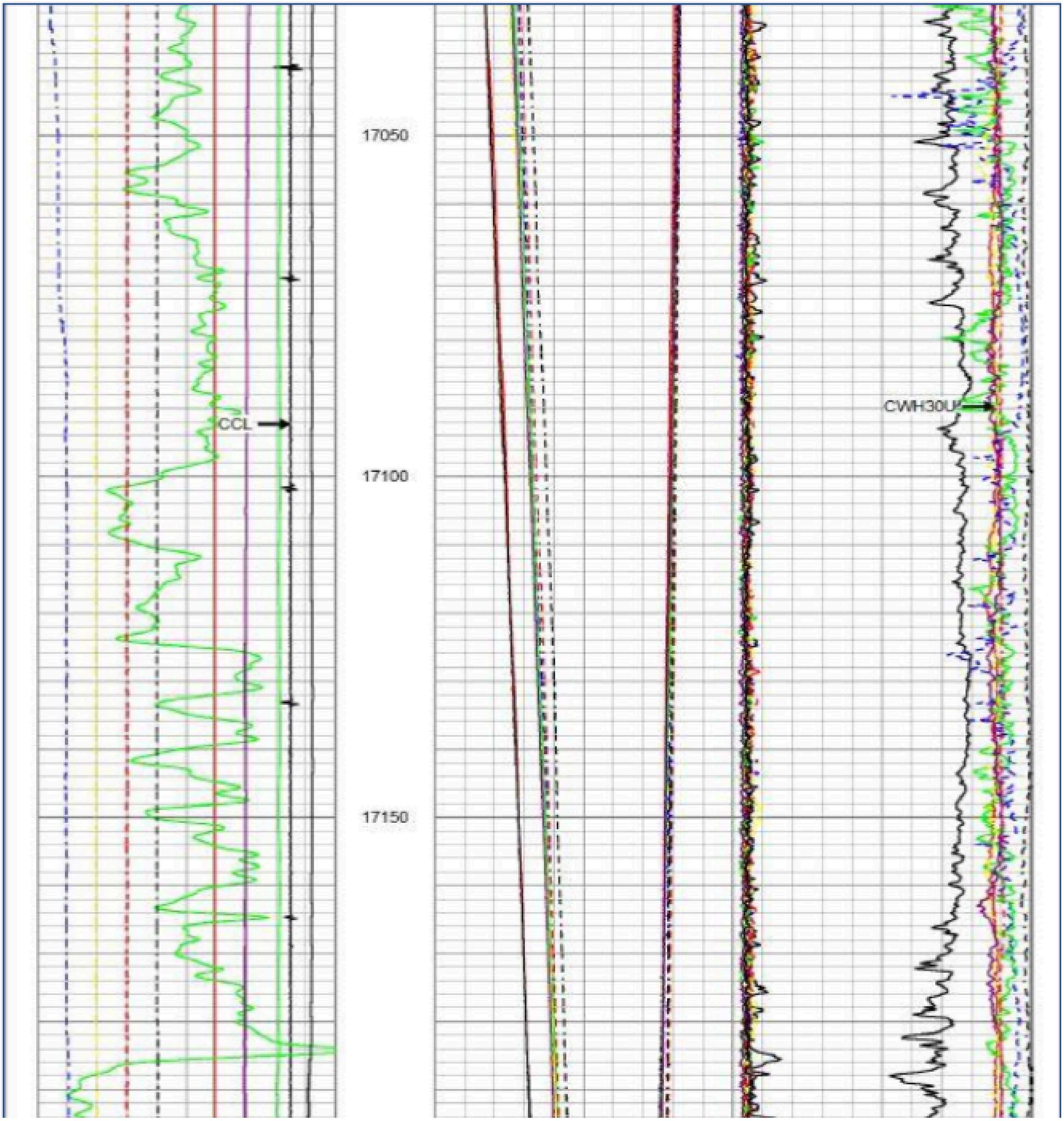
Chapter 6 - Density Porosity



Chapter 6 - Density Porosity Tool

The Density Porosity Tool is designed to measure the electron density and gamma ray absorption properties of a formation. Gamma rays are continuously emitted from a chemical radioactive source in the tool and lose energy as they collide with the electrons of atoms present in the formation. The measurement of gamma rays returning to the tool is used to compute the bulk density (ρb) and photoelectric factor (Pe) of the formation. The primary objectives of logging the Density Porosity Tool are to determine formation porosity and lithology.

Applications

The bulk density (ρb) of a formation is a function of the density of the rock matrix, the amount of porosity present, and the density of fluids that fill the pore space. With a measurement of bulk density from the Density Porosity Tool and assumed or experimental values for the other variables, porosity can be determined from the following equation:

$$\Phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

Where: Φ_d = porosity derived from bulk density
ρ_{ma} = density of rock matrix
ρ_b = bulk density of formation
ρ_{fl} = density of fluids filling the pore space

With knowledge of porosity (Φ) and true resistivity (Rt), the fraction of pore space occupied by water (or water saturation) can be calculated using the Archie equation.

$$S_w{}^n = \frac{a}{\Phi^m} \times \frac{R_w}{R_t}$$

Where: S_w = water saturation of the uninvaded zone
n = saturation exponent
a = tortuosity factor
Φ = porosity
m = cementation exponent
R_w = formation water resistivity
R_t = true resistivity of the uninvaded zone

The ability of a formation to absorb gamma rays is strongly related to the average atomic number (Z) of atoms present in that formation which is dependent upon a rock's molecular composition. The photoelectric factor (Pe) measurement of the Density Porosity Tool can be used for determining rock type, even in complex lithologies.

Knowledge of lithology is vital when predicting the production qualities of a reservoir and when designing completion programs. It also assists log analysts in determining Archie variables such as tortuosity factor (a) and cementation exponent (m) if these data are not known from core analysis or other sources.

Additional applications of the bulk density (ρb) and photoelectric factor (Pe) measurements of the Density Porosity Tool include:

• Determination of volume of shale (VSH) when used in combination with another porosity measurement.

• Identification of gas-bearing formations when used in combination with the Neutron Porosity Tool.

• Estimation of hydrocarbon density.

• Enhanced evaluation of shaly sandstone reservoirs.

• Determination of overburden pressure.

• Estimation of rock mechanical properties when used in combination with acoustic waveform data.

Logging Conditions

The Density Porosity Tool is capable of acquiring data in most well conditions, including:

• Fresh water-based mud

• Saltwater-based mud

• Oil-based mud

• Air-drilled boreholes

The Density Porosity Tool cannot provide accurate data in cased holes.

Physics of the Measurement

The measurement principle of the Density Porosity Tool relates to the energy loss experienced by gamma rays as they travel from their source, through the mudcake and formation, and to the detectors of the tool. These gamma rays interact with the electrons of atoms and are either scattered or absorbed, losing energy in each collision. Gamma rays that return to the detectors of the tool exhibit a wide range of energy levels depending upon what type and how many collisions they suffered.

Gamma rays of different energy levels can be used to quantify the effects of their being scattered and absorbed. Scattering of gamma rays is proportional to the electron density (ρe) of the formation, while their absorption depends upon the average atomic number (Z) of the rock. By measuring the number of gamma rays detected at different energy levels, it is possible to compute the bulk density (ρb) and photoelectric factor (Pe) of the formation.

Gamma Ray Source

The Density Porosity Tool employs a chemical source of cesium-137 to emit a continuous stream of gamma rays. Cesium decays to barium through the emission of a beta particle (electron). The barium product is left in an excited (or unstable) state.

$$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba(\text{unstable}) + {}_{-1}\beta$$

The radioactive barium product then stabilizes through the emission of a single gamma ray with energy of 662 keV[1].

$$^{137}_{56}Ba(\text{unstable}) \rightarrow {}^{137}_{56}Ba(\text{stable}) + \gamma(662\ \text{keV})$$

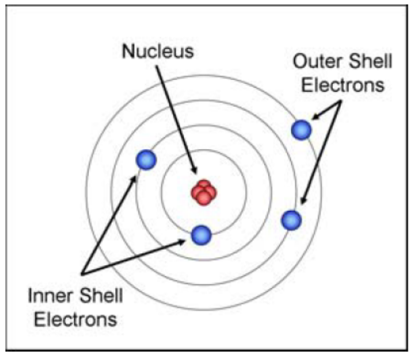
The gamma rays produced by this decay can be thought of as a continuous stream of particles emitted at high energies into the formation. These gamma rays, upon interacting with electrons in the formation, will lose some of their initial energy. The amount of such energy loss can be related to the physical characteristics of the formation, including its density and lithology.

Energy Loss in Gamma Rays

Gamma rays emitted from the Cs-137 source have an initial energy of 662 keV. As these gamma rays travel out through the formation they collide with the electrons of atoms. With each collision, a gamma ray loses some of its energy and is deflected, or scattered, along a different path of travel. Gamma rays undergo many such collisions with some being scattered back to the detectors of the tool while others are simply scattered deeper into the formation and become undetectable. Ultimately, after a number of these collisions and when the energy level of a scattered gamma ray drops below about 100 keV, it can be absorbed by an electron. As a result of scattering and absorption in the formation, a wide range of gamma ray energy levels is measured at the tool's detectors.

The amount of energy lost by a gamma ray in one collision depends in part upon whether it collides with an outer shell electron or an inner shell electron of an atom. Electrons are subatomic particles that orbit the nucleus of an atom in discrete spheres, or shells. Each shell is characterized by a different binding energy which is the attractive force between all electrons within that shell and the nucleus of the atom. The binding energy of inner shell electrons is the greatest and increases proportionally to the atomic number (Z) of the nucleus while the binding energy of outer shell electrons decreases with greater distance from the nucleus.

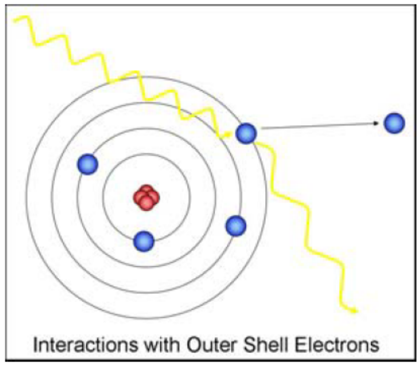
Figure 1. Inner and outer electron shells of an atom.



At higher energy levels (> 100 keV), gamma rays interact with outer shell electrons of the atoms (Fig. 2). If the gamma ray energy is much greater than the electron's binding energy, then the electron takes on some of that energy and is ejected from its shell. The gamma ray is then scattered along a different path of travel and at a lower energy level. Such interactions with outer shell electrons are lithology-independent. The smaller binding energy of an outer shell electron has a weak relationship to the atom's atomic number (Z). Therefore, the energy loss experienced by a gamma ray in its collision with an outer shell electron is independent of the rock's molecular composition.

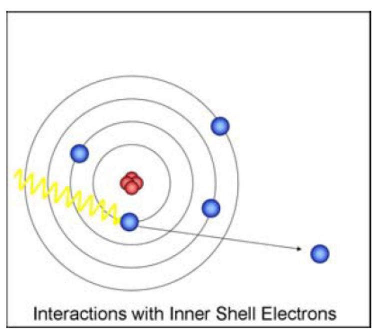
[1] An electron volt (eV) is a unit of energy equal to the kinetic energy acquired by an electron passing through a potential difference of 1 volt. A gamma ray with an energy of 662 keV (kilo-electron volt) would have the same striking power as an electron accelerated through a 662,000 volt potential.

Figure 2. Gamma ray interaction with an outer shell electron.



At lower energies (< 100 keV), gamma rays are capable of interacting with inner shell electrons of atoms (Fig. 3). If the gamma ray energy is slightly greater than the electron's binding energy, then all of the gamma ray's energy is transferred to the electron. The electron is ejected from its shell, but the gamma ray is absorbed and ceases to exist. These interactions with inner shell electrons are lithology- dependent. The larger binding energy of an inner shell electron has a strong relationship to the atom's atomic number (Z). Therefore, the energy loss experienced by a gamma ray when it is absorbed by an inner shell electron does depend upon the rock's molecular composition.

Figure 3. Gamma ray interaction with an inner shell electron.

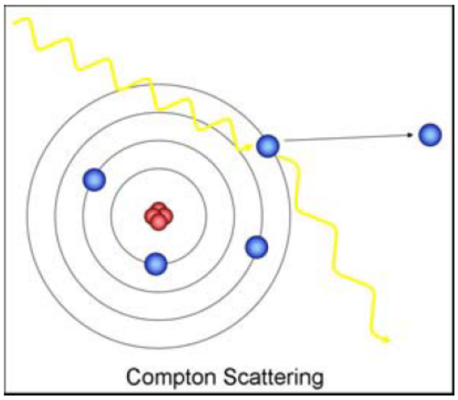


Compton Scattering

Compton scattering is the most important lithology-independent mechanism by which gamma rays interact with electrons. Through this process, a higher energy (> 100 keV) gamma ray collides with an outer shell electron and transfers some of its energy to that electron (Fig. 4). The electron is ejected from its shell and the gamma ray, having lost some of its energy, is scattered along a different path of travel.

Numerous Compton events can result in a single gamma ray reaching a much lower energy level before being detected. However, a gamma ray might suffer such extreme energy loss in multiple Compton events that it is absorbed before it can ever be detected.

Figure 4. Compton scattering interaction with an outer shell electron.



For sedimentary formations with low atomic number components, the probability that a Compton event will occur is lithology-independent and proportional only to the formation's electron density, ρe (units: number of electrons/cm3). The greater the number of electrons present in the formation, the greater the likelihood that this type of interaction will occur. Electron density (ρe) can be related to a formation's bulk density, or ρb (units: grams/cm3), by the following equation:

$\rho b = 1.0704\rho e - 0.1883$

Where: ρb = bulk density of formation (grams/cm3)

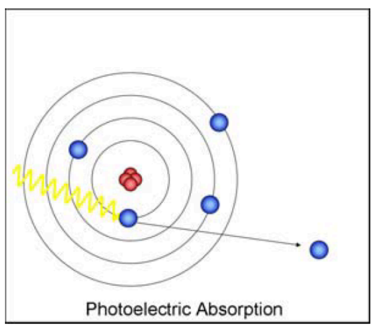
ρe = electron density of formation (number of electrons/cm3)

Therefore, to obtain a measure of a formation's bulk density (ρb), it is necessary to concentrate on those gamma rays detected by the tool at energy levels of greater than 100 keV.

Photoelectric Absorption

Photoelectric absorption is the most important lithology-dependent mechanism by which gamma rays interact with electrons. During photoelectric absorption, a lower energy (< 100 keV) gamma ray collides with an inner shell electron and transfers its entire energy to that electron (Fig. 5). The excited electron is ejected from its shell, but the gamma ray ceases to exist (it is absorbed). Photoelectric absorption ensures that many low energy gamma rays never reach the tool's detectors; however, some low energy gamma rays are not absorbed and are eventually detected.

Figure 5. Photoelectric absorption interaction with an inner shell electron.



The probability that photoelectric absorption will occur is proportional to the atomic number (Z) of the atom responsible for the absorption. For atoms with low atomic numbers (i.e., those present in sedimentary formations), this probability is reflected by the photoelectric factor (Pe) which is defined by the following equation:

$$P_e = \left(\frac{Z}{10}\right)^{3.6}$$

Where: P_e = photoelectric factor (unitless)
Z = average atomic number of rock

The photoelectric factor (Pe) is proportional to the number of gamma rays measured within the Compton scattering range to the number of gamma rays measured within the photoelectric absorption range:

$$P_e \propto \frac{\text{gamma rays in Compton scattering energy range}}{\text{gamma rays in photoelectric absorption energy range}}$$

Therefore, to have a useful method of estimating lithology it is necessary to measure a wide range of gamma ray energies. Compositionally pure formations (e.g., pure quartz sandstone, pure limestone, etc.) have characteristic values of Pe (Fig. 6) depending upon their molecular compositions.

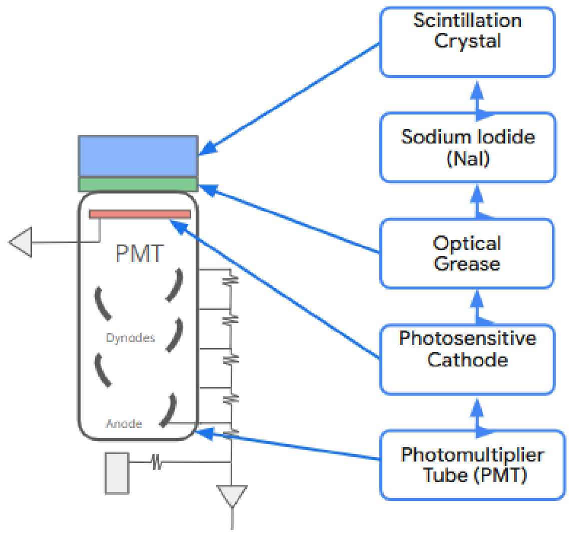
Figure 6. Typical Pe values for selected minerals.

Lithology	Pe
Quartz (Sandstone)	1.81
Calcite (Limestone)	5.08
Dolomite	3.14
Anhydrite	5.05

Scintillation Detection

The Density Porosity Tool employs scintillation detectors (Fig. 7) to measure the amount and energy level of scattered gamma rays. These detectors are positioned at different distances (or spacings) from the gamma ray source and are known as the short-spaced and long-spaced detectors. A gamma ray reaching one of these detectors interacts with a man-made crystal of sodium iodide (NaI) to create a tiny pulse, or scintillation, of visible light. The NaI scintillation crystal is coupled to a photosensitive device, or photo-multiplier tube (PMT), using optical grease that allows the passage of light. This PMT consists of a photo-sensitive cathode, a series of dynodes at successively higher potentials, and a collection anode.

Figure 7. Schematic of a scintillation detector.



The photo-sensitive cathode of the PMT emits electrons each time it is struck by a light pulse passed from the scintillation crystal. These electrons pass through a high voltage field to the first dynode where they have high enough energy to produce several more secondary electrons. These secondary electrons are accelerated to the next dynode in the series where additional multiplication takes place. The avalanche of an ever-increasing number of secondary electrons is ultimately collected at the anode of the PMT which then generates a small electrical pulse for each gamma ray detected. The height of this pulse is proportional to the energy level of the detected gamma ray.

Bulk Density Computation

Once electron density (ρe) is derived from the count rates it must be corrected for borehole diameter and mud weight. The count rate equations used to determine electron density were modeled for an 8-inch borehole filled with fresh water. Electron density will, therefore, be in error unless the borehole diameter and mud weight of the well in which the measurement is made are considered.

Variations in borehole diameter and mud weight adversely affect the number of gamma rays returning to a detector, resulting in values of electron density that are slightly in error. Drilling fluid additives such as hematite and barite compound this effect (iron and barite are efficient gamma ray absorbers). A minor correction is added to the electron density (ρe) measurement for borehole diameters and mud weights different than 8-inches and 8.33 pounds per gallon, respectively. Following the borehole diameter and mud weight correction, bulk density (ρb) is then derived from the electron density measurement by the following industry standard equation:

$$\rho b = 1.0704\rho e - 0.1883$$

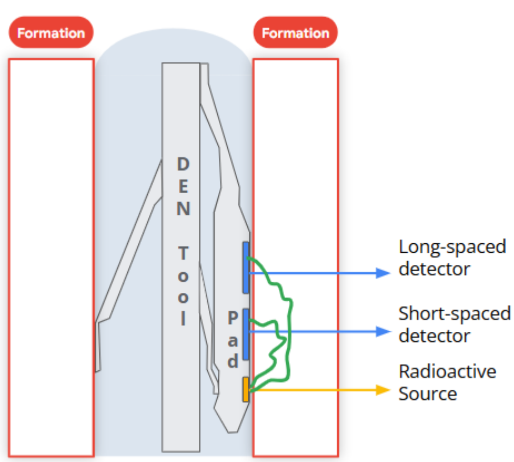
Where: ρb = bulk density of formation (grams/cm3)

ρe = electron density of formation (number of electrons/cm3)

Density Correction for Stand-Off (CORP)

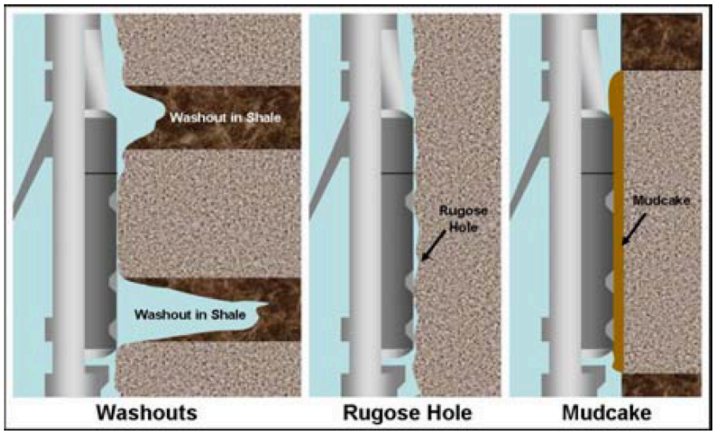
The count rates of gamma rays are used to determine the bulk density (ρb) of the formation. This type of measurement could be performed with a single detector, but would require that detector to be in direct contact with the formation at all times (Fig. 8). In such a case, the count rates of gamma rays would be proportional to the scattering and absorption properties of only the formation.

Figure 8. Hypothetical single-detector density tool in direct contact with the formation. Measured count rates would be proportional only to formation properties.



In open hole, different situations arise that cause a detector to not be in direct contact with the formation (Fig. 9). The presence of washout, rugose or irregular borehole conditions, and mudcake all contribute to detector stand-off. Stand-off is defined as a physical separation between a detector and the formation.

Figure 9. Examples of stand-off conditions in open hole.



Where stand-off is present, a detector is not in direct contact with the formation. Therefore, the count rates of gamma rays within each window are dependent upon the scattering and absorption properties of both the formation and the material—either drilling fluid or mudcake—filling the void between a detector and the formation. Stand-off causes slight differences between the computed value of bulk density (ρb) of a formation and its true density. A correction (called density correction) is applied real-time to the computed bulk density value to correct for the effects of stand-off.

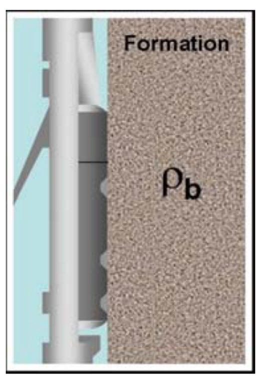
To help minimize and otherwise compensate for the effects of stand-off, the Density Porosity Tool employs more than one detector. In this case we will use as a reference a tool using 2 detectors. The long-spaced detector is mainly sensitive to gamma ray scattering and absorption occurring within the formation. The short-spaced detector, with its shallower depth of investigation, is more susceptible to the scattering and absorption properties of any material creating stand-off. Detectors of the Density Porosity Tool are mounted in a moveable pad (Fig. 10) that is deployed from the body of the tool to ensure good contact with the borehole wall.

Figure 10. Deployable pad of the Density Porosity Tool being removed from the mandrel for calibration.

Although the moveable pad does bring the detectors into contact with the borehole wall, stand-off can still exist between the detectors and the formation because of borehole rugosity or mudcake. In dramatic washouts the pad (and, therefore, the detectors) can lose contact with the borehole wall entirely.

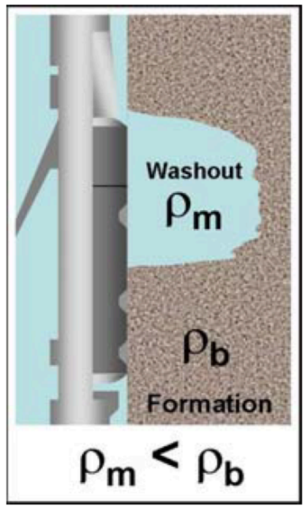
An ideal condition would exist when there is no stand-off and the detectors are in direct contact with the formation (Fig. 11). In this case, the count rates of both detectors would provide for an accurate measure of formation bulk density (ρb). Because stand-off does not influence the count rates, density correction will be zero.

Figure 11. Dual detectors in direct contact with the formation. In this condition, density correction will be zero.



In washouts the Density Porosity Tool pad loses contact with the borehole wall and drilling fluid is introduced into the void between the detectors and the formation (Fig. 12). The density of drilling fluid is usually much less than the density of the formation. Therefore, in washouts the computed bulk density (ρb) of the formation is less than its true density. In this case, a positive correction is applied to compensate for stand-off created by the washout.

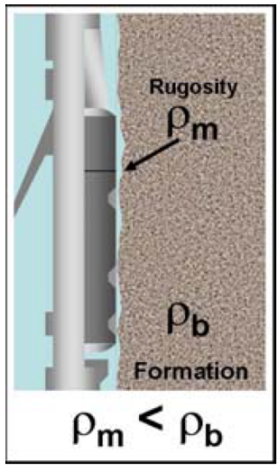
Figure 12. Washout results in a positive correction to bulk density.



The magnitude of this positive correction depends upon the stand-off distance the mud density. As stand-off distance increases, both detectors become more sensitive to the drilling fluid than to the formation, and the magnitude of the positive correction increases.

Rugose borehole conditions exist when the drilling process has resulted in a formation having a rough or irregular drilled surface. In these situations, the detectors cannot consistently maintain direct contact with the formation and small amounts of drilling fluid exist between the detectors and the formation. This rugosity results in a positive correction; however, the magnitude of this positive correction is much smaller than for washouts because of the smaller stand-off distance.

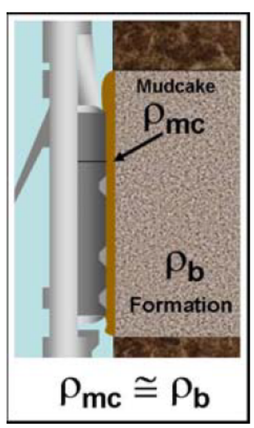
Figure 13. Rugose boreholes result in a small positive correction to bulk density.



Permeable formations are characterized by the development of mudcake which also creates stand-off between the detectors and the formation. The influence of this stand-off (and, therefore, the severity of the correction applied) depends upon both the thickness of the mudcake (hmc) and the contrast between its density and the density of the formation.

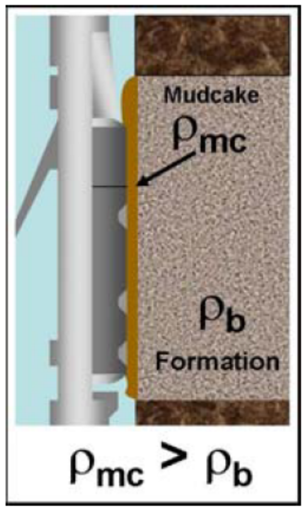
In most normal drilling fluid cases, mudcake density is approximately equal to formation density (Fig. 14). Therefore, little—if any—correction is applied to compensate the computed bulk density (ρb) for mudcake stand-off effects in normal mud conditions.

Figure 14. Normal mudcake results in a negligible correction to bulk density.



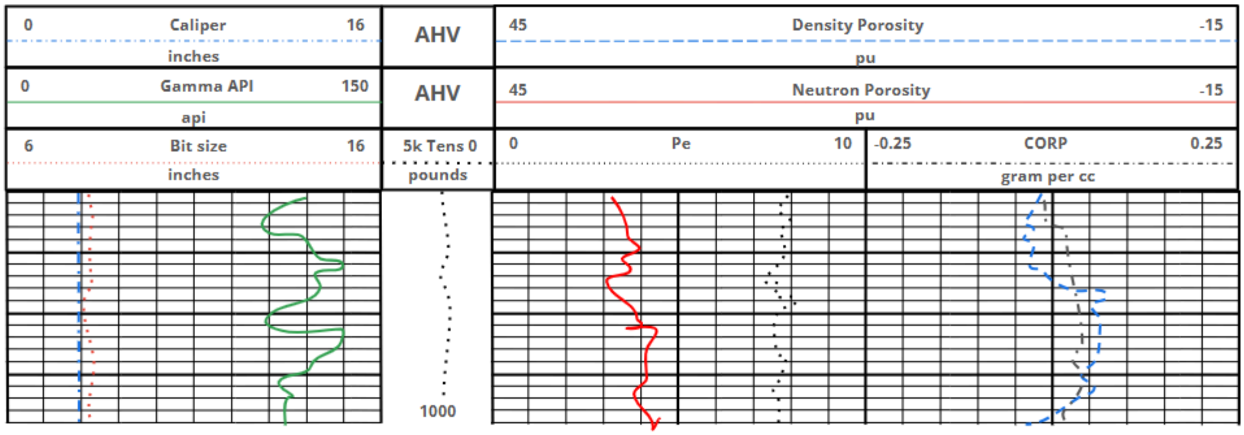
As the contrast between the density of the mudcake and the density of the formation varies, the magnitude and direction of correction changes. In situations where mudcake density is less than formation density (e.g., light-weight drilling fluids) a small positive correction is applied (Fig. 15). However, where very dense weighting additives such as hematite or barite are added to the drilling fluid, the density of the mudcake can be greater than the density of the formation. In these "heavy mud" cases, the correction applied to compensate for mudcake stand-off is negative.

Figure 15. Heavy mud results in a negative stand-off correction to bulk density.



Errors in the computed bulk density (ρb) caused by stand-off are represented on a log by the correction curve (we will call it CORP for this example) (Fig. 16). Stand-off can be created by the presence of washouts, rugose borehole conditions, and mudcake adjacent to permeable formations. CORP can display a value that is less than, equal to, or greater than zero, depending upon the density contrast between the stand-off material—either drilling fluid or mudcake—and the formation. The magnitude of this correction depends upon the stand-off distance.

Figure 16. The CORP curve of this neutron-density porosity log.



It is important to realize that the bulk density (ρb) measurement appearing on a log has already been corrected for the effects of stand-off. Therefore, the CORP curve can be used as a quality indicator of how much correction was required to compensate for the effects of stand-off resulting from washout, borehole rugosity, or mudcake.

Density Correction for Mudcake Lithology

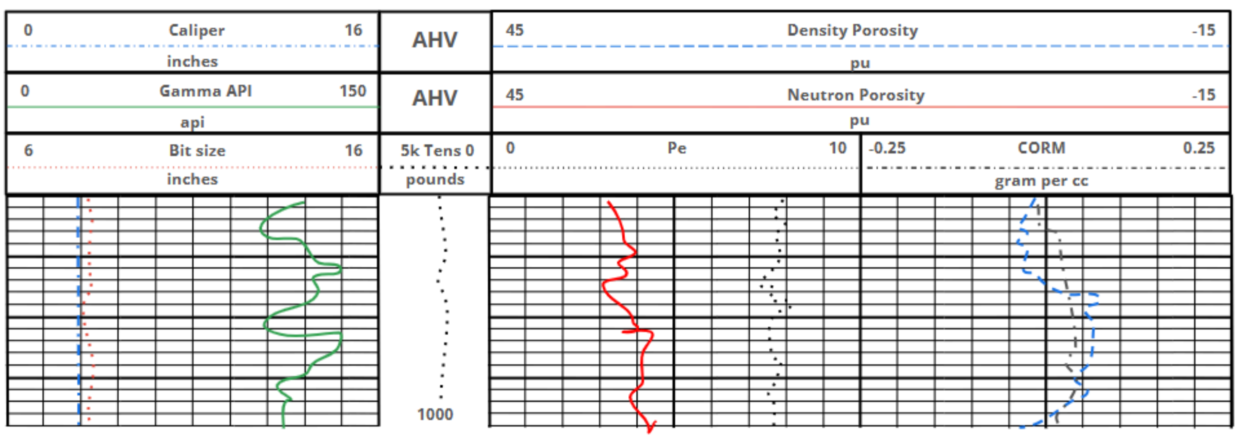
Stand-off causes errors in the computed bulk density (ρb). These errors result from a contrast between the density of the formation and the density of the material creating the stand-off (drilling fluid or mudcake). The effects of stand-off are compensated by the application of CORP (correction plus).

Errors in the computed bulk density (ρb) can also result from a contrast between the lithology of the formation (L) and the lithology of the mudcake (Lmc). In normal drilling fluids, mudcake lithology is very similar to formation lithology; therefore, there is little contrast between the two and the resulting error in ρb is small. In heavy drilling fluids—particularly those weighted with barite—there can be a significant contrast between mudcake lithology and formation lithology. The resulting lithology-related errors on the computed bulk density (ρb) must be considered separately from stand-off related errors.

Barite-weighed drilling fluid produces an extremely dense mudcake. The density of this mudcake can be greater than that of the formation, thus resulting in a negative CORP (stand-off correction, or correction plus). The barite mudcake will also have a lithology effect because of barite's ability to absorb gamma rays. With barite in the mudcake, fewer low-energy gamma rays are. When barite is present, statistical accuracy is improved by eliminating from the calculations the long-spaced detector which is more susceptible to this reduction in count rates count rates of the short-spaced detector are also influenced by this mudcake lithology effect, although less severely than the long-spaced detector. As a result, an additional negative correction is required to compensate bulk density (ρb) for the barite mudcake and, therefore, bring it closer to the true density of the formation.

Errors in the computed bulk density (ρb) caused by mudcake lithology are represented on a log by a curve (we will call it CORM correction minus) curve (Fig. 17). Mudcake lithology usually only presents a problem in barite-weighted drilling fluids. The magnitude of this correction depends upon the lithology contrast between the formation and the mudcake. In the presence of barite mudcake, CORM displays a value that is less than zero, the magnitude of which is related to the barite concentration of the mudcake and mudcake thickness.

Figure 17. The CORM curve this neutron-density porosity log. Both CORM and CORP are typically presented together.



It is important to realize that the bulk density (ρb) measurement appearing on a log has already been corrected for the effects of mudcake lithology. Therefore, the CORM curve can be used as a quality indicator of how much correction was required to compensate for the effects of lithology on bulk density values in barite mudcake situations.