OIL, GAS AND WATER SATURATIONS CALCULATED AS SEPARATE ENTITIES FROM DENSITY, NEUTRON AND RESISTIVITY LOGS

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ABSTRACT

A thorough analysis of a standard suite of open-hole logs can yield a quantitative assessment of oil, gas and water saturations. This is important information when all three fluids exist intermingled within a reservoir. Porosity, together with fluid saturations, both in the flushed zone and uninvaded zone, can be evaluated. Analytical approaches were developed that are extensions of conventional log analysis methodologies.

The analysis methodology requires as a minimum a common modern logging suite of a density log, a neutron log and an appropriate resistivity logging suite that will provide values of uninvaded zone resistivity, flushed tone resistivity, and invasion diameter. A good understanding of the petrophysical properties of the rock matrix is essential.

Interpretation is based on established logging tool responses and relationships, some of which have been routinely ignored or approximated in conventional log analysis. In particular, the depth of invasion determined from the resistivity logs, the neutron log and density log radial geometrical factors and the neutron excavation affect are accounted for and integrated into the analysis.

Two methods were developed. The first method employs a step-wise iterative logic. After flushed zone and uninvaded zone water saturations are conventionally determined, an invasion profile is assumed which will specify how the fluid saturations individually influence the density and neutron logs. The interpreter can choose any one of a series of possible invasion profiles. A constrained solution for gas and oil saturations is then made that is compatible with the separate response equations for the density and neutron logs. The other, more computationally intensive method entails the simultaneous solution of a set of linear and nonlinear equations, including the tool response and material balance equations, using numerical analysis techniques.

Error analysis was used as an interpretational aid to assess the uncertainties of the computed saturations.

Examples are presented from reservoirs in the Texas Panhandle and Louisiana. Good agreements exist with log-determined fluid saturations, core analysis data and production information.

INTRODUCTION

Two log analysis methods were developed to quantify as separate entities, the volumes of oil, gas and water. The first fluid saturation method employs a stepwise iterative logic, similar to most common log analysis procedures. Another approach was developed entailing the solution of a set of simultaneous linear and non-linear equations, specifically the tool response and material balance equations. The methodologies have been applied to field situations and the results compare favorably with core and production data.

Hydrocarbon reservoirs can contain and produce of oil, gas and water simultaneously, the quantities of each being measurable at the surface. However, conventional log analysis only attempts to quantify an in situ water saturation while the hydrocarbon phase is often classified singularly as either oil or gas. In most cases this is sufficient to describe the distribution of fluids in the reservoir. However, in some reservoirs, oil, gas and water occur together. This would be the case of a gas cap expanding into an oil column. Under suitable reservoir conditions, and with a minimum of a conventional modern logging suite of a density log, neutron log and appropriate resistivity logs it is possible to make a quantitative assessment of all three fluid phases.

TOOL RESPONSES

Consider a hypothetical situation where both the density log and neutron log measure only the undisturbed part of the formation. For the density log, the conventional tool response equation is:

$$\rho_{bv} = \phi \bullet \rho_f + (1-\phi) \bullet \rho_{ma} \qquad [1]$$

where:

$$\rho_f = S_w \bullet \rho_w + S_o \bullet \rho_o + S_g \bullet \rho_g \qquad [2]$$

Similarly for the neutron log, the response equation is:

$$\phi_{Nv} = \phi \bullet HI_f + (1-\phi) \bullet HI_{ma} - \Delta\phi_{Nex} \qquad [3]$$

where the hydrogen index of the formation fluid is:

$$HI_f = S_w \bullet HI_w + S_o \bullet HI_o + S_g \bullet HI_g \qquad [4]$$

and the neutron excavation effect (Segesman and Liu, 1971) is:

$$\Delta\phi_{ex} = K \bullet \left(2\phi^2 \bullet HI_f + 0.04\phi\right) \bullet \left(1 - HI_f\right) \qquad [5]$$

and where K is a constant dependent upon lithology.

For cases where the logging tool matrix setting matches the formation lithology, then $HI_{ma} = 0$. It is also assumed that the sum of the three fluid phases is unity:

$$S_w + S_o + S_g = 1 \qquad [6]$$

If at this point the oil saturation is zero and the matrix and fluid properties are known, it is mathematically possible to solve for ϕ, S_g and S_w. This solution would be similar to what is done graphically in charts such as CP-5 (Schlumberger Log Interpretation Charts, 1988). Solutions for several reservoir pressures and temperatures are typically present.

Assuming a typical solution for water saturation using the Archie equation:

$$S_w = \left[\frac{a\phi^{-m} \bullet R_{mf}}{R_t}\right]^{1/n} \qquad [7]$$

when R_w and R_t are known, there would be sufficient data to solve for ϕ, S_w, S_o and S_g. It is also assumed that *a*, *m*, and *n* are known.

Similarly, in the hypothetical situation where the density and neutron logs only measured the flushed zone, there would be a set of equations corresponding to equations 1-7:

$$\rho_{bx} = \phi \bullet \rho_{fx} + (1-\phi) \bullet \rho_{ma} \qquad [8]$$

$$\rho_{fx} = S_{xo} \bullet \rho_{mf} + S_{ox} \bullet \rho_o + S_{gx} \bullet \rho_g \qquad [9]$$

$$\phi_{Nx} = \phi \bullet HI_{fx} + (1-\phi) \bullet HI_{ma} - \Delta\phi_{exx} \qquad [10]$$

$$HI_{fx} = I \bullet S_{xo} \bullet HI_{mf} + S_{ox} \bullet HI_o + S_{gx} \bullet HI_g \qquad [11]$$

$$\Delta\phi_{exx} = K \bullet \left(2\phi^2 \bullet HI_{fx} + 0.04\phi\right) \bullet \left(1 - HI_{fx}\right) \qquad [12]$$

$$S_{xo} + S_{ox} + S_{gx} = 1 \qquad [13]$$

$$S_{xo} = \left[\frac{a\phi^{-m} \bullet R_{mf}}{R_t} \right]^{1/n} \quad [14]$$

Unfortunately, neither of the two previously described situations seldom exist. It is more common that either or both of the nuclear measurements are influenced by both the flushed (and/or invaded zone) and the undisturbed zone.

Investigations by Sherman and Locke (1975) provided quantitative values regarding the depth of investigations of different types of density and neutron logging tools. They experimentally derived J-factor profiles of the relative influence of the flushed and undisturbed zone of a formation. Their experimental evidence was based upon step-function invasion profiles and included an assessment of the effect that porosity has upon the logging sondes' depth of investigation.

Using the J factor for the density tool it is possible to relate the log measured bulk density to that of the flushed zone and the undisturbed zone by:

$$\rho_b = J_D \bullet \rho_{bx} + (1 - J_D) \bullet \rho_{bv} \quad [15]$$

A similar expression follows for the neutron log:

$$\phi_N = J_N \bullet \phi_{Nx} + (1 - J_N) \bullet \rho_{Nv} \quad [16]$$

When an appropriate resistivity log suite is available, "Tornado Charts" can be used to estimate the diameter of invasion, and subsequently the J Factors. In both cases a step function invasion profile is assumed.

The equations relating all tool responses and reservoir properties are now contained in equations 1 through 16. After consolidation into ten effective equations, there are eleven unknown variables: ϕ, S_w, S_o, S_g, S_{xo}, S_{ox}, S_{gx}, P_{bx}, P_{bv}, ϕ_N and ϕ_N. Consequently, without additional information or constraints there is not a unique solution for the unknown variables.

Frequently, it is possible to assume that the oil saturation in both the flushed and virgin zone is equal. Also, an independent measure of porosity may be obtained with a sonic log. Under these or similar conditions, a unique solution is possible.

For the purpose of explaining one of the methodologies, another perspective of the tool responses and reservoir properties is now taken. Expressing the density response in terms of the average fluid properties that the tool would be measuring:

$$\rho_b = \phi \bullet \rho_{fd} + (1 - \phi) \bullet \rho_{ma} \quad [17]$$

where:

$$\rho_{fd} = S_{xd} \bullet \rho_w + S_{od} \bullet \rho_0 + S_{gd} \bullet \rho_g \quad [18]$$

For this discussion, it will be assumed that ρ_w is equal to mud filtrate density, ρ_{mf}.

Similarly for the neutron:

$$\phi_N = \phi \bullet HI_{fn} + (1 - \phi) \bullet HI_{ma} - \Delta\phi_{exn} \quad [19]$$

$$HI_{fn} = S_{xnd} \bullet HI_w + S_{on} \bullet HI_0 + S_{gn} \bullet HI_g \quad [20]$$

$$\Delta\phi_{exn} = K \bullet (2\phi^2 \bullet HI_{fn} + 0.04\phi) \bullet (1 - HI_{fn}) \quad [21]$$

The fluid constraints become:

$$S_{rd} + S_{od} + S_{gd} = 1 \quad [22]$$

and

$$S_{xn} + S_{on} + S_{gn} = 1 \quad [23]$$

Assuming a depth of investigation for the density log, it should be possible to relate S_{xd} (water saturation seen by the density tool) to S_{xo}, and a fluid invasion profile:

S_{xd} = f (S_{xo} , S_w , Invasion Profile) [24]

Similarly for the neutron:

S_{xn} = f (S_{xo} , S_w , Invasion Profile) [25]

SOLUTION METHODOLOGIES

Iterative Method

The first method that was developed to attempt a three-phase solution uses a step-wise logic with some iterations involved. This methodology could be carried out by hand but was designed and implemented as a computerized solution.

While the approach is naturally more accurate for clean formations of known lithology, it can be applied to shaley formations.

The steps for this solution are as follows:

1. Convert the neutron porosity using the appropriate formation matrix and correct for clay effects when necessary.
2. Compute a density porosity, ϕ_D, using the appropriate formation matrix and correct for clay effects when necessary.
3. Compute an initial estimate of gas saturation (S_{ge}) using a numerical solution equivalent to Schlumberger's Chart CP-5. Reservoir pressure and temperature are required. An initial estimate of porosity is also computed in this step.
4. Compute R_t and D_i using "Tornado" chart type solutions.
5. Compute S_w and S_{xo} using an appropriate water saturation equation and inputs of R_{xo} , R_t and porosity from step 3. When no R_{xo} device is available, or the R_{xo} readings are questionable, a relationship between S_{xo} and S_w can be used, such as: $S_{xo} = S_w^{\rho}$ [26]
6. Make an initial estimate of oil saturation (S_{oe}) in the flushed zone from: $S_{oe} = 1 - S_{xo} - S_{ge}$ [27]
7. An invasion profile model is chosen from the following possibilities:
   - Step function
   - Linear
   - Logarithmic
   - Ultra deep invasion
   - No invasion

   Based upon the invasion profile model chosen, D_i , S_{xo} , and S_w , compute S_{xd} and S_{xn} . The computation considers that the density tool's depth of investigation is within four inches from the borehole wall and the neutron's volume of investigation is within ten inches.
8. Using the initial estimate of oil saturation (S_{oe}) along with S_{xd} from step 7, compute a fluid density seen by the density log using equation 18. where:

   $S_{od} = S_{oe}$

   and

   $S_{gd} = 1 - S_{oe} - S_{xd}$
9. Compute a density porosity using the fluid density from step 8. Correct for clay effects when necessary.
10. Using the porosity computed in step 9, solve for S_{on} and S_{gn} using equations 19, 20, 21 and 23. This step requires an initial estimation of the excavation effect in equation 21. After a first computation of S_{on} and S_{gn} , an iteration is made in the excavation effect computation and subsequently S_{on} and S_{gn} . At this point S_{on} is compared with S_{od} . If S_{on} is greater than S_{od} then the solution is

considered as possible. This would be an essential constraint for a water based drilling fluid. If S_{on} is less than S_{od} then the program returns to step 6 where S_{on} is used as the initial estimate of oil saturation for the density log. Steps 6 through 10 are repeated until the test condition is satisfied.

SIMULTANEOUS EQUATIONS METHOD

A second approach for the three-phase solution is based upon the simultaneous solution of equations 1 through 16. As previously discussed, a unique solution is possible when an additional constraint is made. The constraint that was implemented was that oil saturations in the flushed and undisturbed zones were equal.

$$S_{ox} = S_o \qquad [28]$$

Consequently, this method applies to cases where gas is the primary hydrocarbon phase. The steps for this approach are:

1. Compute R_t and D_i using "Tornado" Chart type solutions.
2. Compute J Factors for the density and neutron logs. A numerical solution was formulated from published graphical data.
3. Solve simultaneously for ϕ, S_w, S_o, S_g, S_{xo}, $S_{gx}\rho_{bx}$, ρ_{bv}, ϕ_{Nx} and ϕ_{Nv}, using equations 1 through 16. For this step, a commercially available mathematical package, which includes a routine to find the root of a system of simultaneous non-linear equations, was linked to an industry standard log analysis software package.

EXAMPLES

Brown Dolomite, Panhandle Field of Texas

The Brown Dolomite of the Panhandle Field of Texas had conditions suitable for the application of the methodologies. Lithology is uniformly dolomite with little or no clay. Porosities are often above 20% and the reservoir pressure is below 50 psig.

Figure 1 shows the results of the simultaneous equation method for a Brown Dolomite well in a gas producing area of the field. No core data was available for this well, but cores from three offset wells in the area had average oil saturations ranging from 9 to 16%. Average computed oil saturation for this well is 9%, in agreement with the closest offset cored well.

	Average ϕ	Average S_o
Log Analysis	0.18	0.09
Closest Offset Well Core Analysis	0.13	0.09

In making the log averages, intervals were excluded if log porosity was less than 10%, if there was any indication of hole washout as indicated by a caliper or there was any presence of clay as indicated by the gamma ray log.

Pettit Limestone, Black Lake Field, Natchitoches Parish, Louisiana

The lithology is limestone and clay free except for the top and bottom of the reservoir. No core data exists on any wells with sufficient modern log data, but there is an abundance of core data on older wells.

Original field fluid contacts were fairly uniform with a gas/oil contact at 7835 ft. subsea and an oil/water contact at 7870 ft. subsea. Core data from offset wells indicated consistent oil saturation (frequently 20-30%) below the oil/water contact. The core analysis also detected the presence of small amounts of oil in the gas column.

Previous production has decreased the reservoir pressure considerably and current well behavior indicates that gas has expanded into the oil zone and a liquid hydrocarbon phase has developed in the gas column.

Figure 2 shows the results of the iterative method for a recent well. The original gas/oil contact and oil/water contacts are respectively at 8062 ft. and 8098 ft. log depths. Although quantitative confirmation is not available, the original gas/oil contact can easily be seen. The analysis shows some gas below the original gas/oil contact and significant oil saturations in the gas column. The residual oil interval below the oil/water contact is seen in the analysis.

ERROR ANALYSIS

Error analysis methods as described by Freedman and Ausburn (1985) were applied to quantify the uncertainties of the computed saturations. In particular, the uncertainty in oil saturations computed in the Brown Dolomite example was analyzed.

In the Brown Dolomite example, invasion was deep and both density and neutron logs were, for all practical purposes, reading entirely in the flushed zone. The computation of oil saturation is then essentially computed by subtracting the values of invaded zone water saturation and gas saturation from unity:

$$S_o = 1 - S_{xo} - S_{gx} \qquad [29]$$

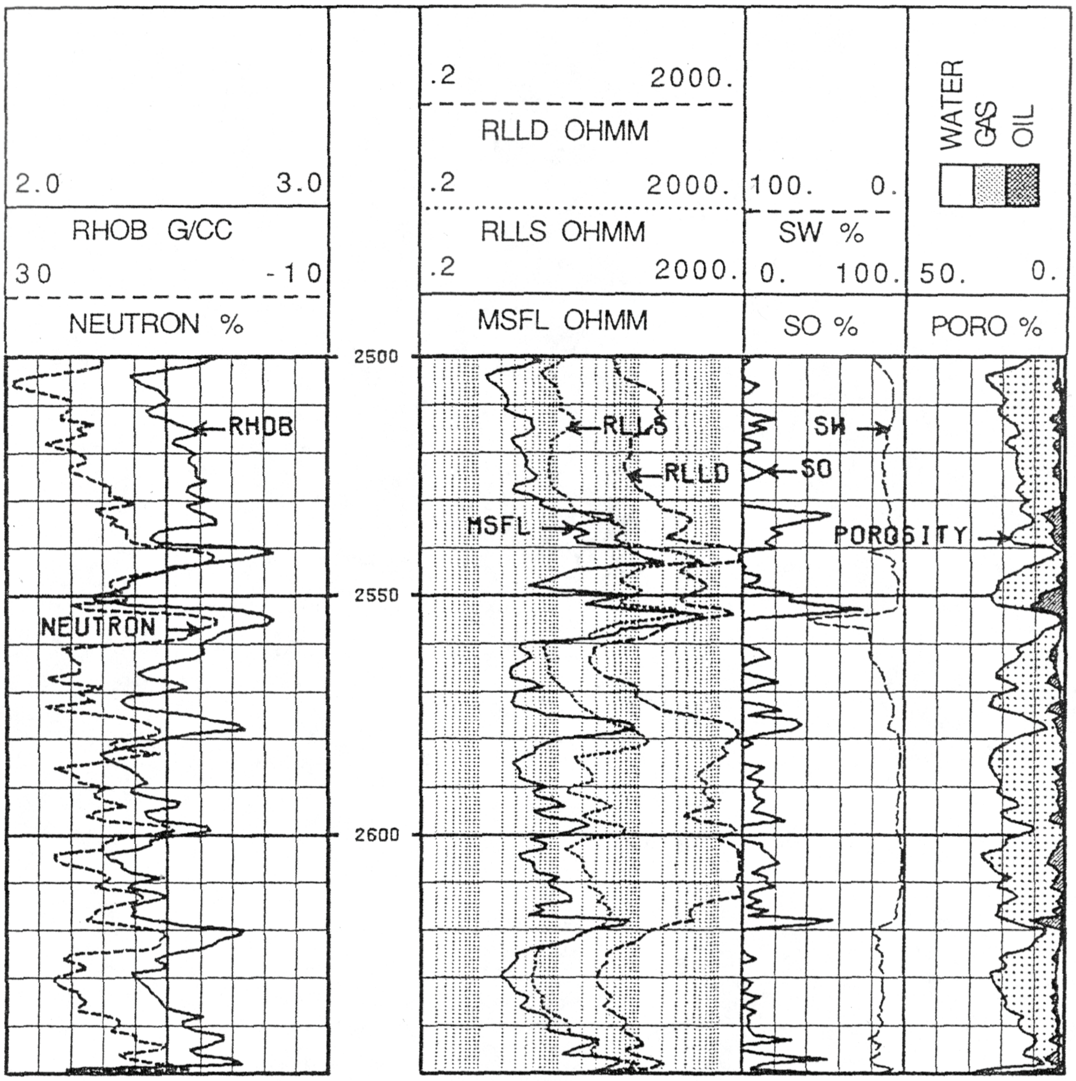

Figure1: *Brown Dolomite Example*

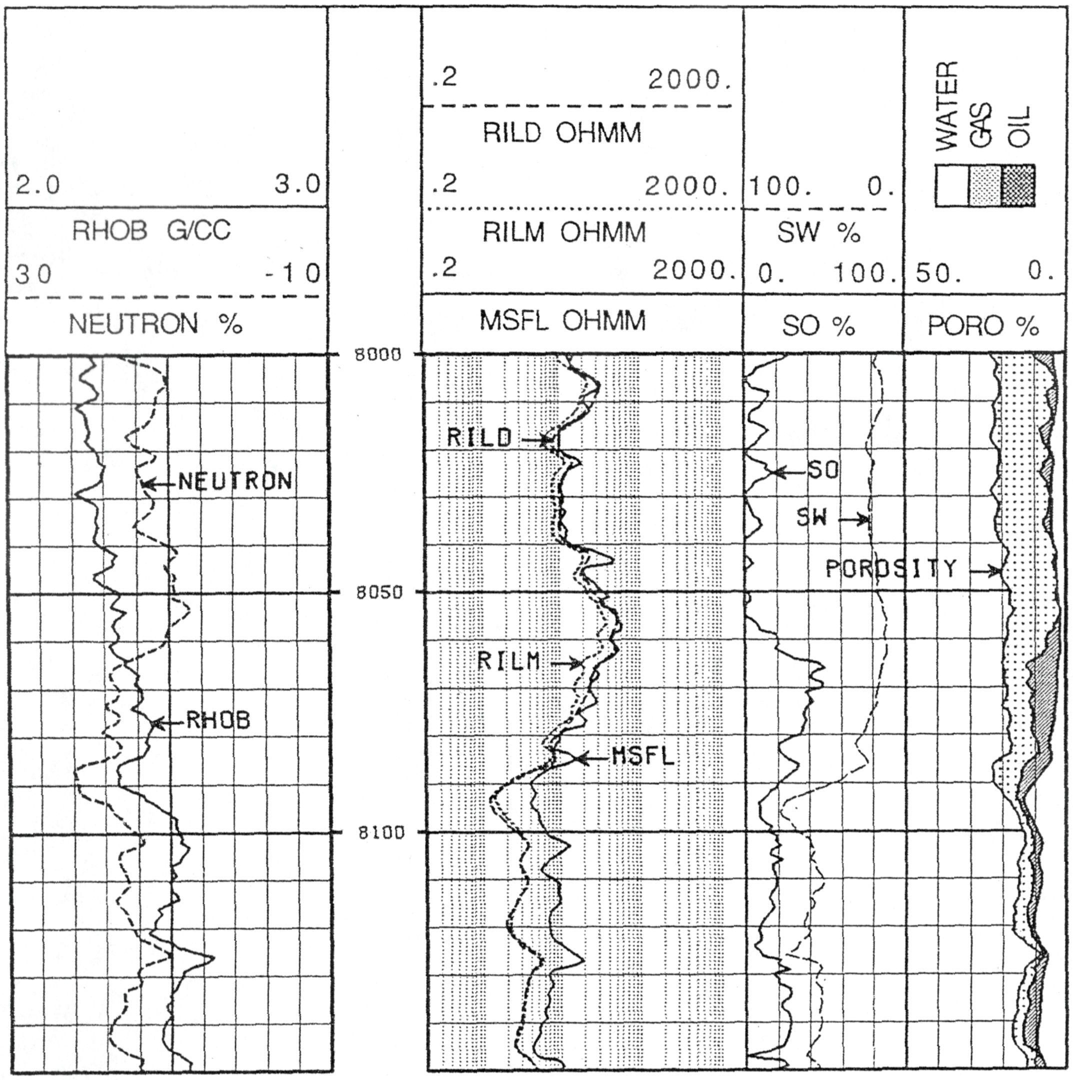

Figure 2: *Pettit Limestone Example*

Consequently, the uncertainty in S_o can then be expressed by:

$$(\sigma\, S_o)^2 = (\sigma\, S_{gx})^2 + (\sigma\, S_{xo})^2 \qquad [30]$$

For the Archie equation, the uncertainty in S_{xo} is expressed by:

$$\sigma_{S_{xo}}^2 = \left(\frac{\partial S_{xo}}{\partial a}\right)^2 \bullet \sigma_a^2 + \left(\frac{\partial S_{xo}}{\partial R_{mf}}\right)^2 \bullet \sigma_{R_{mf}}^2 + \left(\frac{\partial S_{xo}}{\partial R_{xo}}\right)^2 \bullet \sigma_{Rxo}^2 + \left(\frac{\partial S_{xo}}{\partial \phi}\right)^2 \bullet \sigma_\phi^2 + \left(\frac{\partial S_{xo}}{\partial m}\right)^2 \bullet \sigma_m^2 + \left(\frac{\partial S_{xo}}{\partial n}\right)^2 \bullet \sigma_n^2 \qquad [31]$$

where:

$$\frac{\partial S_{xo}}{\partial a} = \frac{1}{na} S_{xo} \quad [32]$$

$$\frac{\partial S_{xo}}{\partial R_{mf}} = \frac{1}{nR_{mf}} S_{xo} \quad [33]$$

$$\frac{\partial S_{xo}}{\partial R_{xo}} = \frac{-1}{nR_{xo}} S_{xo} \quad [34]$$

$$\frac{\partial S_{xo}}{\partial \phi} = \frac{-m}{n\phi} S_{xo} \quad [35]$$

$$\frac{\partial S_{xo}}{\partial m} = \frac{-\ln(\phi)}{n} S_{xo} \quad [36]$$

$$\frac{\partial S_{xo}}{\partial n} = \frac{-\ln(S_{xo})}{n} S_{xo} \quad [37]$$

To similarly compute the uncertainty in S_{gx}, an equation relating S_{gx} to its influencing variables is needed. As invasion is deep, a chart CP-5 type solution, such as the one used to initially estimate gas saturations in the iterative method should be adequate. For the reservoir conditions found in the Brown Dolomite, gas saturation as computed by the iterative method is:

$$S_{gx} = 0.87\left(\frac{\phi_D - \phi_N}{\phi_N}\right)^{1.95} + 0.03 \quad [38]$$

The uncertainty is expressed by:

$$(\sigma S_{gx})^2 = \left(\frac{\partial S_{gx}}{\partial \phi_N}\right)^2 \bullet (\sigma \phi_N)^2 + \left(\frac{\partial S_{gx}}{\partial \phi_D}\right)^2 \bullet (\sigma \phi_D)^2 \quad [39]$$

where:

$$\frac{\partial S_{gx}}{\partial \phi_N} = -1.6965\left(\frac{\phi_D - \phi_N}{\phi_N}\right)^{0.95} \bullet \frac{1}{\phi_N} \quad [40]$$

$$\frac{\partial S_{gx}}{\partial \phi_D} = 1.6965\left(\frac{\phi_D - \phi_N}{\phi_N}\right)^{0.95} \bullet \frac{\phi_N}{\phi_D} \quad [41]$$

Using the above equations, the uncertainty in S_o was computed using the following estimated input uncertainties:

$\sigma R_{mf} = \pm 0.10 R_{mf}$ (10% error in R_{mf})

$\sigma R_{xo} = \pm 0.10 R_{xo}$ (10% error in R_{xo})

$\sigma\phi = \pm 0.01$ (1 porosity unit)

$\sigma\phi_D = \pm 0.01$ (1 porosity unit)

$\sigma\phi_N = \pm 0.01$ (1 porosity unit)

$\sigma m = \pm 0.05$ (2.5% error for m=2)

$\sigma n = \pm 0.05$ (2.5% error for n=2)

$\sigma a = \pm 0.025$ (2.5% error for a=1)

Figure 3 shows the computed uncertainties plotted versus porosity. The average uncertainty in oil saturation is .08 PV (pore volume) of oil and decreases at higher porosities where it approaches .05 PV. In the computation of the average oil saturation for this well, intervals where porosities were less than 10% were excluded.

One conclusion from the error analysis for this example is that, on a foot-by-foot basis, the computed oil saturations have an uncertainty approximately equal to the computed values themselves. However, the computations made for this well and similar wells in the area suggested that in looking at averages over the Brown Dolomite, meaningful results were obtained. These multi-well results were supported by core analysis in the study area analyzed.

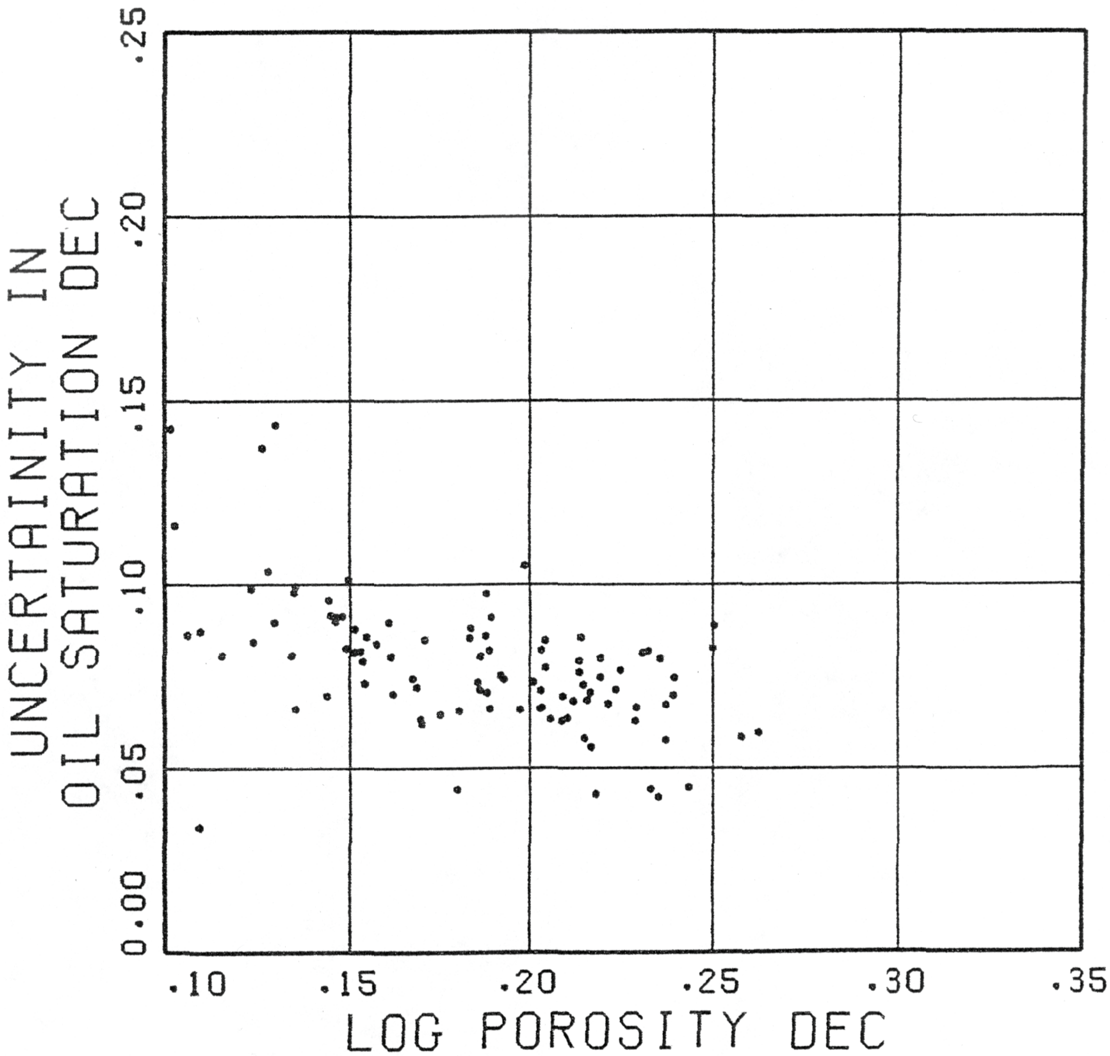

Figure 3: *Error Analysis Results for Brown Dolomite Example*

CONCLUSIONS

A thorough analysis of a standard suite of open-hole logs can yield a quantitative assessment of oil, gas and water saturations.

Two methods were developed to quantify as separate entities, the volumes of oil, gas and water. The methods are based on conventional log response equations that take into consideration the invasion profile, the neutron excavation effect and the depth of investigation of density and neutron logs.

The methods have been applied to field situations where the petrophysical properties of the reservoir were adequately understood. The analyses gave meaningful results that compared favorably with core and production data.

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NOMENCLATURE

a	Constant in Archie equation for determination of formation factor
D_i	Diameter of fluid invasion
HI_f	Apparent hydrogen index of the undisturbed reservoir fluid
HI_{ma}	Apparent hydrogen index of the formation matrix
HI_w	Apparent hydrogen index of the undisturbed formation water
HI_o	Apparent hydrogen index of oil at reservoir conditions
HI_g	Apparent hydrogen index of gas at reservoir conditions
HI_{fx}	Apparent hydrogen index of fluids in the flushed zone
HI_{mf}	Apparent hydrogen index of water in the flushed zone
HI_{fn}	Apparent average hydrogen index of fluids measured by the neutron log in the case where its depth of investigation includes both the flushed zone and the undisturbed formation
J_D	Geometrical factor giving fractional response of density log due to the flushed zone
J_N	Geometrical factor giving fractional response of neutron log due to the flushed zone
K	Matrix dependent constant used in neutron excavation effect correction
m	Porosity exponent in the Archie equation
n	Saturation exponent in the Archie equation
p	Exponent in empirical relationship to determine S_{xo} from S_w
R_w	Formation water resistivity
R_t	True formation resistivity
R_{mf}	Resistivity of mud filtrate in flushed zone
R_{xo}	Formation resistivity in flushed zone
S_w	Water saturation of fluid in the undisturbed formation
S_o	Oil saturation in the undisturbed formation
S_g	Gas saturation in undisturbed formation
S_{xo}	Water saturation in the flushed zone
S_{ox}	Oil saturation in the flushed zone
S_{gx}	Gas saturation in the flushed zone
S_{xd}	Average water saturation measured by the density log
S_{od}	Average oil saturation measured by the density log
S_{ge}	Gas saturation estimated from chart CP-5
S_{gd}	Average gas saturation measured by the density log
S_{xn}	Average water saturation measured by the neutron log
S_{on}	Average oil saturation measured by the neutron log
S_{gn}	Average gas saturation measured by the neutron log
S_{oe}	Estimated oil saturation
ϕ	Formation porosity
ϕ_N	Neutron porosity
ϕ_{Nv}	Neutron porosity that would be recorded if the neutron log measured only the undisturbed zone
ϕ_{Nx}	Neutron porosity that would be recorded if the neutron log measured only the flushed zone
ϕ_D	Density porosity

$\Delta\phi_{ex}$ Neutron excavation effect if the neutron log measured only the undisturbed zone

$\Delta\phi_{exx}$ Neutron excavation effect if the neutron log measured only the flushed zone

$\Delta\phi_{exn}$ Average neutron excavation effect for neutron log

ρ_b Bulk density

ρ_{bv} Bulk density that would be recorded if the density log measured only the undisturbed zone

ρ_{ma} Apparent grain density of the formation matrix

ρ_f Apparent density of the undisturbed reservoir fluid

ρ_w Apparent density of the formation water

ρ_o Apparent density of oil at reservoir conditions

ρ_g Apparent density of gas at reservoir conditions

ρ_{bx} Bulk density that would be recorded if the density log measured only the flushed zone

ρ_{fx} Apparent density of fluids in the flushed zone

ρ_{mf} Apparent density of mud filtrate in the flushed zone

ρ_{fd} Apparent average density of fluids measured by the density log

σ Uncertainty in an input or computed variable X_i

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