EXPERIMENTAL DETERMINATION OF ENVIRONMENTAL CORRECTIONS FOR A DUAL-SPACED NEUTRON POROSITY LOG

by

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ABSTRACT

All environmental corrections which affect the determination of formation porosity have been experimentally and/or theoretically determined for a dual - detector thermal neutron porosity tool. Corrections which are a function of tool design have been derived from experimental data in over 100 laboratory test formation environments. These corrections are presented both in analytical form and as charts with the defining data points included. The theoretical bases for other corrections are discussed, and the resulting correction curves are presented. Field logs run in a variety of borehole and formation conditions are compared with core data to verify the accuracy of the corrections. The effects of trace elements with large thermal neutron capture cross sections have also been quantified.

BASIC CONCEPTS

The concept of dual detector neutron porosity logging was introduced more than a decade ago. The theory and experimental verification of the concept have been reported previously.[1-5]

Basic criteria of neutron logging can be briefly summarized using the illustration in Figure 1. A hypothetical tool containing a source of relatively high energy neutrons and a single thermal neutron detector is shown positioned in a borehole penetrating an earth formation. Hydrogen, which has almost the same mass as a neutron, is by far the most efficient moderator of high energy neutrons of all elements commonly found in earth formations. In formations containing large concentrations of hydrogen, neutrons from the source are efficiently moderated and remain relatively close to the source prior to capture, as illustrated in the left portion of Figure 1. Conversely, neutrons migrate farther from the source in formations containing small concentrations of hydrogen as illustrated in the right portion of Figure 1. A thermal neutron detector placed at least a few inches from the source will therefore register a higher count rate in lower porosity formations. Since hydrogen in most earth formations is concentrated in the pore fluids as water or hydrocarbon rather than in the rock matrix, the count rate response of the detector can be related to formation porosity.

The count rate in a single neutron detector is also affected significantly by the hydrogen in the borehole region, and hence by borehole size and rugosity, mudcake or cement thickness, and tool standoff. It is also affected by the neutron moderating and capture properties of other elements within

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the formation and borehole. Since most of these parameters are usually highly variable and/or poorly defined, it is often not possible to determine accurately if a change in detector count rate is due to a

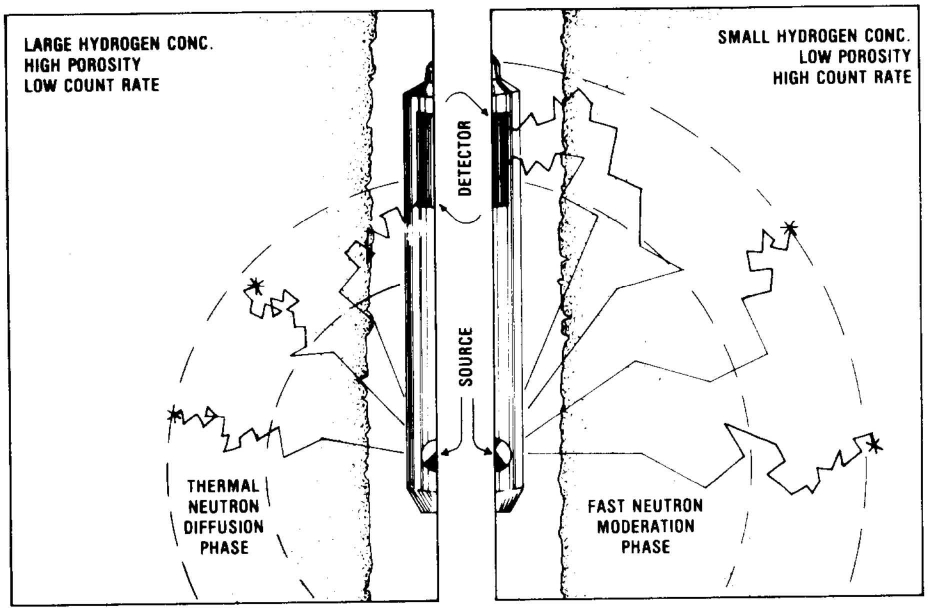

Fig. 1 — Hypothetical Single Detector Neutron Tool in Borehole Environment.

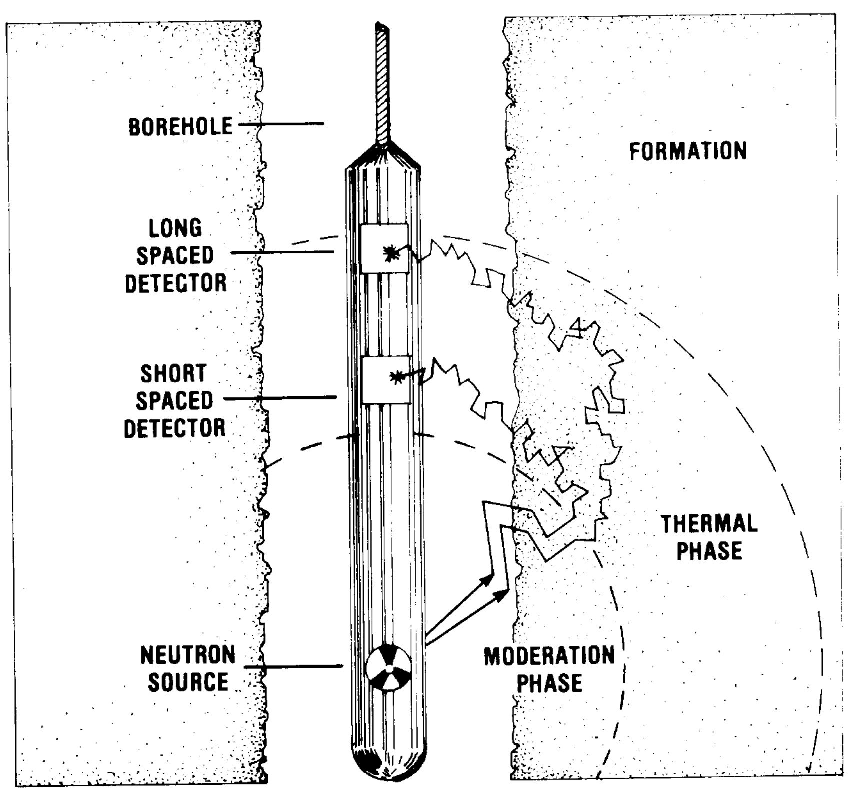

Fig. 2 — Hypothetical Neutron Path Lengths for a Dual Detector Neutron Porosity Tool in a Borehole Environment.

change in formation porosity or to a change in one of these other parameters.

Allen, et al, showed[1] that if a second detector of similar design were placed in the tool at a different distance from the source, the ratio of count rates from the two detectors will retain porosity sensitivity while minimizing sensitivity to most other environmental conditions. This can be visualized for borehole effects, albeit simplistically, using Figure 2. Hypothetical paths followed by two neutrons as they are moderated between the source and detectors are shown for a dual-detector tool. Observe from the Figure that the paths within the borehole are approximately the same in reaching each detector. In addition, mostly high energy neutrons are present along borehole paths leaving the source, and mostly thermal neutrons are present along borehole path segments into each detector. Therefore, borehole attenuation effects will be similar for each detector and will tend to cancel in a dual-spaced count rate ratio measurement.

The effectiveness of this cancelling (or compensation) is a function of tool design parameters such as source-detector spacings, shielding, detector types, and neutron source energy. No dual-spaced tool, however well designed, will be totally independent of these variables. Therefore, to quantitatively convert dual-spaced neutron tool response into porosity units, one must implement corrections, commonly called departure curves, for changes in these parameters. Departure curves must also be developed to allow the log analyst to correct for changes in variables such as formation temperature and pressure, which are independent of tool design, but still affect the final porosity determination.

The following sections discuss the equipment, procedures, and theoretical or experimental data used to derive the corrections for the Welex Dual Spaced Neutron (DSN*) tool. All experimental data points related to departures which are dependent upon tool design are superimposed on the correction charts. A more comprehensive discussion of all aspects of single and dual-detector neutron logging can be found in Reference 6.

DSN EQUIPMENT AND DATA ACQUISITION PROCEDURES

The DSN tool contains a 19 Ci ($\approx 4 \times 10^7$ neutrons/sec) Am-Be source and two high pressure He^3 thermal neutron detectors mounted within a 3-3/8 in. outer diameter pressure housing. The tool is rated at 200 °C and 20,000 psi. The distance between effective detector centers is approximately 1.5 ft. Azimuthal collimation was not used on the detectors because the small reduction in borehole effects was more than offset by increased log statistical variations resulting from a reduction in count rates.

Experimental data used to derive the environmental corrections were collected in laboratory test formations ranging from 4 to 6 ft. in diameter and 6 to 8 ft. in thickness. These dimensions are considerably larger than the experimentally determined minimums required to eliminate vertical or horizontal edge effects. Over 100 combinations of formation and borehole conditions were used. The tool was decentralized with a bowspring as in actual open hole logging operations. Although designed to log in the field at 30 ft./min., all measurements were made with the tool stationary for a time sufficient to reduce statistical variations to a negligible level. Error bars shown on experimental data represent actual variations in the test formation porosities within each bed.

The various environmental corrections can be quite small and thus require very accurate measurements to determine their magnitude. Therefore, in order to insure proper tool calibration,

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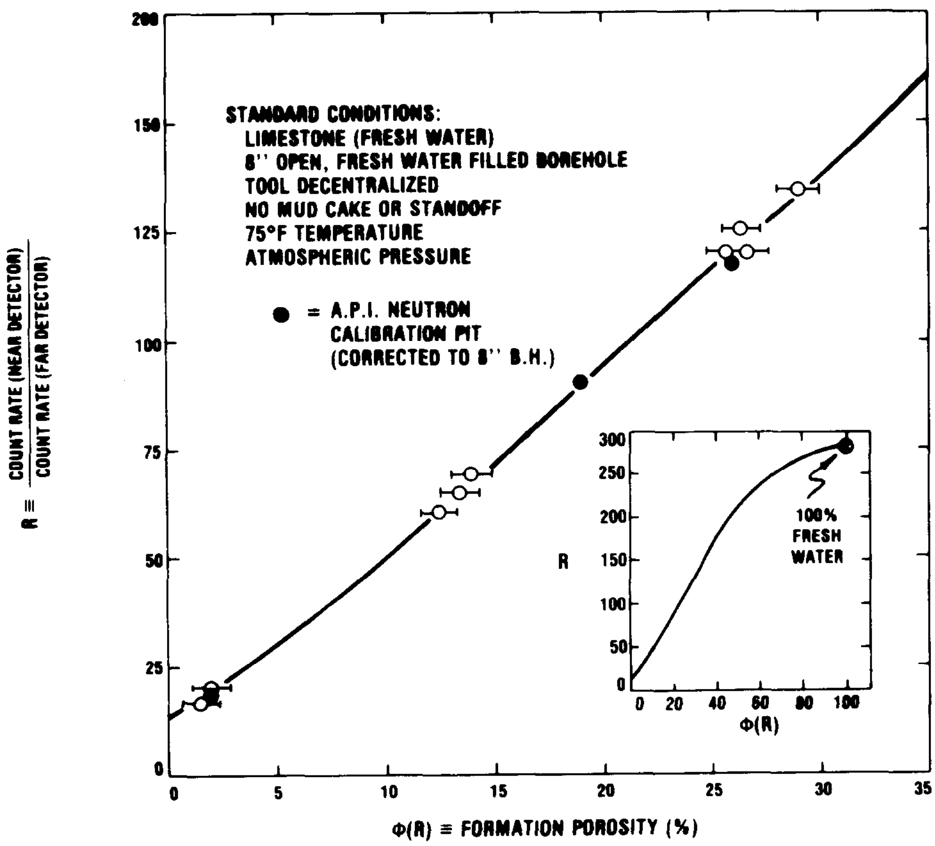

Fig. 3 — Basic Dual Spaced Neutron Tool in Standard Conditions.

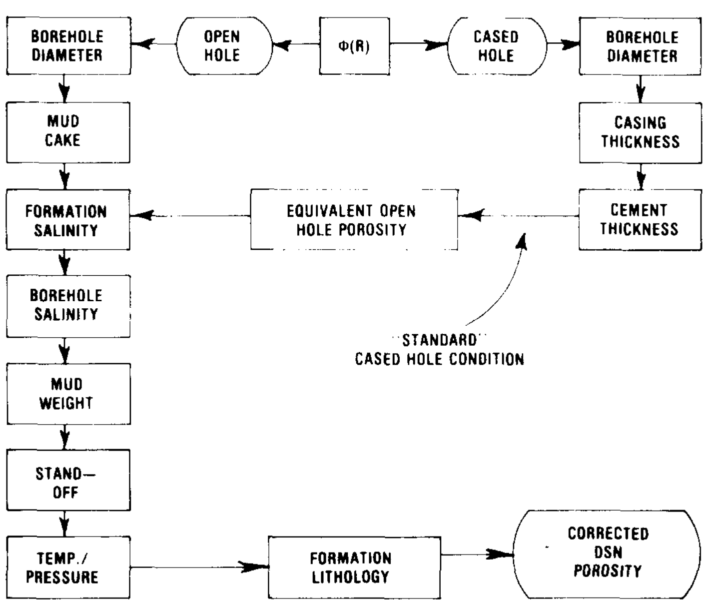

Fig. 4 — Flow Chart of Dual Spaced Neutron Corrections.

reference measurements were made in "standard" test formations throughout the course of data collection. Additional detector calibration checks were made periodically using the standard DSN field calibrator block and field calibration procedure.

The DSN field tool transmits count rate data from each detector to the surface. These data are then converted to porosity values using either a microprocessor based system or a computer based Digital Logging System (DLS*). All test formation measurements described in this paper were processed using the microprocessor system.

In field operations, the DSN tool can be run alone or in combination with casing collar, gamma ray, compensated density, and induction log subsections. All test formation measurements described in the following sections were made with only the DSN subsection. It should be emphasized that most corrections presented in this paper are a function of tool design parameters and are, therefore, applicable only to Welex DSN logs.

DSN RESPONSE

The basic relationship between formation porosity, $\Phi(R)$, and the ratio of count rates recorded in the near spaced to far spaced detectors, R, was measured in fresh water saturated limestone test formations at 75 °F and atmospheric pressure with uncased, 8 in. fresh water filled boreholes with no mud cake. The tool was decentralized with no standoff. These conditions are defined as "standard" open hole conditions. Results of the measurements are shown in Figure 3. A curve was least-squares fitted to the data yielding an analytical expression for the response of the tool, in standard open hole conditions, of

$$(1) \quad \Phi(R) = -2.552 + (2.513 \times 10^{-1} \times R) - (9.30 \times 10^{-5} \times R^2) \quad \text{when } R \leq 200$$

$$\Phi(R) = 227.5 - (1.980 \times R) + (5.311 \times 10^{-3} \times R^2) \quad \text{when } R > 200$$

where $\Phi(R)$ is in porosity units (p.u.).

DSN CORRECTIONS

The basic DSN porosity response, $\Phi(R)$, represents true formation porosity only if the borehole and formation conditions are "standard". When different conditions are encountered, corrections must be applied to $\Phi(R)$, as shown in the flow chart of Figure 4. Although the corrections may be numerous, they are much smaller in magnitude than corrections for a single-detector neutron porosity tool and, in many cases, tend to cancel algebraically.

Most of the corrections described on the following pages have been derived from experimental data acquired in laboratory test formations. The remaining corrections were computed using well established theoretical techniques, or derived indirectly from experimental data. Data points are superimposed on graphical representations of the corrections. Corresponding analytical equations, which can be used in automatic corrections during logging or in post-processing of the log, are presented in the Appendix.

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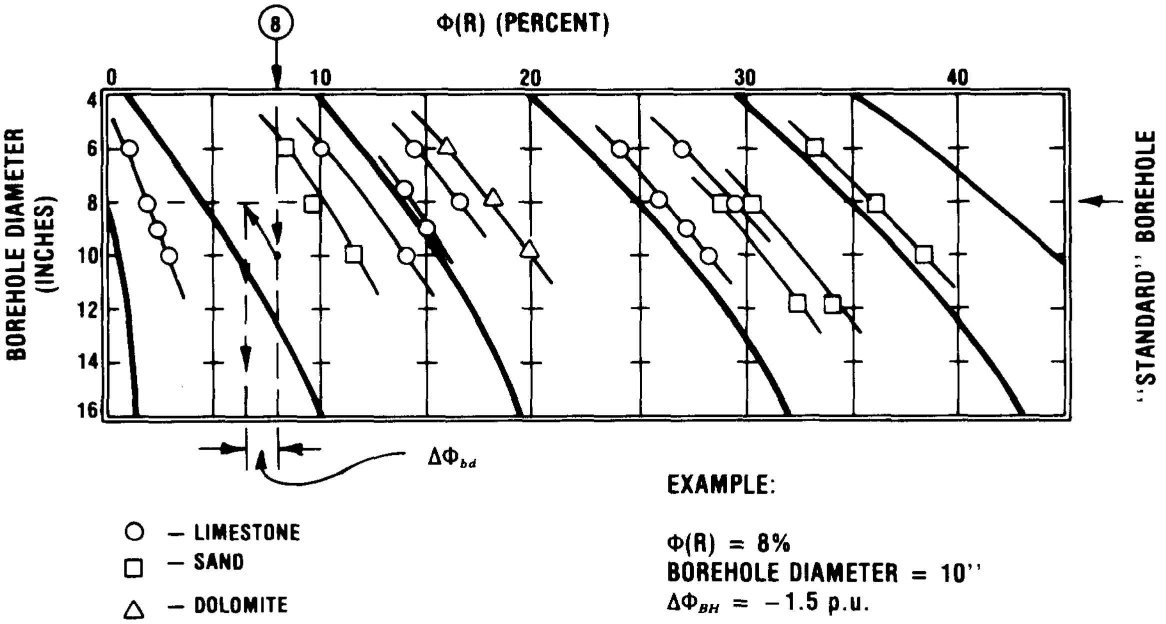

Fig. 5 — Borehole Size Correction.

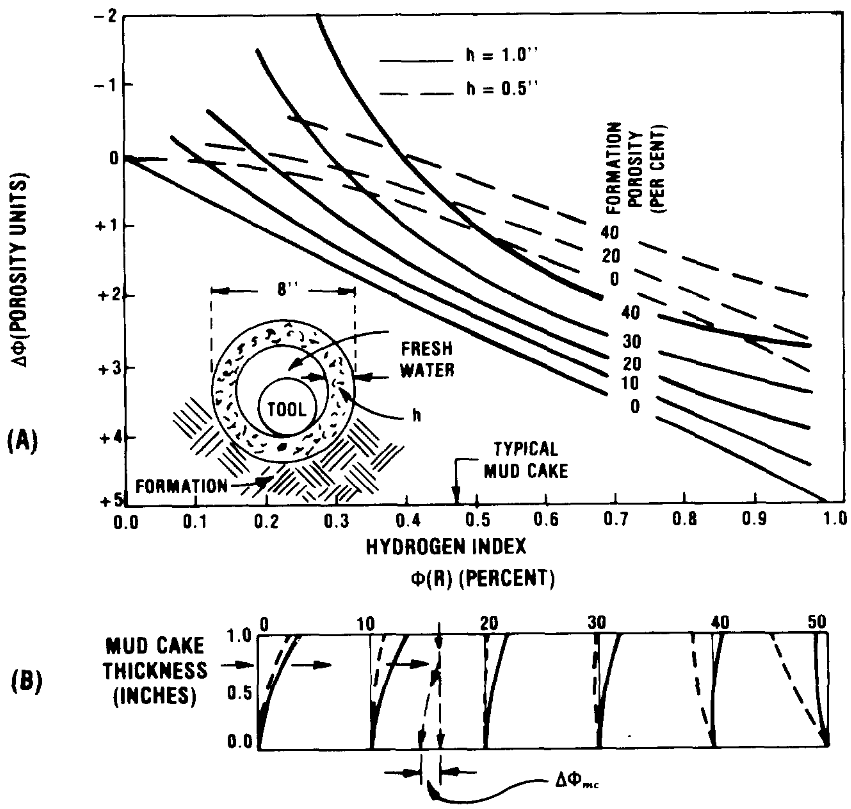

Fig. 6 — Mud Cake Correction.

Open Hole Corrections

Borehole Diameter Correction

The basic DSN porosity, $\Phi(R)$, was measured in eleven sets of test formations of varying porosity and lithology. For a given set of formations, borehole diameters ranged from 6 to 12 in. with all other parameters remaining approximately constant. Variations in $\Phi(R)$ as a function of borehole diameter are shown in Figure 5. From this chart, the correction for borehole diameter, $\Delta\Phi_{bd}$, is obtained and when added algebraically to $\Phi(R)$, yields an equivalent porosity that would be observed in an 8 in. borehole. The example graphically illustrates the correction procedure. Also note that DSN hole size corrections are lithology independent, since the same shape departure curves fit formations of different rock type.

Mud Cake Correction

Cylinders with wall thickness of 0.5 and 1.0 in. with varying hydrogen indices (I_H) were placed in test formations of differing porosity. The formations contained 8 in., fresh water filled boreholes and the tool was decentralized. The porosity reading with the cylinders in place, minus the corresponding reading with the cylinders removed, is defined as $\Delta\Phi$. From these data and standoff data discussed later, families of curves relating $\Delta\Phi$ to I_H were constructed as a function of formation porosity and cylinder thickness h as shown in Figure 6-A.

The I_H of filter cake made with a range of lignosulfate mud weights, was found to range between 0.40 and 0.55. Using an I_H of 0.47 for a typical mud cake and the relationship between I_H and $\Delta\Phi$, a correction for mud cake, $\Delta\Phi_{mc}$, was derived and is shown in chart form in Figure 6-B. The figure also graphically illustrates the correction procedure for a 0.75 in. mud cake at $\Phi(R) = 16\%$. The solid curves should be used if the log has been automatically corrected for borehole size, as will be discussed later. If automatic borehole correction is not used, the dashed curves in Figure 6-B are applicable and bit size rather than caliper size should be used in the previously discussed borehole size correction.

Formation and Borehole Salinity Corrections

The response of the DSN tool was measured in a variety of test formations which were saturated with water ranging in salinity from fresh to 235,000 ppm NaCl and with open, fresh water filled boreholes. Aluminum liners with 1/16 in. thick walls were used to isolate borehole from formation fluid. From these data, a chart was developed to determine the formation water salinity correction, $\Delta\Phi_{fs}$, and is shown in Figure 7-A. As can be seen in the example, $\Delta\Phi_{fs}$ is always negative.

Similar measurements were made in test formations with constant formation porosity and salinity, but with borehole water salinity ranging from fresh to 250,000 ppm NaCl. A chart was developed from these data to determine $\Delta\Phi_{bs}$, the borehole salinity correction, and is shown in Figure 7-B. The example illustrates that the correction is always positive.

It is of interest to note that since $\Delta\Phi_{fs}$ and $\Delta\Phi_{bs}$ are roughly equal in magnitude and opposite in sign, the effects of salinity tend to cancel if the fluids in the formation and borehole have the same salinity. Measurements in gas filled boreholes indicate, as with other dual-detector neutron tools[2], that the DSN porosity sensitivity is severely degraded. A pad type epithermal neutron porosity device such as the Welex Sidewall Neutron (SWN*) porosity tool should be used in gas filled boreholes[6].

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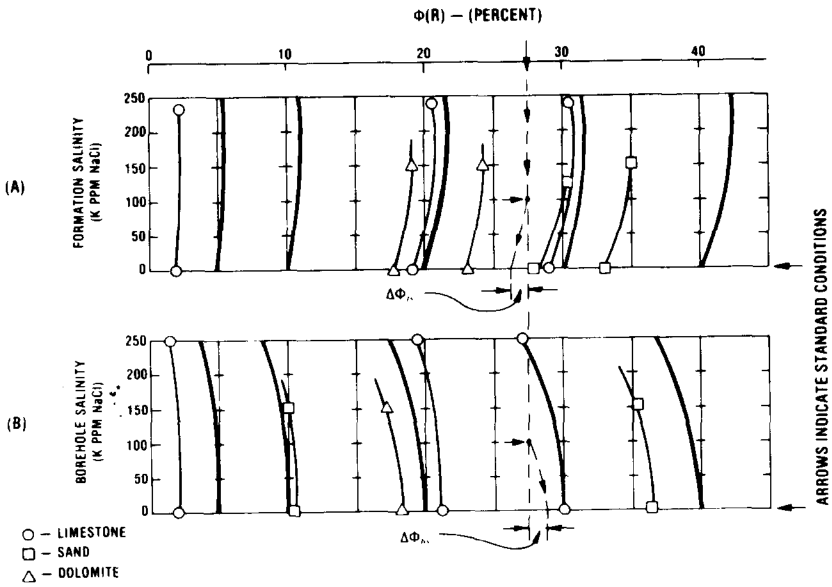


Fig. 7 — Formation and Borehole Salinity Corrections.

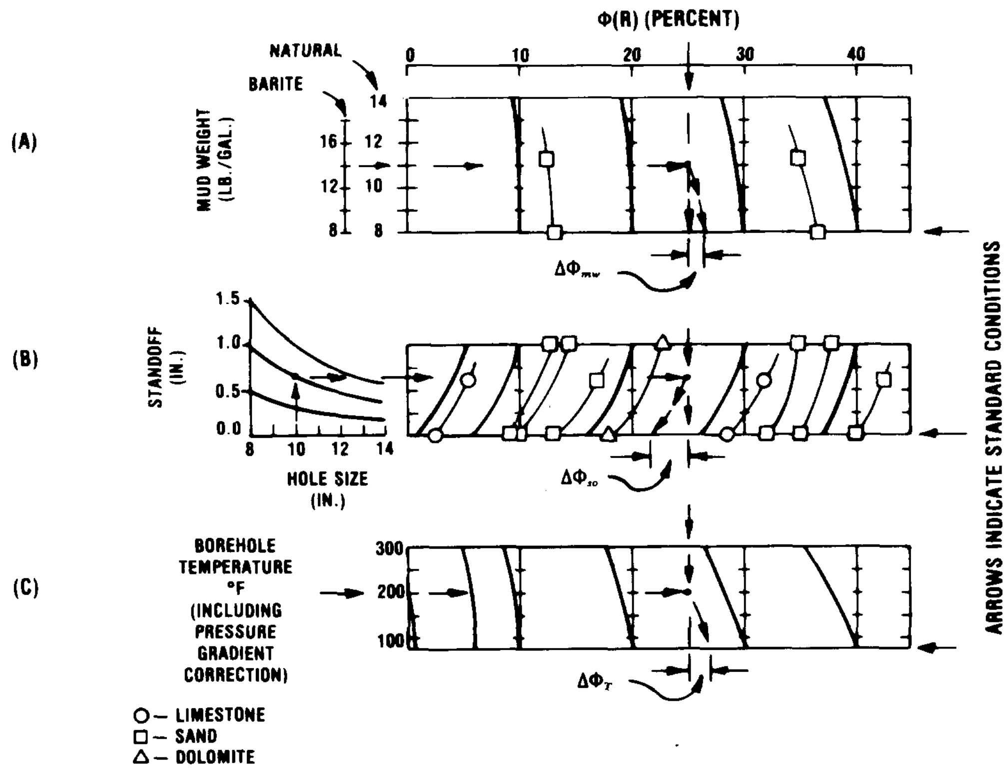


Fig. 8 — Mud Weight, Standoff, and Temperature Corrections.

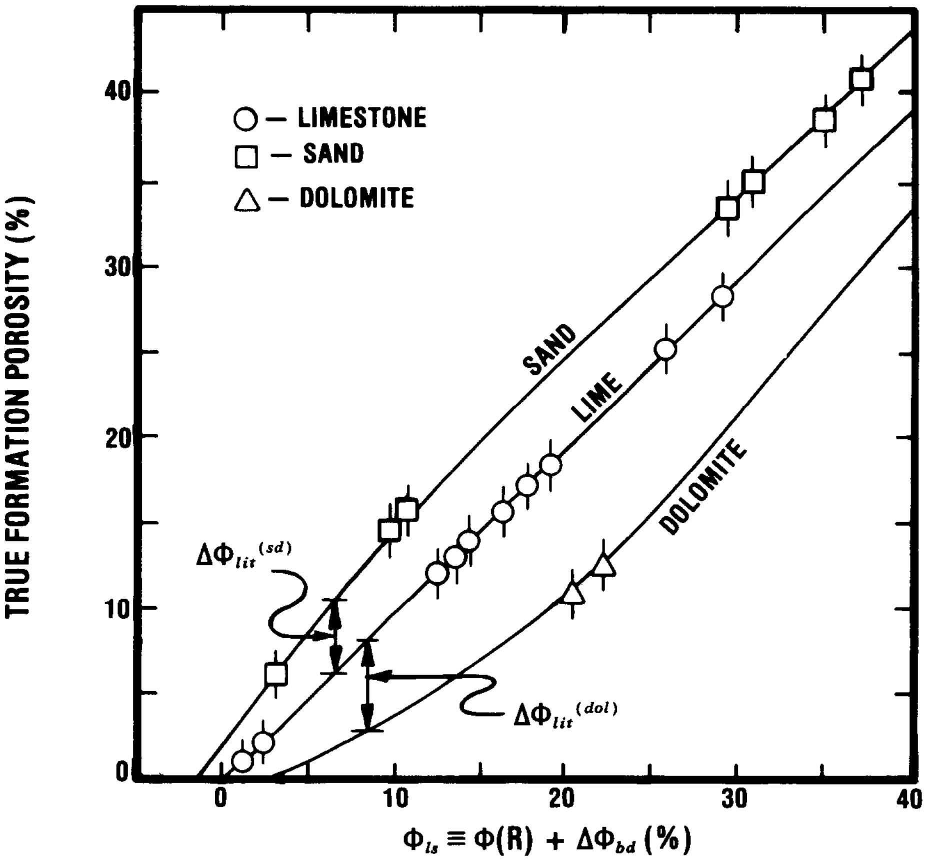
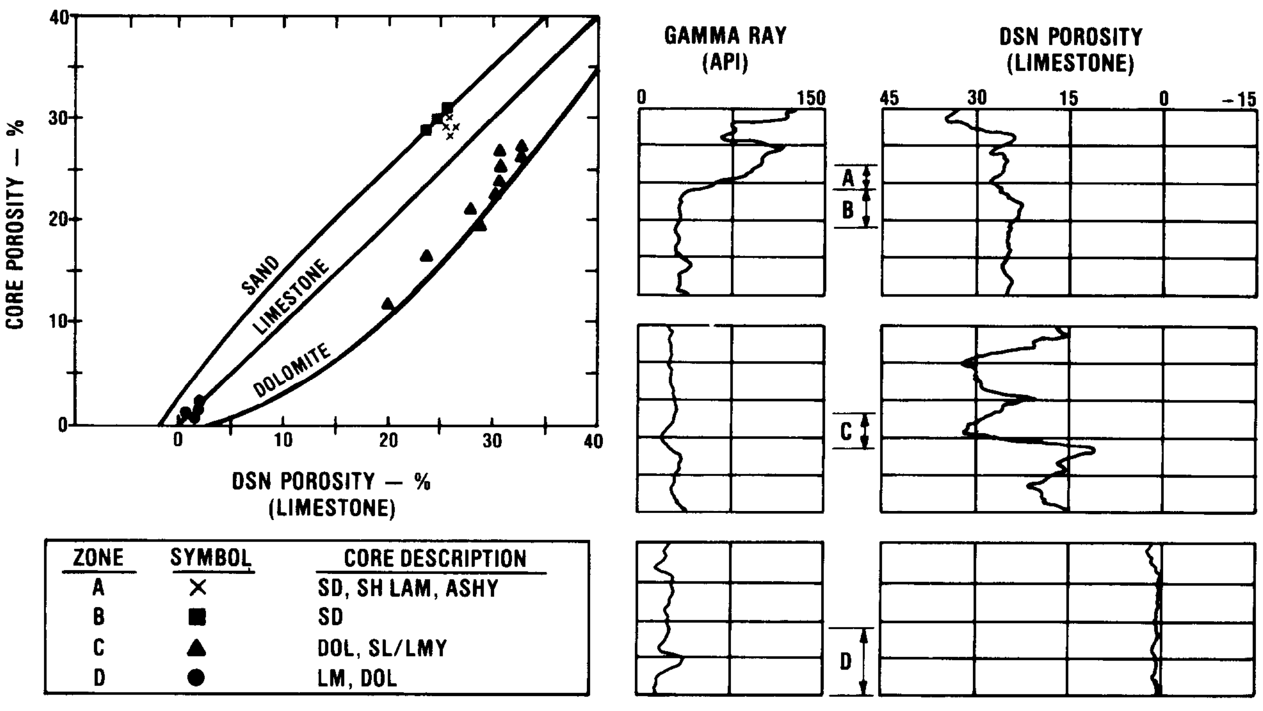


Fig. 9 — Lithology Effects.



ZONE	SYMBOL	CORE DESCRIPTION
A	×	SD, SH LAM, ASHY
B	■	SD
C	▲	DOL, SL/LMY
D	●	LM, DOL

Fig. 10 — Comparison of Log and Core Porosity Data.

Mud Weight, Standoff, and Temperature Corrections

Tool response was measured in two test formations with boreholes filled with 15.8 lb./gal. barite mud. These data were used to construct the chart for mud weight correction, $\Delta\Phi_{mw}$, shown in Figure 8-A. The natural mud weight correction was calculated from the barite mud data on the basis of I_H difference between the two types of mud. Particle densities of barite and natural mud of 4.5 gm/cm^3 and 2.7 gm/cm^3, respectively, were used in the calculations.

The DSN tool is normally run decentralized. DSN logs run in combination with other services may introduce a fixed standoff of the DSN sub from the borehole wall. A chart for determining standoff correction, $\Delta\Phi_{so}$, was constructed from data measured in test formations with varying porosity, lithology, and borehole diameters using tool standoff in fresh water ranging up to 1.5 in. This chart is shown in Figure 8-B, with a 1.0 in. standoff in a 10 in. borehole used as an example.

The temperature correction chart shown in Figure 8-C was calculated using the change in I_H of the formation fluid as a function of pressure and temperature. A temperature gradient of 1 °F per 100 ft. was assumed with a mud weight of 10 lbs./gal. (52 psi/100 ft.). The Excavation Effect[7] was included in the calculation. The example shows that the temperature correction, $\Delta\Phi_T$, is always positive.

Lithology Correction

The DSN tool is calibrated in "standard" open hole conditions, which assumes a limestone matrix. If other lithologies are encountered, appropriate lithology corrections must be applied to the basic porosity response, $\Phi(R)$.

Porosities Φ_{ls} were measured in limestone, sand, and dolomite test formations and corrected to an 8 in. borehole diameter when necessary ($\Phi_{ls} = \Phi(R) + \Delta\Phi_{bd}$). These values of Φ_{ls} are plotted as a function of true formation porosity in Figure 9. The sand curve was obtained by least-squares fitting the experimental data points. Due to a lack of dolomite test formations with wide porosity ranges, it was necessary to calculate the dolomite curve on the basis of neutron migration lengths in pure $CaMg(CO_3)_2$, using a technique described by Edmundson and Raymer[8]. Data points shown on the dolomite curve were measured in Kasota dolomite test formations and corrected for major assayed impurity concentrations. The lithology correction, $\Delta\Phi_{lit}$, is defined graphically in Figure 9 and analytically in the Appendix.

Figure 10 shows a comparison of DSN log porosity values with core porosity from four zones of varying lithology. The logs were run assuming a limestone matrix. Lithology curves from Figure 9 are superimposed on the plot. The core data verify these curves, especially in porosity ranges in which test formations were not available.

CASED HOLE CORRECTIONS

For DSN logs run in cased holes, additional corrections must be made for the casing and cement annulus. Cased hole corrections are used to normalize tool response to "standard" cased hole conditions of 8 in. borehole diameter, 0.3 in. casing thickness, 1.5 in. cement sheath thickness, fresh water filled borehole, and fresh water saturated limestone formation.

At this point, it should be recalled that the basic tool calibration relating the ratio of detector count rates to formation porosity (Equation 1) was made in standard open hole rather than standard cased hole

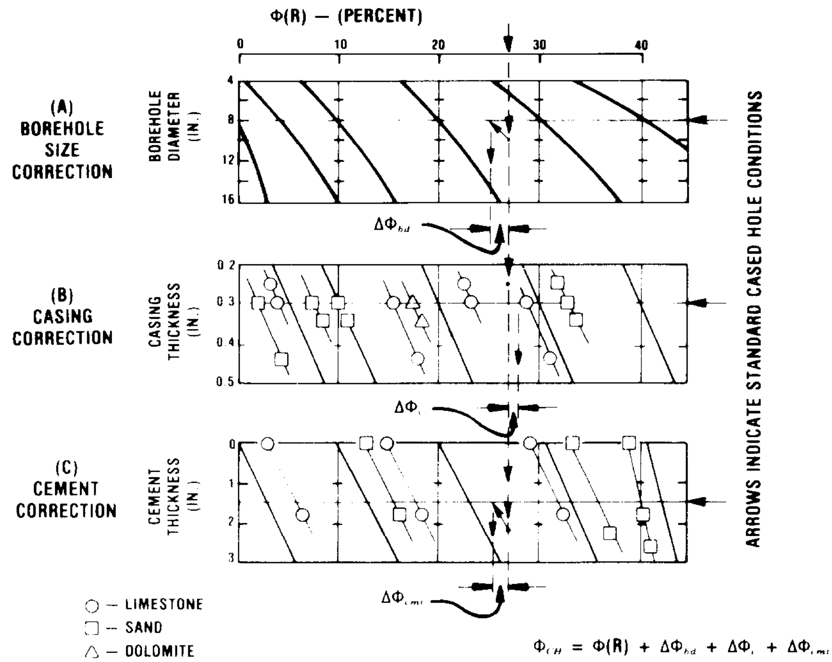


Fig. 11 — Cased Hole Corrections.

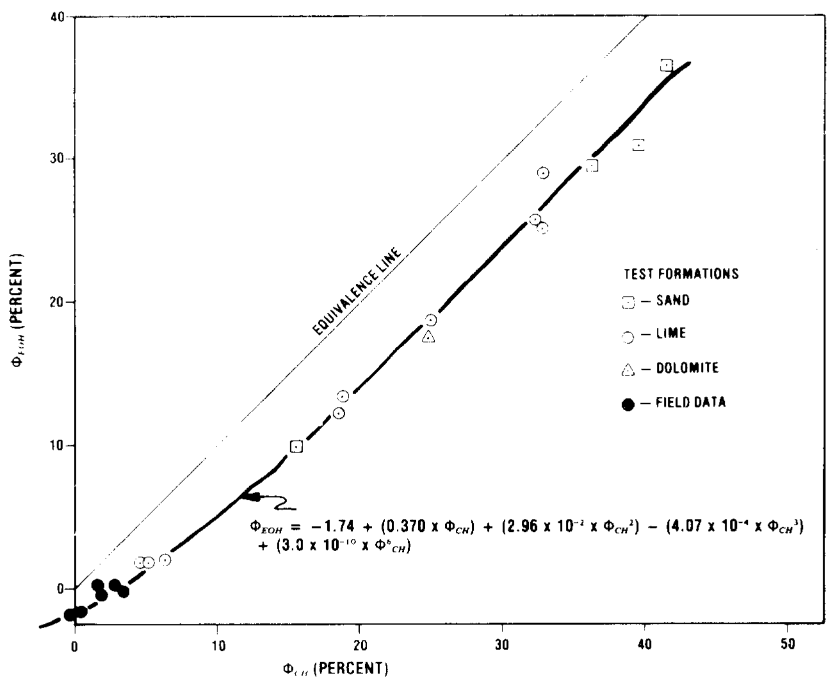


Fig. 12 — Equivalent Open Hole Porosity as a Function of Standard Cased Hole Porosity.

conditions. The ratio observed for a given formation porosity will be greater in standard cased hole conditions than in standard open hole conditions. As a result, calculated cased hole porosities will be erroneously large and must, therefore, be converted to equivalent open hole porosities. Once this conversion is made, previous open hole corrections are applicable.

Borehole Diameter, Casing Thickness, and Cement Thickness Corrections

The borehole diameter correction chart, which is identical to the previously discussed open hole chart, is reproduced for reference in Figure 11-A.

Tool response was measured in cased hole test formations, without a cement annulus, with casing wall thickness ranging from 0.25 in. to 0.43 in. These data were used to develop the chart for determining the casing thickness correction, $\Delta\Phi_c$, as shown in Figure 11-B.

Similar measurements were made using type H cement sheaths with wall thicknesses up to 2.5 in. The resulting chart for determining the cement thickness correction, $\Delta\Phi_{cmt}$, is shown in Figure 11-C.

As illustrated graphically with the example in Figure 11, standard cased hole porosity, Φ_{CH}, is computed from the relation

$$(2) \quad \Phi_{CH} = \Phi(R) + \Delta\Phi_{bd} + \Delta\Phi_c + \Delta\Phi_{cmt}.$$

Note that as the formation I_H approaches the I_H of the bound water in cement, the correction becomes smaller. For $\Phi(R) \approx 50\%$, no correction would be required since both the formation and cement have approximately the same hydrogen index.

Figure 12 shows a plot of Φ_{CH} as a function of corresponding equivalent open hole porosities, Φ_{EOH}. The curve was obtained by least-squares fitting the data points yielding the equation

$$(3) \quad \Phi_{EOH} = -1.74 + (0.370 \times \Phi_{CH}) + (2.958 \times 10^{-2} \times \Phi^2_{CH}) - (4.070 \times 10^{-4} \times \Phi^3_{CH}). + 3.0 \times 10^{-10} \times \Phi^6_{CH}$$

LOG PRESENTATION

True formation porosity, Φ_{true}, is computed from the equations

$$(4) \quad \Phi_{true} = \Phi(R) + \Delta\Phi_{bd} + \Delta\Phi_{mc} + \Delta\Phi_{fs} + \Delta\Phi_{bs} + \Delta\Phi_{so} + \Delta\Phi_T + \Delta\Phi_{lit} + \Delta\Phi_{mw} \text{ (Open Hole)},$$

or

$$(5) \quad \Phi_{true} = \Phi_{EOH} + \Delta\Phi_{fs} + \Delta\Phi_{bs} + \Delta\Phi_{so} + \Delta\Phi_T + \Delta\Phi_{lit} + \Delta\Phi_{mw} \quad \text{(Cased Hole)}.$$

For open hole conditions, the borehole size correction is normally made automatically using the caliper signal from the compensated density log usually run in combination with the DSN log. If desired, porosity can be recorded assuming either limestone, sand, or dolomite as the lithology base during logging. Porosities recorded at the wellsite on open hole logs are therefore usually of the form:

$$(6) \quad \Phi_{LOG} = \Phi(R) + \Delta\Phi_{bd} + \Delta\Phi_{lit}.$$

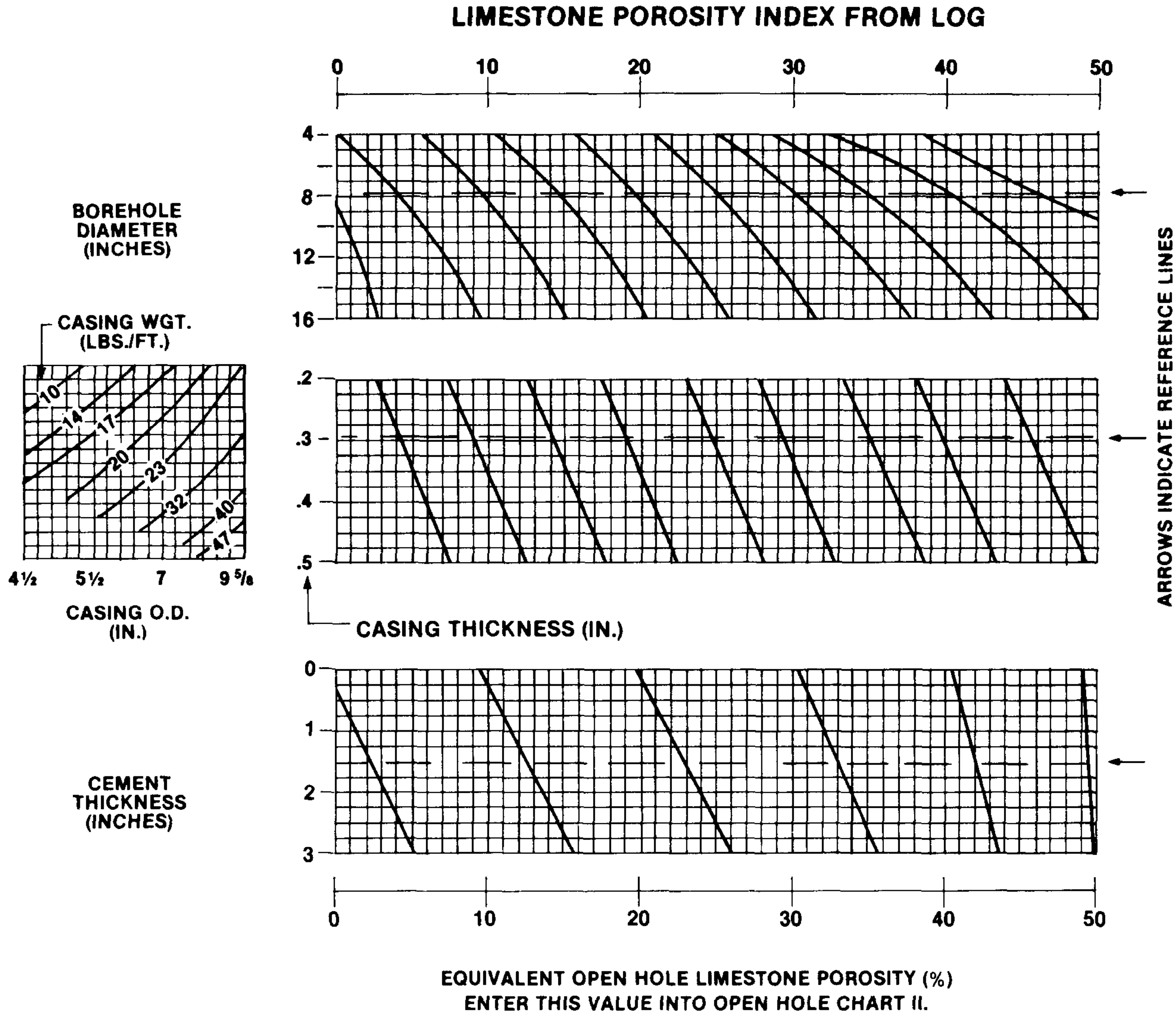


Fig. 13 — Dual Spaced Neutron Interpretation Charts for Cased Boreholes.

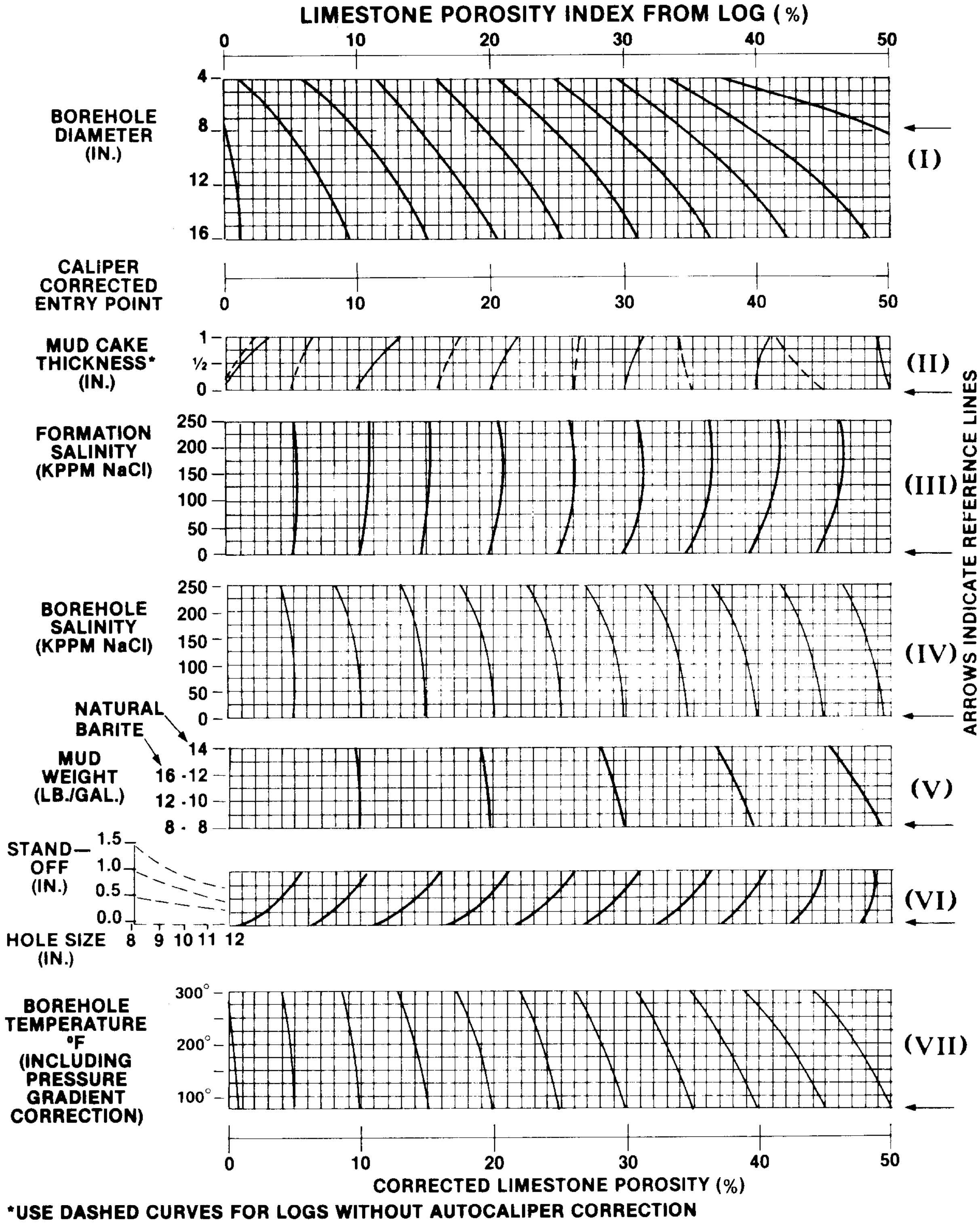


Fig. 14 — Dual Spaced Neutron Interpretation Charts for Uncased Boreholes.

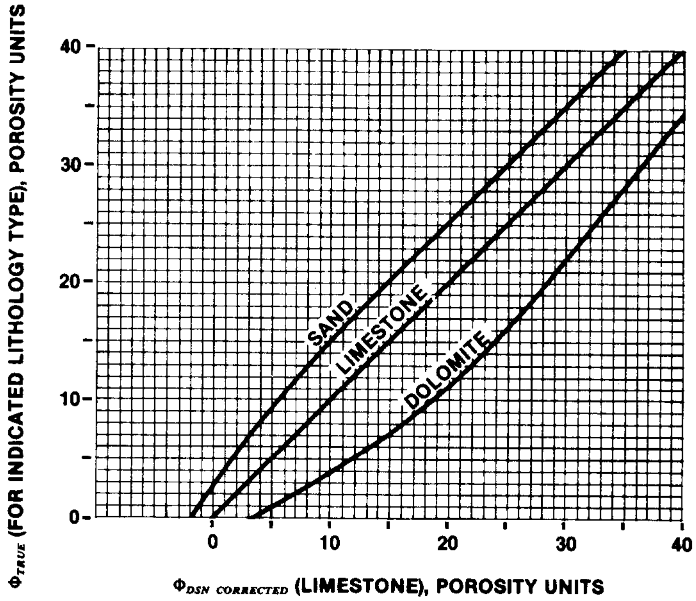


Fig. 15 — Dual Spaced Neutron Lithology Response.

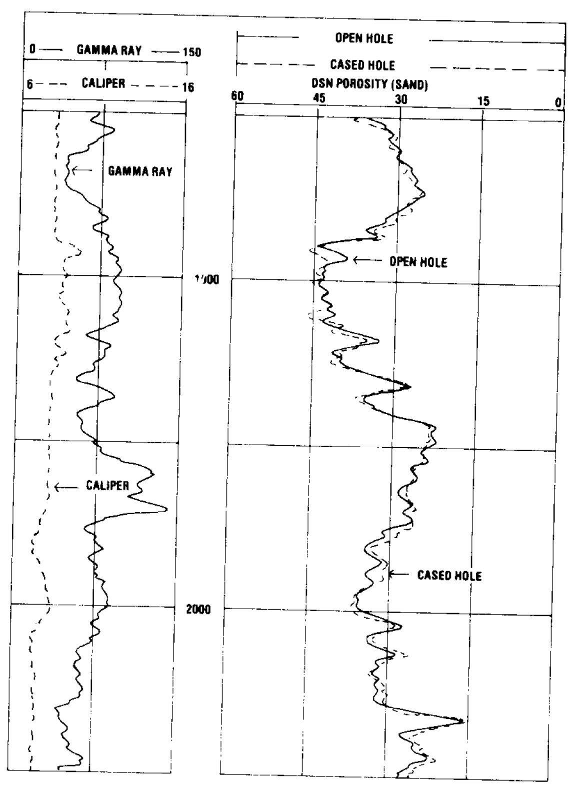


Fig. 16 — Comparison of Cased Hole and Open Hole DSN Logs.

For logs in cased boreholes, the bit size, casing thickness, and cement thickness (or alternately the casing size and weight) are specified and the equivalent open hole porosity, Φ_{EOH}, is computed automatically while logging. If a lithology other than limestone is specified, the lithology correction is again made automatically, yielding a log reading of:

$$(7) \quad \Phi_{LOG} = \Phi_{EOH} + \Delta\Phi_{lit}.$$

When bit and casing sizes are not specified in cased holes, standard cased hole conditions are assumed. All cased hole porosities are calculated assuming that the casing is centered in the cement annulus. If this is not the case in an actual well, slightly lower porosities than expected will generally be calculated. This occurs because the tool will normally travel up the casing on side of minimum cement annulus thickness, and hence any cement thickness correction will be overestimated.

The remaining environmental corrections can also be made automatically with computer based surface equipment now in the field. Automatic corrections are not recommended for conditions that can change significantly over the intervals logged.

All environmental corrections have been summarized in "working" charts in Figures 13, 14, and 15. These charts, or alternatively, the corresponding analytical equations in the Appendix, can be used to convert Φ_{LOG} to true porosity, bypassing all corrections made automatically while logging.

Figure 16 illustrates normal log presentation as overlays of DSN logs run before and after 5-1/2 in., 17 lb. casing was set. Both logs were run assuming a sandstone matrix. The cased hole log was corrected automatically while logging assuming an 8 in. diameter borehole, a 1.25 in. thick cement annulus, and a 0.30 in. thick casing.

Agreement is, in general, quite good with minor discrepancies occuring in higher apparent porosity zones where the borehole diameter deviates appreciably from 8 in. This discrepancy occurs because the open hole log is continuously and automatically adjusted for variations in borehole diameter using the signal from the caliper, while the cased hole log response is adjusted using fixed borehole parameters. As a result, cased hole porosities read slightly high when the borehole diameter exceeds 8 in., and slightly low when the borehole diameter is less than 8 in. The cased hole log can, however, be corrected manually or by subsequent computer processing using the open hole caliper reading and cased hole corrections shown in chart form in Figure 13 or analytically in the Appendix.

THE Σ EFFECT

The effects of trace elements with high thermal neutron cross sections, Σ, on the response of dual detector thermal neutron devices, have been discussed by Allen, et al[4]. Two group diffusion theory was used to show that relatively small concentrations of strong neutron absorbers such as boron or gadolinium will result in anomalously high apparent porosity readings. Most shales contain much higher concentrations of these trace elements when compared with "clean" formations. One would, therefore, expect a dual detector thermal neutron device to indicate a higher apparent porosity in shaly formations than predicted on the basis of the hydrogen index of free and bound liquids.

Since chlorine also has a large thermal neutron capture cross section, one might expect to see a similar increase in apparent porosity in salt water saturated formations. This is not necessarily observed. With proper tool design, the increase in measured porosity due to the Σ effect can be almost completely

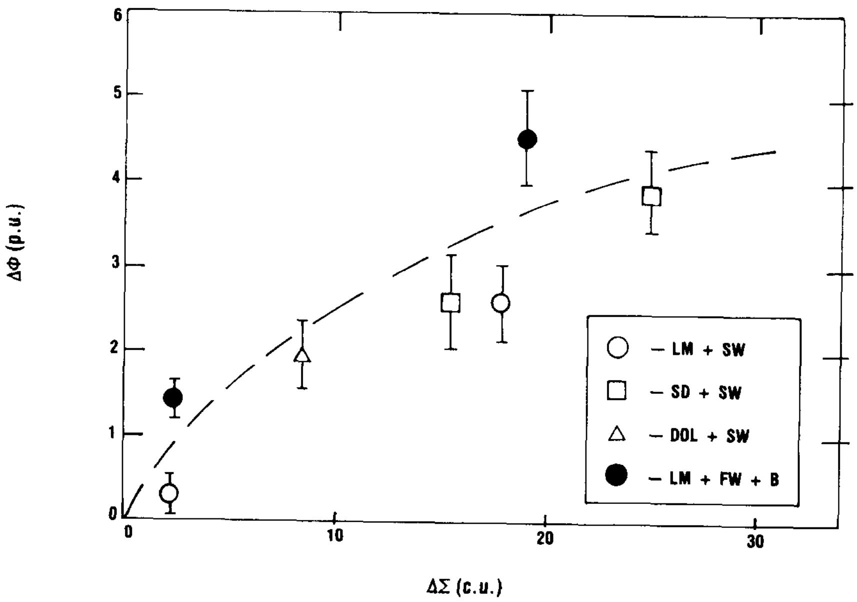


Fig. 17 — Increase in Apparent DSN Porosity, ΔΦ, as a Function of Increase in the Formation Thermal Neutron Capture Cross Section, ΔΣ.

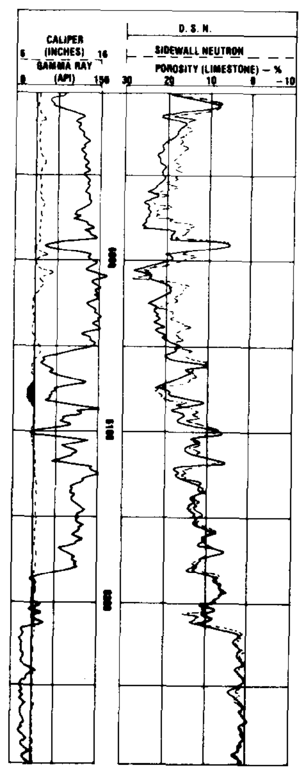


Fig. 18 — Comparison of DSN and SWN Logs.

offset by a decrease in measured porosity due to the reduction of the hydrogen index of the water as salinity increases. For the DSN tool, cancelling is reflected in the relatively small formation and borehole salinity corrections.

To quantify the magnitude of the Σ effect for the DSN tool, measurements were made in limestone test formations similar to those in the API pits, but saturated with fresh water containing approximately 1800 ppm boron. The boron increases the formation capture cross section without significantly changing the formation hydrogen index. Additional measurements were made in similar limestone formations saturated with salt water, and in salt water saturated sand and dolomite formations. These measurements also indicated an increase in apparent porosity due to the Σ effect, after correcting for decreases in formation fluid hydrogen indices.

Figure 17 illustrates $\Delta\Phi$, the increase in apparent DSN porosity reading, as a function of the increase in formation capture cross section, $\Delta\Sigma$, where

$$(8) \quad \Delta\Phi \equiv \Phi'_a - (\Phi_{true} \times I_H) \quad \text{(p.u.)}$$

$$(9) \quad \Delta\Sigma \equiv ((\Sigma_{fl} - 22)\Phi_{true})/100 \quad \text{(c.u.)}$$

and

Φ'_a = the measured porosity corrected for all environmental effects, except formation water salinity (p.u.)

Φ_{true} = the true formation porosity (p.u.)

Σ_{fl} = the capture cross section of the formation fluid (capture units, c.u.)

I_H = the hydrogen index of the formation fluid.

The error bars represent uncertainties in the true formation porosity. Small corrections were applied to $\Delta\Sigma$ if the capture cross section of the formation matrix, Σ_{ma}, differed significantly from those of the API and other formations ($\Sigma_{ma} \approx 10$ c.u.) used to define the basic response of the DSN tool.

From Figure 17, it can be seen that if the Σ of a formation is approximately 10 c.u. greater ($\Delta\Sigma = 10$ c.u.) than a "clean" formation ($\Sigma_{ma} \approx 10$ c.u.), the apparent porosity read from the DSN log can overestimate porosity by approximately 2.5 porosity units ($\Delta\Phi = 2.5$ p.u.). As mentioned previously, this will not occur if the increase in Σ is due to saline formation water, because the decrease in hydrogen index tends to cancel the Σ effect. In shales, and in formations into which high Σ trace element fluids have been injected, the Σ effect will be observed.

Figure 18 shows a comparison of a DSN log and the Σ independent single detector Welex epithermal sidewall neutron (SWN) porosity log in an interval containing both clean and shaly intervals. Apart from the differences in bed resolution, agreement is very good in the clean zones. In the shale intervals, the apparent porosity from the DSN log is consistently 3 to 4 porosity units greater than from the SWN log. The trace element related increase in the Σ of the shales is estimated to be 10 to 12 capture units. Using Figure 17, it can be seen that the Σ effect of the DSN log accounts for most of the discrepancy. The remaining discrepancy can be attributed to a slight underestimation of porosity in shales on the SWN log. Assuming that the bound water is saline, the SWN log will read low due to a decrease in hydrogen index, with no compensating effects from the increased Σ of the bound water.

In the interval 6074-6082 ft., porosity read from the SWN tool is greater than the DSN porosity. The caliper indicates mud cake within this interval. The higher SWN porosity is probably due to inadequate mud cake removal by the SWN pad, illustrating an advantage of compensated devices, such as the DSN tool, where changing borehole conditions exist.

We have not developed a precise analytical correction for the Σ effect as a function of V_{sh}, the shale fraction of the formation. It is usually difficult to delineate increases in Σ due to trace elements from increases due to bound water and salinity. An approximate correction can, however, be made by first assuming[9] that shale has 10 capture units attributable to trace elements when compared to a clean zone. Increases in formation Σ due to trace elements in the shale fraction would then be

$$(10) \quad \Delta\Sigma \approx 10 \times V_{sh}.$$

This value would then be entered into the chart in Figure 17 to determine $\Delta\Phi$ from the Σ effect. This correction should be made in addition to the normal bound water corretion[3,10] within the shale fraction. The correction for Σ effects in shaly formations will usually be much smaller than the bound water correction, rarely exceeding one porosity unit in zones of interest.

In log-inject-log projects, fluids containing high cross section trace elements are sometimes injected to increase the Σ of the formation. In these situations, Φ_{corr}, the porosity read from the DSN log and corrected for all other environmental effects, can also be corrected for the Σ effect. In this situation, $\Delta\Sigma$ is computed from

$$(11) \quad \Delta\Sigma = ((\Sigma_{fl} - \Sigma_w)\Phi_{corr})/100$$

where Σ_{fl} = the cross section of the injected fluid
Σ_w = the cross section of the injected fluid prior to trace element addition.

$\Delta\Sigma$ is then used with the chart in Figure 17 to determine $\Delta\Phi$, and true formation porosity is computed from the equation

$$(12) \quad \Phi_{true} \approx \Phi_{corr} - \Delta\Phi.$$

It should be emphasized that if the formation into which the fluid is injected is shaly, Φ_{corr} must first be corrected for the bound water within the shale, as previously mentioned.

SUMMARY

All environmental corrections which affect determination of porosity have been determined experimentally or theoretically for a dual-detector thermal neutron porosity tool. These corrections are presented in both analytical form and as charts. In addition, the effects of trace elements with large thermal neutron capture cross sections have been quantified.

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APPENDIX

EQUATIONS FOR DSN ENVIRONMENTAL CORRECTIONS

Environmental corrections, which were presented in graphical form in the text, are presented in analytical form in the Appendix. The corrections which are normally made automatically during logging are based upon these equations. The equations for the remaining corrections are often used in computer post-processing of the log. All porosity values and corrections expressed in the Appendix are in fractional porosity units.

Basic Porosity Equation

$$\Phi(R) = (-2.552 \times 10^{-2}) + (2.513 \times 10^{-3} \times R) - (0.930 \times 10^{-6} \times R^2) \quad \text{when } R \leq 200$$

$$\Phi(R) = (2.2754) - (1.980 \times 10^{-2} \times R) + (5.311 \times 10^{-5} \times R^2) \quad \text{when } R > 200$$

where $R \equiv$ the calibrated ratio of count rate from the short spaced detector to count rate from the long spaced detector.

Borehole Size Correction ($\Delta\Phi_{bd}$)

$$\Delta\Phi_{bd} = (D-8)\,[-0.0025 - 0.1063\,\Phi(R) + 0.5419\,\Phi(R)^2 - 0.6946\,\Phi(R)^{2.8}] + 0.001445\,(D-8)^2\,\Phi(R)$$

where $D \equiv$ the diameter of the borehole in inches

If extreme conditions are encountered such that $\Delta\Phi_{bd}$ calculated from the above equation is less than -0.16 (i.e. $|\Delta\Phi| > 0.16$). then $\Delta\Phi_{bd}$ is set at -0.16.

Equivalent Open Hole Conversion

$$\Phi_{EOH} = -0.0174 + (0.3702\Phi_{CH}) + (2.958\Phi^2_{CH}) - (4.070\Phi^3_{CH}) + (3.00\,\Phi^6_{CH})$$

where $\Phi_{CH} = \Phi(R) + \Delta\Phi_{bd} + \Delta\Phi_c + \Delta\Phi_{cmt}$

Mud Cake Correction ($\Delta\Phi_{mc}$)

$$\Delta\Phi_{mc} = [-0.0120 - 0.061\Phi(R) + 0.271\Phi(R)^2]h_{mc} + [-0.0129 + 0.088\Phi(R) - 0.154\Phi(R)^2]h^2_{mc}$$

(automatic caliper compensated)

$$\Delta\Phi_{mc} = [-0.0048 - 0.039\Phi(R) + 0.353\Phi(R)^2]h_{mc} + [-0.0221 + 0.107\Phi(R) - 0.195\Phi(R)^2]h^2_{mc}$$

(no caliper compensation)

where h_{mc} = the mud cake thickness in inches.

Formation Salinity Correction ($\Delta\Phi_{fs}$)

$$\Delta\Phi_{fs} = \Phi(R)\ [(-3.5 \times 10^{-4} \times S) + (6.0 \times 10^{-7} \times S^2)]$$

where S = water salinity in thousand ppm NaCl

Borehole Salinity Correction ($\Delta\Phi_{bs}$)

$$\Delta\Phi_{bs} = \Phi(R)\ [(-2.0 \times 10^{-4} \times S) + (1.9 \times 10^{-6} \times S^2)]$$

Mud Weight Correction ($\Delta\Phi_{mw}$)

$$\Delta\Phi_{mw} = \Phi(R)\ [1.04 \times 10^{-2} \times (W-8) + 3.47 \times 10^{-4}(W-8)^2]$$

(NATURAL MUD)

$$\Delta\Phi_{mw} = \Phi(R)\ [5.21 \times 10^{-3} \times (W-8) + 8.68 \times 10^{-5} \times (W-8)^2]$$

(BARITE MUD)

where W = mud weight in pounds per gallon

Standoff Correction ($\Delta\Phi_{so}$)

$$\Delta\Phi_{so} = b_1V + c_1V^2$$

where $V = a_2 + b_2D + c_2D^2$

$b_1 = -0.0254 + (0.0683\Phi(R)) - (0.0881\Phi(R)^2)$

$c_1 = 0.0025 - (0.0081\Phi(R)) - (0.0099\Phi(R)^2)$

and for $X \leqslant 0.5$

$a_2 = 14X$

$b_2 = -1.6X$

$c_2 = 0.05X$

or for $X > 0.5$

$a_2 = -6.5 + 25X$

$b_2 = 1.5 - 4.6X$

$c_2 = -0.08 + 0.21X$

where

D = borehole diameter (inches)

X = standoff (inches)

Temperature Corrections ($\Delta\Phi_T$)

$$\Delta\Phi_T = (0.008 + 0.062\Phi(R) + 0.092\Phi(R)^2)\,((T-75)/225)$$

where T = borehole temperature in °F

Lithology Correction ($\Delta\Phi_{lit}$)

$$\Delta\Phi_{lit} = 0.0311 + 0.220\Phi_1 - 0.4778\Phi_1^2 \quad \text{(SAND)}$$

$$\Delta\Phi_{lit} = -0.0152 - 0.655\Phi_1 + 1.397\Phi_1^2 \quad \text{(DOLOMITE)}$$

where

$$\Phi_1 \equiv \Phi(R) + \Delta\Phi_{bd} + \Delta\Phi_{mc} + \Delta\Phi_{fs} + \Delta\Phi_{bs} + \Delta\Phi_{so} + \Delta\Phi_T + \Delta\Phi_{mw}$$

(OPEN HOLE)

$$\Phi_1 \equiv \Phi_{EOH} + \Delta\Phi_{fs} + \Delta\Phi_{bs} + \Delta\Phi_{so} + \Delta\Phi_T + \Delta\Phi_{mw}$$

(CASED HOLE)

Casing Thickness Correction ($\Delta\Phi_c$)

$$\Delta\Phi_c = 0.171\,(0.3 - h_c),$$

where h_c = casing thickness in inches, or if casing size and weight are entered into the logging truck computer, h_c, is automatically computed from the equation

$$h_c = 0.5[D_{CSG} - (D^2_{CSG} - 0.3667\,W_{CSG})^{0.5}]$$

where D_{CSG} = outside diameter of the casing (in.)

W_{CSG} = casing weight (lbs./ft.)

Cement Thickness Correction ($\Delta\Phi_{cmt}$)

$$\Delta\Phi_{cmt} = (1.5 - h_{cmt})\,[0.020 - 0.0667\Phi(R)^2]$$

where h_{cmt} = cement thickness in inches. If casing size and weight are entered into the logging truck computer, h_{cmt} is automatically computed from the equation

$$h_{cmt} = 0.5(D - D_{CSG})$$

where D = the diameter of the borehole (in.)

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