A METHOD OF AVERAGING CAPILLARY PRESSURE CURVES*

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ABSTRACT

Capillary pressure data can be useful to calculate reservoir saturations provided a realistic average capillary pressure curve can be derived for a particular rock type. Since capillary pressure characteristics are known to vary with porosity (or permeability), a mathematical procedure is developed whereby the resulting average curve is a single relationship dependent on that parameter. This average curve is especially useful in evaluating low porosity carbonate reservoirs as well as providing a basis for generating one or more representative capillary pressure curves for reservoir simulation.

INTRODUCTION

Capillary pressure data must be one of the most neglected sources of information for determining reservoir saturations. Many so-called water table anomalies can usually be resolved with the help of capillary pressure data which more often than not has already been measured and filed away. This is not to say that capillary pressures have never been used in a quantitative manner, as they often have been a factor in determining Unit equity in low porosity carbonate reservoirs where the characteristic high resistivities necessary for conventional water saturation calculations are difficult to measure. Typical examples of fields in Western Canada where capillary pressures have been used to calculate reserves and/or equities are:

Oil	Gas
Harmattan East	Jumping Pound West
Harmattan Elkton	Lookout Butte
Homeglen-Rimbey	Rigel
Simonette	Waterton
Sturgeon Lake	Wildcat Hills
Weyburn	

If it is accepted that capillary pressure data can be useful to calculate saturations, why are these applications not more common? One reason must be the difficulty in combining the widely varying shapes of curves to establish a single representative curve for a particular rock type. This paper presents a mathematical procedure to derive a single capillary pressure relationship from which a saturation can be calculated for a given rock type at the appropriate subsea depth; the rock type can be expressed as a continuously varying parameter such as porosity or permeability. This relationship can also be used as a basis for generating one or more representative capillary pressure curves for reservoir simulation.

STATING THE PROBLEM

It is an easy task to average the four capillary pressure curves shown in Figure 1 at high values of capillary pressure

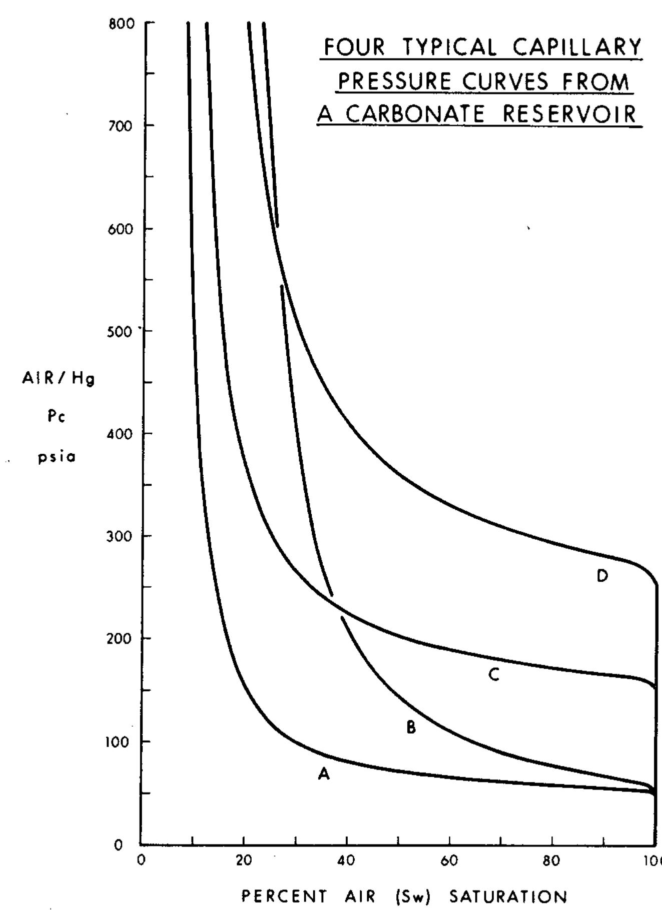

FIGURE 1

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(Pc); likewise it is also easy to derive an average entry pressure at 100 percent air saturation. However, the shape of the average curve between these end points is subject to considerable interpretation and therefore will vary according to the personal preferences of the engineer.

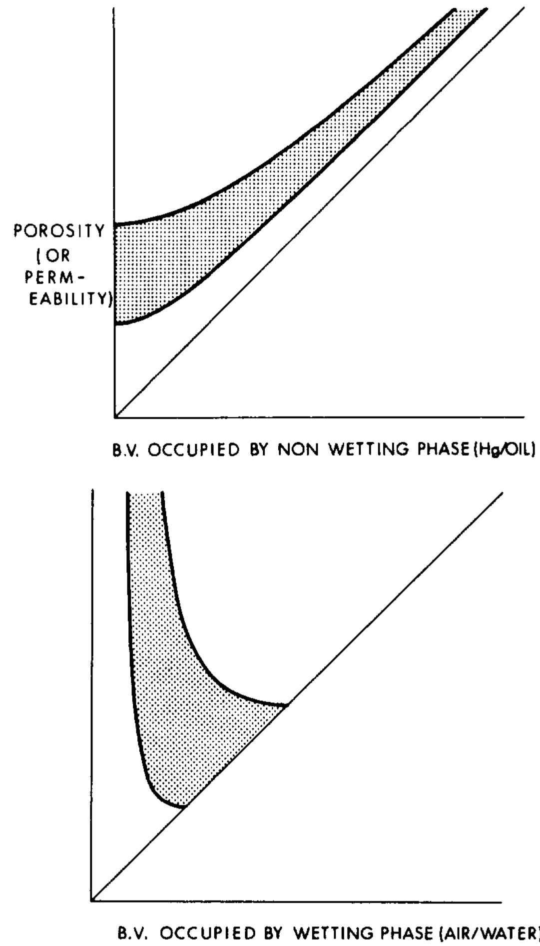
When data varies as much as these four capillary pressure curves, the question always should be posed as to whether an average curve would have any meaning at all. Clearly, the rock depicted in Figure 1 with the highest entry pressure (Curve D) obviously has poorer reservoir potential than the others. Assuming all four curves were measured on essentially the same rock type, then it would be expected that the porosity and/or permeability of this sample would be less than that for the other three. If this poor quality rock does not, for example, contribute to reservoir net pay, then it should not be included in the average curve which is going to be applied to net pay. In this case it is relatively easy to combine the remaining three curves to come up with a composite average.

On the other hand, if all the four curves in Figure 1 are potential reservoir rock and have the expected trend of generally increasing porosity or permeability from the poorest (Curve D) to best (Curve A) capillary pressure characteristics, then the data must be presented as a function of that varying parameter. Although permeability would be the logical choice of the parameter, the resulting average curve could not be applied to a non-cored interval; therefore the more practical choice is porosity (since it can be measured by logging) and this will be used as the "rock quality" parameter for the remainder of this paper.

DISPLAYING CAPILLARY PRESSURE DATA

Including porosity as an additional parameter has increased the dimensions of the analysis by one. Consequently the method of displaying the data is important and the two presented in Figure 2 are recommended. By expressing the saturations in terms of bulk instead of pore volume, the large scatter of saturation values usually observed at low porosities has a minimal effect on the overall trend. Of the two displays, the plot using bulk volume occupied by the non-wetting phase is preferred for the reason that the trend through most reservoir data will have the smallest change of curvature of curvature making it more suitable for curve fitting methods.

Figure 3 shows an example of one of these plots at a specific capillary pressure which is within the range to which the average relationship will be applied. Note that samples which were interpreted as having no mercury injected at the specific capillary pressure are not included in the plot; those observed to be on the zero line acutally had small quantities injected. Also shown on this plot are two least square fit lines to the data; the displaced rectangular hyperbola not only appears to fit the data points better, but also has a lower standard error of estimate than the second order polynomial. However, the type of line chosen to fit the data is immaterial, as the proposed averaging procedure can handle whatever relationship the engineer prefers, albeit a straight line, constant water-filled porosity line or sophisticated curve.



Two Methods Of Plotting Capillary Pressure Data At A Specific Pc (psia)
FIGURE 2

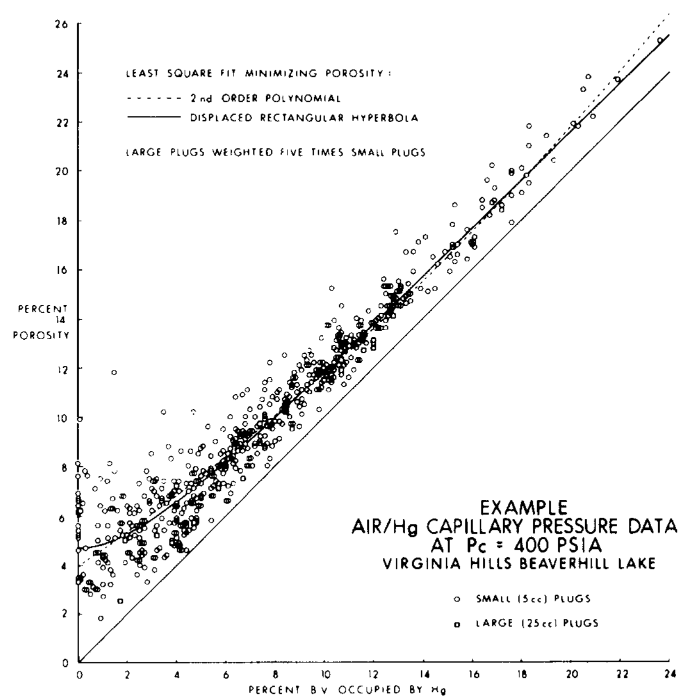


FIGURE 3

Having decided which line to use, the process is repeated for various values of capillary pressure as shown in Figure 4.

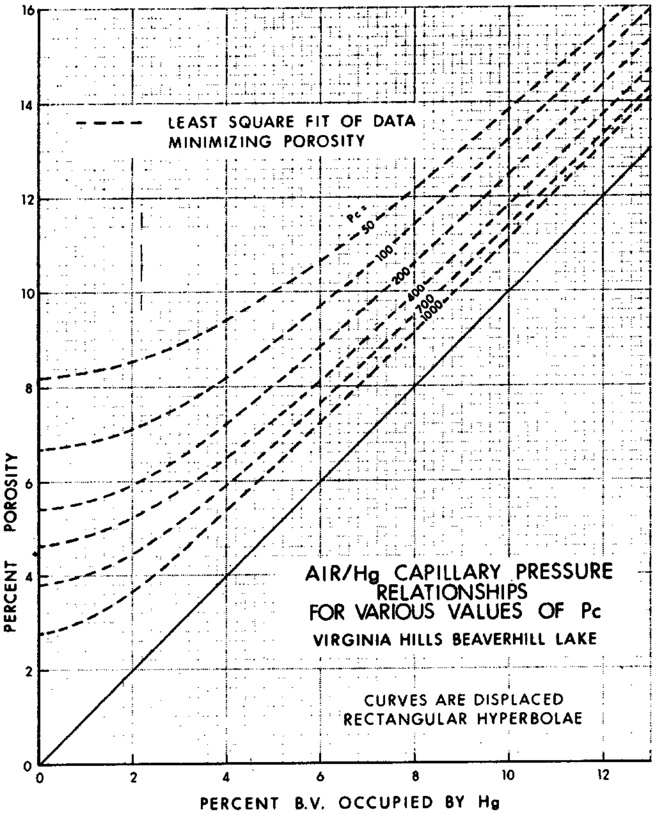


FIGURE 4

Note how these lines contain minor irregularities in shape from one another. For instance, the porosity separation between the Pc = 200 and 400 lines is almost constant throughout the range of bulk volume occupied by mercury whereas elsewhere the separation decreased with increasing bulk volume occupied. These inconsistencies are probably not characteristic of the rock type but are due to non-random sampling of the capillary pressure plugs. The following averaging process effectively smooths out these inconsistencies and presents the series of curves in the form of a single mathematical formula.

THE AVERAGING PROCESS

The equation of a displaced rectangular hyperbola has two constants, one describing the shape of the curve and the other its position. The sum of these two constants happens to be the entry porosity or intercept on the porosity ordinate in Figures 3 and 4. These constants can be plotted against capillary pressure as shown in Figure 5. The proposed averaging process *smooths out the inconsistencies in these constants* by expressing them as a simple function of capillary pressure. From Figure 5 it will be seen that the trends of the constants are essentially linear with the logarithm of capillary pressure. Two least square fits minimizing the deviations of the constants completely define the capillary pressure system.

By using the lines to determine what the two constants should be, a displaced rectangular hyperbola can be drawn for

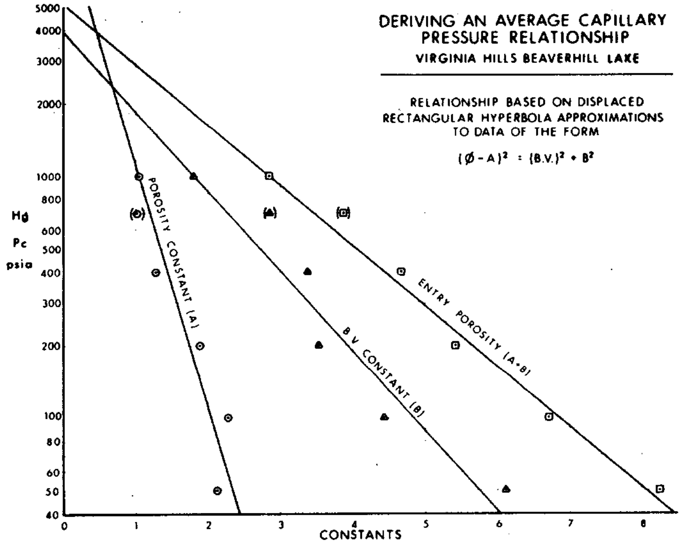


FIGURE 5

any value of capillary pressure. Thus these two lines represent a composite set of average capillary pressure curves for the reservoir. Figure 6 shows the average hyperbolae corresponding to the same capillary pressures at which the original least square fits were obtained. Note how there is now a gradual change in shape and position of the curves from high to low capillary pressure.

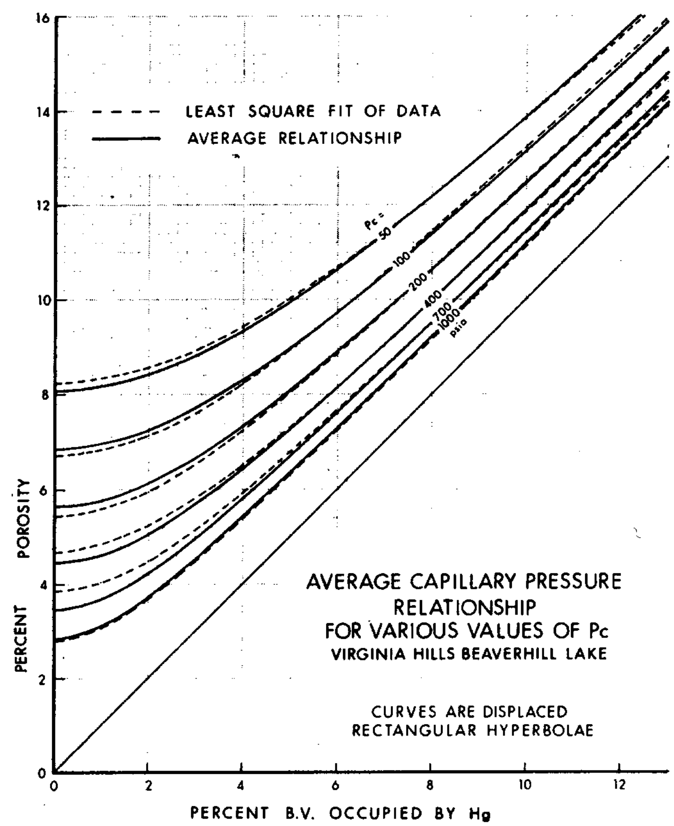


FIGURE 6

SOME COMMENTS ON THE AVERAGE CURVES

The average curves can be more conveniently displayed in the form of percent saturation versus capillary pressure for various porosity values as shown in Figure 7. Note how better porosity rock can still contain hydrocarbons when poorer rock is 100 percent water bearing at the same capillary pressure, i.e. same structural elevation. For example, at a capillary pressure of 100 psia rock less than 6.9 percent porosity is *statistically* 100 percent water-bearing, whereas rock greater than 7.9 percent could qualify for pay using a 60 percent water saturation cut-off criterion.

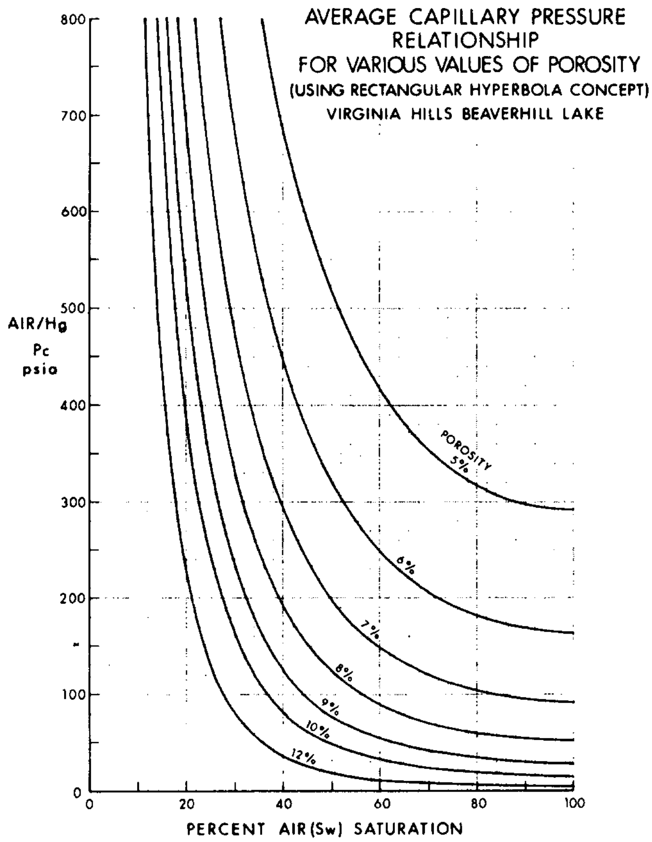


FIGURE 7

Of course an appropriate relationship between capillary pressure and height above the free water table (zero capillary pressure) must be determined. The free water table must also be determined from log, oil base core and/or production test data; the free water table is constant in a common aquifer and should not be confused with the 100 percent water level which will be higher than the free water table and vary with porosity.

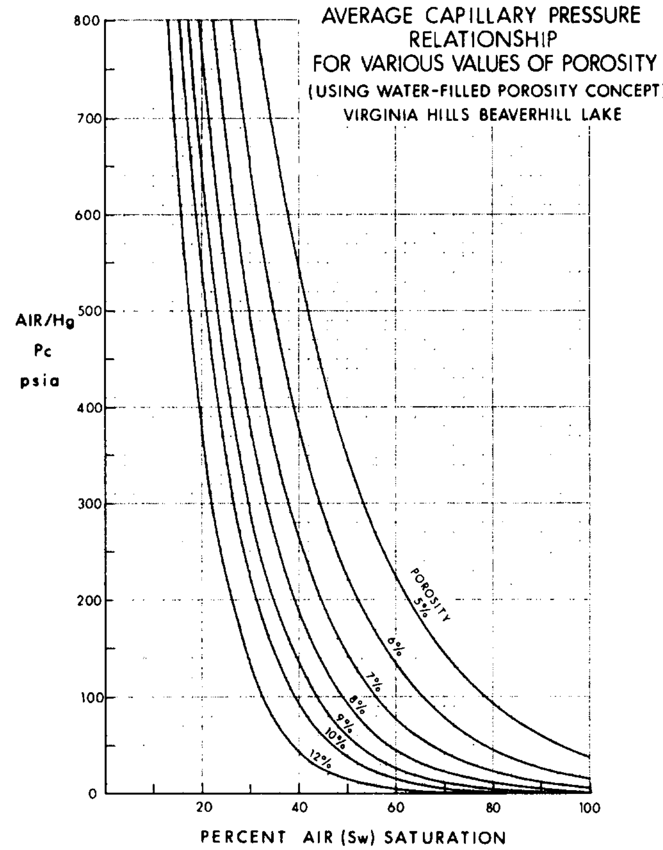


FIGURE 8

This analysis was done using two constants to define the shape of the curves. If the second order polynomial had been used, then there would have been three constants to plot against capillary pressure. The constant water-filled porosity line is a 45-degree line through the data and is defined by only one constant. If the constant water-filled porosity concept had been used, the average curves shown on Figure 8 would be developed using the same data. However, the data in Figure 3 does not appear to fit a 45-degree line which was confirmed by a higher standard error of estimate from the least square fit. Accordingly the curves shown on Figure 8 are not as representative of the reservoir under analysis as the displaced rectangular hyperbolae curves given in Figure 7.

For reservoir simulation purposes, a single representative capillary pressure curve can be obtained using the field average porosity, or alternatively, several curves may be derived for different porosity ranges.

A COMPARISON WITH INDUCTION LOG SATURATIONS

The free water table was chosen in the example reservoir by matching induction log with average capillary pressure saturations in the transition zone. The whole reservoir was then re-evaluated using average capillary pressure saturations and an example well evaluation is given in Table I. The lowest

TABLE I

EXAMPLE WELL EVALUATION COMPARING SW FROM INDUCTION LOG AND AVERAGE CAPILLARY PRESSURE RELATIONSHIP

VIRGINIA HILLS WELL EVALUATION 4-2-65-13W5

SW(RT) FROM 6FF40 INDUCTION ELECTRICAL LOG
SW(Pc) FROM CAPILLARY PRESSURE DATA
RECTANGULAR HYPERBOLA - POROSITY CONSTANT = $4.02214-0.98972 \times LOG_{10}Pc$
BULK VOL CONSTANT = $10.85097-3.01721 \times LOG_{10}Pc$
Pc = 3.30×HEIGHT WATER TABLE 5740 FT SS

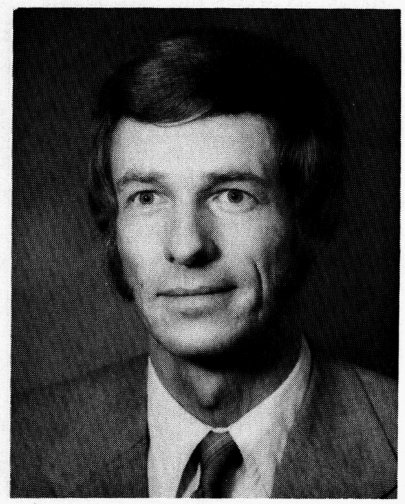
INTERVAL LOGGED	INTERVAL SUBSEA	GROSS FT	MC FT	NET RT	NET Pc	POR PC	PERM MD	IEL RT	SW RT	SW Pc
HOPE CREEK										
9226-9229	5482-5485	3	3	3	3	5.9	27.0	160	19	27
9229-9231	5485-5487	2	-	-	-	1.7	0.8	150	81	100
9231-9235	5487-5491	4	3	3	3	5.1	1.0	115	27	33
9235-9241	5491-5497	6	-	-	-	5.0	1.0	190	22	35
9241-9243	5497-5499	2	2	2	2	8.0	8.0	120	15	19
9243-9248	5499-5504	5	1	1	1	4.0	0.2	100	39	52
MAIN ZONE										
9255-9256	5511-5512	1	1	1	1	11.9	178.0	80	13	12
9259-9264	5515-5520	5	5	5	5	7.6	3.0	45	29	21
9269-9271	5525-5527	2	2	2	2	6.4	7.0	55	31	27
9271-9273	5527-5529	2	2	2	2	15.0	13.0	58	11	9
9273-9277	5529-5533	4	3	3	3	5.0	1.0	70	35	40
9277-9279	5533-5535	2	-	-	-	4.0	0.4	73	47	61
9279-9283	5535-5539	4	4	4	4	12.2	8.2	50	15	12
9291-9304	5547-5560	13	8	8	8	9.6	4.0	50	19	17
9304-9308	5560-5564	4	4	4	4	18.0	14.0	23	14	8
9314-9316	5570-5572	2	2	2	2	9.6	5.0	90	14	18
9321-9323	5577-5579	2	2	2	2	10.4	3.5	58	17	16
9329-9334	5585-5590	5	5	5	5	10.0	2.3	21	33	18
9340-9344	5596-5600	4	4	4	4	9.5	4.0	29	27	20
9344-9348	5600-5604	4	1	1	1	8.3	0.5	75	19	24
9360-9364	5616-5620	4	4	4	4	12.7	45.0	60	13	15
9364-9373	5620-5629	9	9	9	9	14.3	33.0	25	19	13
9373-9381	5629-5637	8	8	8	8	12.5	16.0	30	19	16
9381-9385	5637-5641	4	4	4	4	12.2	13.0	60	13	17
9391-9396	5647-5652	5	5	5	5	9.3	6.0	35	25	25
9396-9402	5652-5658	6	1	-	-	4.0	4.0	25	80	100
9402-9411	5658-5667	9	-	-	-	2.5	0.2	25	100	100
9411-9414	5667-5670	3	3	-	-	6.0	0.8	12	78	62
9420-9431	5676-5687	11	6	6	6	8.0	6.0	28	34	40
SUMMARY	HOPE CREEK			9	9	5.9			22	28
	MAIN ZONE			79	79	10.9			20	17

interval in this well actually produced oil even though is was some 20 feet below the accepted field water level which was determined from logs and drill-stem tests; in this instance the field water level appears to have been based on the 100 percent water level for rock of lower porosity. Note how the capillary pressures confirm this pay as well as effectively match the remaining saturation values within the accuracy of the induction log and the statistical variation of the average capillary pressure curves. As would be expected the lower porosity and tighter rock have higher water saturations by both measurements.

CONCLUSIONS

A procedure for averaging capillary pressure curves has been developed. Minor water level anomalies in an example reservoir can be resolved using the derived average capillary pressure curves. The agreement between water saturations calculated by two independent methods gives confidence in both the induction log values as well as those derived from capillary pressures. The average curves can also be used to represent typical capillary pressure characteristics in reservoir simulation.

ABOUT THE AUTHOR



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