7	10	74	5	1521	0.100	0.76	0.89	0.044	0.95	0.045	0.95
8	10	74	183	25000	0.053	0.94	0.82	0.048	0.95	0.052	0.95
9	9	58	24	552	0.070	0.80	0.88	0.058	0.92	0.051	0.94
10	8	48	23	204	0.098	0.77	0.92	0.043	0.91	0.042	0.92
11	10	80	89	1183	0.070	0.83	0.95	0.039	0.96	0.047	0.94

For 3 wells the proposed New Method gives the best correlation coefficient and for 4 other wells the method by Johnson gives the best correlation. For 3 wells the New Method and the method by Johnson give the best correlation coefficient. For the last well the Caplog method gives the best correlation coefficient.

Even if a J-function was used for each formation the evaluation of the J-function did not give better correlation coefficient than the proposed New Method and the method by Johnson (1987).

Evaluation of capillary pressure data by the new method and the method by Johnson (1987) show that the correlation coefficient, R^2, is less sensitive to porosity than the correlation coefficient from the Leverett J-function and the Caplog method.

In the comparison of the different methods all the capillary pressure data were used. In Table 9 the correlation coefficient R^2 for each capillary pressure and evaluation method is listed for well 9. The proposed New Method and the method by Johnson give the best correlation of water saturation estimated from the highest capillary pressure.

TABLE 9 Comparison of correlation coefficients, R^2, vs. P_c (well 9).

P_c Bar]	J-function R^2	Cap-Log R^2	Johnson R^2	New Method R^2
0.1	0.47	0.03	0.85	0.89
0.2	0.79	0.83	0.93	0.94
0.5	0.63	0.57	0.91	0.91
1.5	0.65	0.92	0.98	0.98
3.0	0.39	0.91	0.97	0.97
5.0	0.30	0.82	0.95	0.96

The capillary pressure versus water saturations from two P_c measurements (well 9) compared to the capillary pressure versus water saturation evaluated by the different methods, are presented graphically in Figure 9 and 10. For the highest capillary pressures, S_w evaluated from the method of Johnson (1987), and S_w from the new method are very close to S_w from the capillary pressure experiment. S_w from the Leverett J-function, and from the Caplog method, are not so close to S_w from the capillary pressure experiment. None of the methods give S_w close to the experimental water saturation for low capillary pressure (< 0.2 bar).

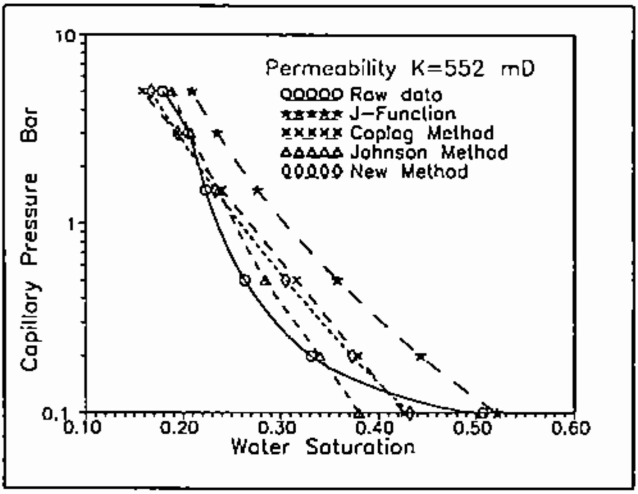

FIGURE 9 Pc measurements compared to P_c vs. S_w evaluated by the different methods.

CONCLUSION

Based on each methods capability to predict the observed relationship between input parameters and the raw capillary pressure data, it was found that the proposed New Method was superior to the Leverett J-function in all cases, in general superior to the Caplog method, and equal to the Johnson method.

Evaluation of capillary pressure data by the alternative method and the method of Johnson (1987) show that the correlation coefficient, R^2, is less sensitive to porosity, than the correlation coefficient from the Leverett J-function and the Caplog method.

The proposed new method and the Johnson method are especially superior to the Caplog method and the J-function for high capillary pressure.

The capillary pressure data should be correlated by both the New Method and the method by Johnson in order to choose the one with the best correlation coefficient.

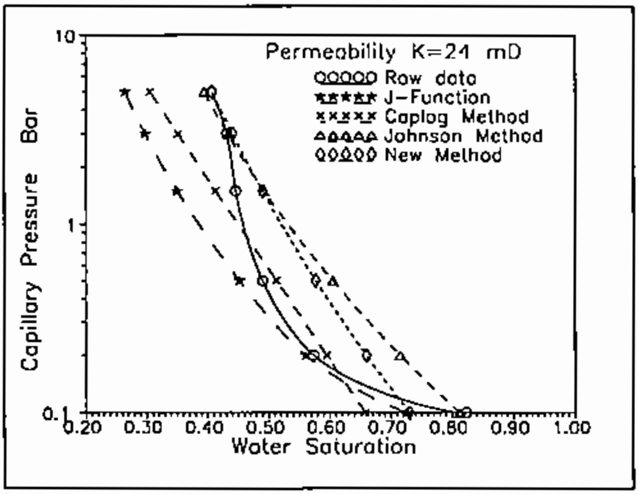

FIGURE 10 Pc measurements compared to P_c vs. S_w evaluated by the different methods.

ACKNOWLEDGEMENTS

I would like to thank Associate Professor Kristofer Kolltveit at the University of Bergen, Norway for his valuable advises. I will also thank Norsk Hydro A/S, Saga Petroleum A/S, Elf Petroleum Norge A/S and GECO PRAKLA A/S for permission to publish this work.

REFERENCES

ALGER, R.P., LUFFEL, D.L. and TRUMAN, R.B. (1989). New Unified Method of Integrating core capillary Pressure Data With Well Logs, *SPE Formation Evaluation* June 1989, 145-152.

HESELDIN, G.M. (1974). A Method of Averaging Capillary Pressure Curves, *Proceedings of 1974 SPWLA Annual Logging Symposium*, June 2-5, paper E.

JOHNSON, A. (1987) Permeability Averaged Capillary Data. A Supplement to Log Analysis in Field Studies. *Proceedings of the SPWLA 28th Annual Logging Symposium*, paper EE.

LEVERETT, M.C. (1941). Capillary Behavior in Porous Solids, *Transactions, AIME* 142, 151-69.

LEVERETT, M.C., LEWIS, W.B., and TRUE, M.E. (1942) Dimensional Studies of Oil-Field Behavior, *Transactions, AIME* 146, 175-93.

WRIGHT, H.T. and WOODDY, L.D. (1955). Formation Evaluation of the Borregas and Seeligson Field, Brooks and Jim Wells Country, Texas. *Symposium of Formation Evaluation, AIME*, October, 1955.

NOMENCLATURE

a,b,c,d,f	Constants
A,B,C,D,E,F	Constants
h	Height above free water level
$J(S_W)$	Leverett capillary pressure function, dimensionless
K	Klinkenberg corrected permeability, md
P_c	Capillary pressure, bar
R^2	Correlation coefficient
S_w	Water saturation, fraction
V_{bh}	Bulk volume hydrocarbon, fraction
$\Delta\rho$	Water/hydrocarbon density difference
ρ_h	Formation hydrocarbon density
σ	Standard deviation
ϕ	Porosity, fraction
γ_l	Interfacial tension between the fluids at laboratory conditions
γ_r	Interfacial tension between the fluids at reservoir conditions